Formal analysis of confidentiality conditions related to data leakage

Ibrahim Shiyam

Doctor of Philosophy

University of York
Computer Science

September 2016

This thesis is dedicated

To my parents, Zareena Ali and Ali Hassan Fulhu,
for their endless love and support throughout my life.

To my wife Fathimath Humam and daughter Aishath Zara Shiyam,
for their patience and understanding.

To my brother, Ahmed Shah Ali,
for always being there for me.

Abstract

The size of the financial risk, the social repercussions and the legal ramifications resulting from data leakage are of great concern. Some experts believe that poor system designs are to blame. The goal of this thesis is to use applied formal methods to verify that data leakage related confidentiality properties of system designs are satisfied. This thesis presents a practically applicable approach for using Banks's confidentiality framework, instantiated using the *Circus* notation.

The thesis proposes a tool-chain for mechanizing the application of the framework and includes a custom tool and the Isabelle theorem prover that coordinate to verify a given system model. The practical applicability of the mechanization was evaluated by analysing a number of hand-crafted systems having literature related confidentiality requirements.

Without any reliable tool for using BCF or any *Circus* tool that can be extended for the same purpose, it was necessary to build a custom tool. Further, a lack of literature related descriptive case studies on confidentiality in systems compelled us to use hand-written system specifications with literature related confidentiality requirements.

The results of this study shows that the tool-chain proposed in this thesis is practically applicable in terms of time required. Further, the efficiency of the proposed tool-chain has been shown by comparing the time taken for analysing a system both using the mechanised approach as well as the manual approach.

Contents

List of Tables

List of Figures

Acknowledgements

This work was supported by a scholarship from the Islamic Development Bank (IDB).

First and foremost, I thank my mother Zareena Ali and my father Ali Hassan Fulhu for going the whole nine yards to support me throughout my life.

I am indebted to my supervisor Jeremy Jacob for believing in me and for trusting me through the rugged terrain of my PhD journey. To benefit an open door policy from my supervisor was a testament of his support towards my research. Thank you for not giving up on me the day I walked in and told that I must pursue the impractical path of manually evaluating systems if I am to make progress towards my goal.

I thank my wife Fathimath Humam for her sacrifice and understanding throughout the length of this journey. I can't thankyou enough. It was my best source of inspiration that my lovely daughter Aishath Zara Shiyam understood and mentioned often on her own that her 'daadoo' needs to do his never ending work to get his 'third hat'.

A special thank you to my brother Ahmed Shah Ali who has support me throughout this journey and throughout my life.

Apart from my supervisor, my dear friend Pedro De Oliveira Salazar Ribeiro has been the most significant contributor to my research in terms of being a sound board as well as a wonderful critique. I thank my colleague Gerard Ekembe Ngondi for being my other sound board and critique, especially towards the final months of my PhD.

In the PLASMA group, I must specially thank José Manuel Calderón Trilla and Glyn Faulkner for the valuable discussions in functional programming. And to Rudy Braquehais for giving me a crash course on property based testing.

I thank the various people who have explained me various concepts during the various stages of my journey including Michael J. Banks for the lengthy Skype conversation to explain me the lifted semantics, Leonardo de Freitas for agreeing for me to visit his office at the University of Newcastle and explaining and showing me the guts and bones of the CZT tool, Simon Foster for introducing me to the Isabelle/UTP framework, Frank Zeyda[1] and Neeraj Kumar Singh[2] for the valuable advice on shaping my approach towards customising the Isabelle/UTP framework and finally Jan Burse[3] and Abderrahmane Feliachi[4] for Isabelle theorem prover related discussions.

A special thanks to Jim McCarthy of the Department of Defence in Australia for contacting me almost 10 months later to let me know that they had declassified the Z mathematical tool-kit which was classified at the time I had requested for it.

I thank Justice Hassan Saeed and my dear friend Sharif Ahmed of the Family Court in the Republic of Maldives for assisting me in getting the case management procedure of that court. Finally, I thank my friends Dr. Faisal Saeed and Dr. Mohamed Adil for devoting their valuable time for me to test my technical explanations on them, the positive feedback of which was used to adjust the explanations so that people from outside the domain can understand.

[1] University of Newcastle

[2] University of Toulouse

[3] XLOG Technologies GmbH

[4] RATP Group

Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

1 Introduction

1.1 Confidentiality

Confidentiality is one of the three classic goals of the data security triad where the other two are integrity and availability (Article 29 Working Party, 2013, p. 27). Confidentiality of a system is an assurance that information will not be leaked to an unauthorised audience by that system. Confidential information may include Personally Identifiable Information (PII) (Antón and Earp, 2001) and business secrets amongst other things. Disclosure of confidential information has the potential to compromise privacy, results in huge financial losses and also have social repercussions. The massive data leakage of Personally Identifiable Information of 33 million users at Ashley Madison in 2015 (BBC News, 2015) is a perfect example of such damage. However, this has been dwarfed by the recent announcement of the 2014 data breach at Yahoo Inc. (The New York Times Company, 2016).

> "*Security experts say the breach could bring about class-action lawsuits, in addition to other costs. An annual report by the Ponemon Institute in July found that the costs to re-mediate a data breach is $221 per stolen record. Added up, that would top Yahoo's $4.8 billion sale price*"
> (The New York Times Company, 2016).

The financial aspects of such data leakages in organisations has been published in the media (see Table 1.2). However, the author was not able to find details on the approaches which the perpetrators used for stealing confidential information from these organisations[1]. Therefore, there is no way to conclude whether these data leakages were due to poor system design. Studies conducted by security experts such as Cast Software .Inc (2014), Verizon Enterprise Solutions (2014) and Depaula (2016) have identified poor system design as one of the reasons for data leakage. One such aspect of a poor system design can be the inconsistency between the functional requirements of a system and its confidentiality requirements. If a functional requirement and a confidentiality requirement of a system are inconsistent, confidential data maybe revealed through an implementation that only satisfies such a functional requirement.

To address the thesis scope and challenges, one must consider system development approaches that ensure that the confidentiality requirements are engineered into the design of an information system. Further, one must ensure that the chosen approach supports a mathematically accurate transformation from a system model to an implementation.

1.2 Confidentiality engineering

Confidentiality engineering can be defined as the integration of tools and techniques within the system development process whereby practitioners can verify the conformance of a system design against a given set of confidentiality requirements. Given that confidentiality is a non-functional property[2], how can engineers verify whether the design of a system respects both the functional as well as the non-functional requirements of a system? Model driven verification (Holzmann and Joshi, 2004) and formal

---

[1] The author did find such information for the Target data leakage. The approach is reported as follows. "According to Krebs, sources close to the investigation said the attackers first gained access to Target's network on Nov. 15, 2013 with a username and password stolen from Fazio Mechanical Services, a Sharpsburg, Pa.-based company that specializes in providing refrigeration and HVAC systems for companies like Target.

Fazio apparently had access rights to Target's network for carrying out tasks like remotely monitoring energy consumption and temperatures at various stores.

The attackers leveraged the access provided by the Fazio credentials to move about undetected on Target's network and upload malware programs on the company's Point of Sale (POS) systems"
(IDG Communications, 2013).

[2] In the field of software engineering, functional requirements describe what the system is supposed to do whereas non-functional requirements describe the qualities of the system functions (Onabajo, 2009, p. 21).

Thesis scope and challenges

The focus of the research presented in this thesis is on analysing models of information systems for data leakage, by detecting inconsistencies between functional requirements and confidentiality requirements. The motivation for this research is discussed in Section 1.4

The hypothesis presents two main challenges.

1. Find an approach for system engineers to verify whether their system designs respect the data leakage related confidentiality requirements of a system.
2. Find an approach for system engineers to ensure that their system designs are transformed into implementations that are correct by construction.

These challenges demand the need for system development approaches where the engineers can verify that:

- The system designs are confidentiality assuring.
- The step by step transformation from system designs to implementation can be verified as preserving the embedded confidentiality assurances.

verification (Blanchet, 2008; Hadj-alouane et al., 2005) are different approaches whereby system designs can be verified for conformance to a given set of requirements.

Banks's Confidentiality Framework (BCF) (Banks, 2012), discussed in this thesis, is based on aspects of the information flow theories by Jacob (1988) and Morgan (1998). Using BCF, the information flow in a system can be analysed. Login and logout functions that are usually implemented to secure a system are part of an access control mechanism that does not protect against information flow related security issues.

> *"Information flow (IF) analysis is a suitable verification technique that focuses on the information propagation throughout the system (end-to-end) rather than mere data access (point-to-point). IF analysis can identify leaks, so-called interferences, that circumvent access control mechanisms"*
> (Accorsi and Wonnemann, 2010, p. 194).

The case for formal methods. Formal methods are techniques based on mathematics to describe system properties.

> "*A method is formal if it has a sound mathematical basis, typically given by a formal specification language. This basis provides the means of precisely defining notions like consistency and completeness and, more relevantly, specification, implementation, and correctness*" (Wing, 1990, p. 8).

Correctness of a system can be described as an assurance that a software does exactly what it is supposed to do. This assurance is often seen as a reflection of the success percentage of applying a collection of test scenarios on the system. However some of the correctness demanding systems such as mission critical systems, military systems and life-saving systems needed a much more correctness-guaranteed approach for their design, development and verification (Cofer, 2010; Hall and Chapman, 2002). This is due to the criticality of the target application environment as well as the financing involved in such huge projects. The approach for testing systems using test cases does not provide such correctness guarantees as the set of test cases define a finite set of scenarios.

> "*Program testing can be used to show the presence of bugs, but never to show their absence!*" (Dijkstra, 1972).

Potter, Sinclair and Till (Potter et al., 1996b) believe that formal methods was born out of this push towards assuring the 'accuracy and correctness' of software. This belief was further supported by many academics in the software engineering discipline where they commonly agreed that errors introduced early in the development process are much harder and time-consuming to fix if detected later and also consequently cost a lot more (Woodcock and Davies, 1996, p. 1; Bowen, 1996, p. 31; Peine et al., 2008, p. 9; Defence Science and Technology Organisation, 2008, p. 4; Cant et al., 2002, p. 2; Sommerville, 2010, p. 243) .

Confidentiality vs. Privacy. Many researchers including Jamal et al. (2014), Hayashi (2013), Moore and McSherry (2013), McClelland (2002), Mayer (2002), Anderlik and Rothstein (2001) and Mlinek and Pierce (1997) argue that people often use the terms *confidentiality* and *privacy* interchangeably. For example, Hansen (1971), Mayer (2002) and Tschantz and Wing (2008) used the word *privacy* interchangeably with *confidentiality*, when discussing techniques that are used to analyse scenarios with a confidentiality requirement.

Both these words are used in relation to information secrecy. The topic of this thesis is focused on proposing an approach to make a certain confidentiality framework practical. Therefore, it is important to clarify the difference between these two terms and explain how one is related to the other.

A knowledge map of the field of information security research is presented in Figure 1.1. The objective of presenting Figure 1.1 is to show the association between *confidentiality*, *privacy* and *security* which are sometimes used interchangeably. Further, the knowledge map also highlights the area of the information security research discussed in this thesis.

privacy refers to "the right of individuals or cooperative users to maintain confidentiality and control over their information when it's disclosed to another party" (Porambage et al., 2016, p. 37).

confidentiality refers to "the assurance on non-disclosure of sensitive resources to unauthorised subjects" (Margheri et al., 2015, p. 34).

In summary, *privacy* is an individual's desire for information secrecy whereas *confidentiality* is an assurance for information secrecy. Privacy demands form a subset of information secrecy requirements, where other requirements might include secrecy of company information or government information, to name but two.

As shown in Figure 1.1, there are many aspects of confidentiality such as legal (Al-Fedaghi, 2012, p. 6), financial (Rubinstein, 2011, p. 1456), ethical (Orb et al., 2001) and data leakage related (Gordon, 2007) to name a few. In this thesis, we consider the data leakage related aspect of confidentiality. An introduction to data leakage is given in Section 1.3.

1.3 Data leakage through communication channels

Shabtai et al. (2012, p. 5) state that data leakage is the intentional or unintentional distribution of private or sensitive data to an unauthorised entity. Private and sensitive data are considered confidential and may include personal, corporate, military or government data. Some intentional and unintentional activities that may result in a data leakage are shown in Figure 1.2.

Different technological approaches are being used to provide data leakage detection and prevention such as designated Data Leak Prevention (DLP) systems[3], access control and encryption mechanisms, advanced/intelligent[4] security measures and standard security measures such as firewalls, antivirus systems and intrusion detection systems.

Apart from direct theft, data leakage may occur as a result of poor information infrastructure design (Cast Software .Inc, 2014; Depaula, 2016; Verizon Enterprise Solutions, 2014) as well as poor data management practices amongst others. Among the mechanisms that may help in detecting and mitigating data leakages, is the implementation of information security policies. The information infrastructure of an organisation must be governed by such policies to ensure that the security of the data is always maintained whether in transit or at rest. This includes integrating such policies within the top-level

[3] "*Designated DLP solutions are intended to detect and prevent attempts to copy or send sensitive data, intentionally or unintentionally, without authorization, mainly by personnel who are authorized to access the sensitive information*" (Shabtai et al., 2012, p. 9).

[4] "*Advanced or intelligent security measures include machine learning and temporal reasoning algorithms for detecting abnormal access to data*" (Shabtai et al., 2012, p. 9).

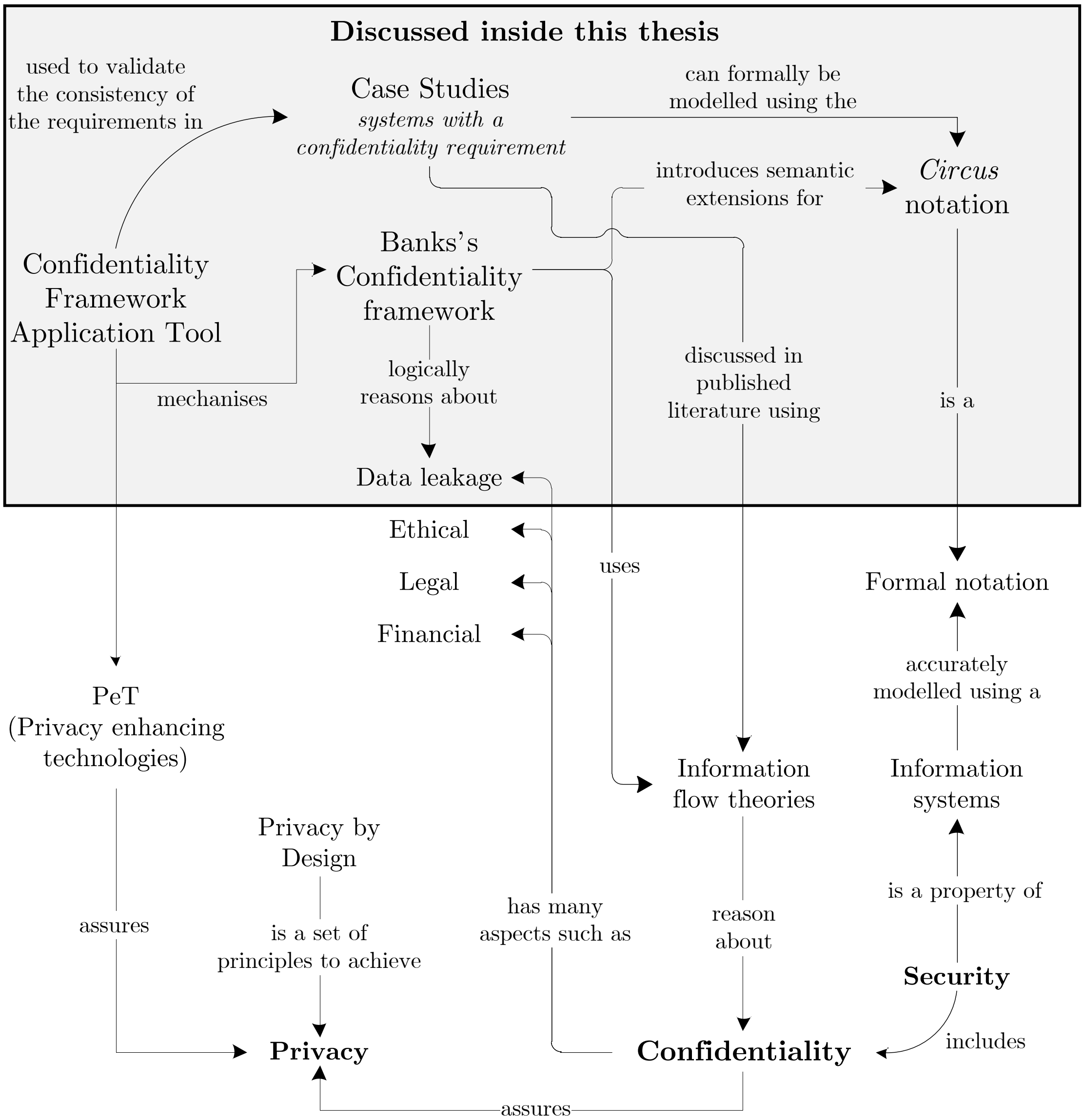


Figure 1.1: How the work in this thesis is related to the rest of the information system security research

design of information systems. The focus of the research in this thesis is to provide a practically applicable approach for using a formal framework that supports such integrations.

Channels are used to communicate information between agents[5] in an information system. Within the context of an information system, an individual with a low security clearance may use various channels to gather data that maybe classified at a higher classification. Such channels may include *side channels*, *covert channels*, *inference channels* and *overt channels*.

side channel A side channel is a physical observable side-effect of a computation, that an adversary can measure (Lawson, 2009, p. 65).

covert channel A covert channel is described as "any communication channel that can be exploited by a process to transfer information in a manner that violates the systems security policy" (Latham, 1986, p. 80).

inference channel An inference problem exists when a user with a lower security clearance uses information which he is authorized, to draw conclusions about information at a higher security clearance (Garvey et al., 1991, p. 119). Such a link that may allow the flow of information from a higher security class to a lower security class is an *inference channel*.

overt channel An overt channel is described as "a communication path within a computer system or network designed for the authorized transfer of data" (Lucena et al., 2006, p. 147).

BCF codifies the information a user may not gain by observing *overt channels* in an information system. The aim of this thesis is to extend the value of BCF. This has been achieved by mechanising BCF and evaluating the mechanisation to understand how effective it is for analysing system models for data leakages.

[5] "*Agents are active components forming the system. They can be humans, devices, legacy software, etc*" (De Landtsheer and Van Lamsweerde, 2005, p. 41).

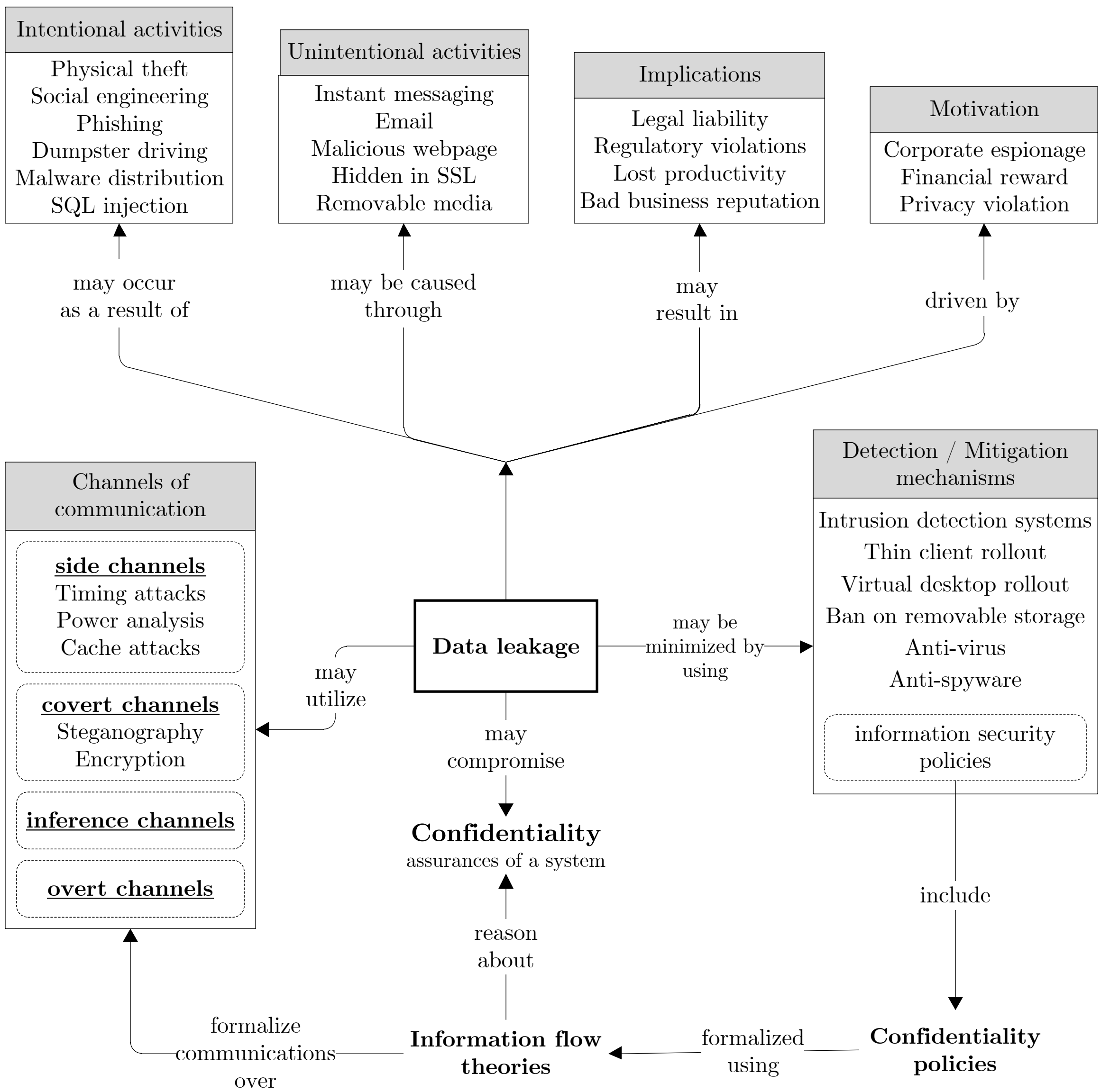


Figure 1.2: Aspects of a data leakage

1.4 Motivation

The regulatory demand for secure by design practices during system development and the size of the financial risk due to data leakage incidences motivate work on techniques to integrate confidentiality engineering during the system development process. System development practices that guarantee confidentiality, contribute towards assuring privacy as well as trustworthy computing. In this regard the work presented in this thesis is highly encouraging.

The untrusted access to confidential information leads to privacy violations. Such digital-era related privacy concerns have been raised as early as in the 1990s. One of the recommendations of the study conducted by The New York Public Service Commission during 1989 and 1990 on privacy in telecommunication services recommended that privacy promoting technologies should be encouraged in future service offerings (Rotenberg, 1993).

Technology and policy experts in security, privacy and networking who participated in the 2003 conference on the Grand Challenges in Trustworthy Computing organised by the Computing Research Association (2003) declared that:

- ensuring trustworthiness of important societal applications such as electronic voting systems and healthcare record databases is one of the great challenges in trustworthy computing.
- a possible progress on ensuring trustworthiness of important societal applications will be to assure users that systems are designed with strong mathematical guarantees that eventually can achieve confidentiality of records amongst other security requirements.

Even though software designers have started to include non-functional properties such as performance and reliability in the system development process, "security still remain an afterthought" (Giorgini et al., 2004, p. 2). The same issue has been highlighted by a number of author's (CAUSE, 1997, p. 3; Mouratidis et al., 2003, p. 63 ; Mouratidis et al., 2005, p. 610; Schumacher et al., 2005, p. xi; Weiss and Mouratidis, 2008, p. 169; Williams, 2009, p. 67; Churchill, 2009, p. 131; David and Prosch, 2010, p. 3 ; Le M'etayer, 2010, p. 323; Rubinstein, 2011, p. 1411; Le Métayer, 2011, p. 10 ; European Digital Rights, 2012, p. 8; Burgemeestre et al., 2013, p. 153 ; Cavoukian and Dixon, 2013, p. 212 ; El-Hadary and El-Kassas, 2014, p. 463) .

In this regard, this thesis explores ways in which the value of a validation framework for systems with a confidentiality requirement can be extended. The eventual goal is to have a well tested and mature confidentiality validation framework so that the framework can be integrated into professional software development tool kits. The work presented in this thesis contributes towards realising this goal.

1.4.1 Mandatory regulation demanding secure-by-design practices

Privacy legislations and regulations in many countries (General Services Administration, 2005; Office for National Statistics, 2002; Office of Parliamentary Counsel, 1988; U.S. National Institute of Standards and Technology, 2014) mandate that personally identifiable information must never be released to unauthorised individuals. However, decisions about the implementation mechanisms to achieve legislative compliance is solely left to the parties who handle personal data of individuals. Dr. Ann Cavoukian (2009) first introduced the phrase *Privacy by Design* (see Figure 1.1) to refer to such mechanisms, back in the 90s.

> "*Privacy by Design refers to the philosophy and approach of embedding privacy into the design specifications of various technologies*" (Cavoukian, 2009).

Both the preliminary and the final report of the U.S. Federal Trade commission (FTC) on "Protecting Consumer Privacy in an Era of Rapid Change" in 2010 and 2012 consecutively recommends companies to adopt *Privacy by Design* practices by building privacy at every stage of their product development (Federal Trade Commision (FTC), 2012; Federal Trade Commission, 2010). However, the FTC stopped short of using the phrase *Privacy by Design* in its call to the U.S. Congress, but rather requested them to consider enacting baseline privacy legislation and reiterated its call for data security legislation.

The General Data Protection Regulation of The European Parliament and The European Council (2016) states that organisations must implement "data protection by design and by default" whereby organisations must ensure that personal data will be "processed in a manner that ensures appropriate security of the personal data, including protection against unauthorised or unlawful processing and against accidental loss, destruction or damage, using appropriate technical or organisational measures ('integrity and confidentiality')". The European Digital Rights (2012) and European Parliament (2014) elaborate these measures by specifying that technical aspects should include the design of software and hardware and that organisational aspects should include internal and external policies and current best practices, a call advocated earlier by Dr. Ann Cavoukian (2009) and later repeated by the U.S. FTC (Federal Trade Commision (FTC), 2012; Federal Trade Commission, 2010).

This shows a shift from general compliance recommendations and directives towards legislation and regulation that mandates the adoption of secure-by-design practices during software design and development. It is also important to note here that this European Parliament regulation also applies to organisations outside the European Union (EU) that collect personal data from EU citizens. Hence, the regulation throws a broader net than the Euro-zone and practically covers all multinational companies in the world.

1.4.2 Cost of data leakages

Data leakages cost millions of dollars to companies around the world. For example, as per the Article 83 of the General Data Protection Regulation (The European Parliament and The European Council, 2016, p. 82), companies with severe data breaches will be fined either 2% of the company's worldwide annual turnover or €$10,000,000$ which ever is greater. In addition, a data leakage has many other associated losses including loss of customer confidence and legal fees and settlements related to multiple lawsuits.

Table 1.2 presents a list of major data leakages between 2011 to 2015 where each single breach compromised more than 1 million unique customer records. Table 1.1 presents the ratio of the cost of the data leakage to the net asset value of that company, just to give an idea of the size of the risk to an organisation from data leakage. This shows that data security translates into a financial risk for an organisation.

Organisation	Information lost	Records compromised (in millions)	Year	Net asset value of the company (in $M)	Cost of the data breach (in $M)	Risk ratio on net asset value of the company
Anthem Insurance[a]	personal information	80	2015	24,251	8,000	32.99%
The Home Depot [b]	personal and financial information	56	2014	12,520	8,120	64.85%

Table 1.1: Financial risk ratio against net asset value of two companies where more than 1 million records were compromised

[a] Company value has been taken from the 2014 Annual Report of Anthem, Inc. (Anthem, 2014) submitted to the U.S. Securities Exchange. When calculating the total cost of the data breach at Anthem, Inc., the stated lower bound of $100 (Lockton Inc., 2015) as the per record cost of the breach was considered.

[b] Company value has been taken to be the different between the total assets and liabilities in the Home Depot financial report in (MarketWatch, 2014). When calculating the total cost of the data breach at The Home Depot, the average cost of $145 paid for each stolen record in 2014 has been considered (Ponemon Institute LLC, 2014).

The cost of a data leakage cannot be realized for sometime. In the case of The Home Depot data breach, the 2014 annual report of The Home Depot (2014) has revealed that the gross expense for their 2014 data breach stood at $63m . However, the report also stated that "*We expect to incur significant legal and other professional services expenses associated with the Data Breach in future periods*". The 2015 annual report of The Home Depot (2015) has revealed that the gross expense related to its 2014 data breach had increased to $232m.

Organisation	Information lost	Records compromised (in millions)	Year	Source
Ashley Madison	personal info	33	2015	(BBC News, 2015)
TalkTalk	personal and financial info	4	2015	(Gemalto, 2015)
U.S. office of personnel management	personal info	21	2015	(Gemalto, 2015)
Experian	personal info	15	2015	(Guardian News, 2014)
Anthem Insurance	personal info	80	2015	(Lockton Inc., 2015)
Adult FriendFinder	personal info	3.8	2015	(Gemalto, 2015)
Community Health System	personal info	4.5	2014	(Verizon, 2015)
Experian	personal info	200	2014	(Guardian News, 2014)
The Home Depot	personal and financial info	56	2014	(The Home Depot, 2014)
JP Morgan	personal info	76	2014	(The New York Times Company, 2014)
eBay	personal info	145	2014	(Verizon, 2015)
Adobe	personal info	38	2013	(BBC News, 2013)
Target	personal and financial info	70	2013	(The Association of Data Protection Officers, 2015)
Evernote	personal info	50	2013	(The Association of Data Protection Officers, 2015)
Epsilon	personal info	60	2011	(The Association of Data Protection Officers, 2015)
Sony	personal info	78	2011	(The Association of Data Protection Officers, 2015)

Table 1.2: Data leakages between 2011-2015 where more than 1 million records were compromised

1.5 Hypothesis

Banks (2012) proposed a formal framework that can be used for the formal analysis of data leakage related confidentiality requirements in systems. Banks's Confidentiality Framework (BCF) can be used to demonstrate that the formal model of a system does not leak data through legitimate communication channels of the system in violation of any confidentiality requirements of the system. The manual application of BCF is practically infeasible (Section 4.2). Further, there are no tools that can be used to analyze system models using BCF. However, there are different tools and frameworks that can be used to derive and analyse formal predicates from system models, similar to BCF (Section 2.2).

The hypothesis

The hypothesis of this thesis is that a practically applicable approach exists that supports the process of analysing system models using Banks's Confidentiality Framework (BCF) (Banks, 2012) to verify if those models respect the integrated confidentiality requirements pertaining to data leakage through legitimate channels.

1.5.1 The challenges

In order to justify the hypothesis, the following issues were addressed.

- Identify the step-by-step process for applying BCF.
- Identify what is required for applying BCF such as:
  - how formal models of systems should be presented.
  - how confidentiality requirements should be encoded in system models.
- Identify how the process of applying BCF can be automated.
- Identify how the predicates generated through BCF can be translated to a format that can be simplified by a tool.
- Identify a tool that can simplify complex predicates.
- Identify a formal language that can be used to specify systems and confidentiality requirements in a way that the combined specification can be type checked with an existing tool.

1.5.2 Testing the hypothesis

In order to test the hypothesis, the following tasks were required.

1. Constructing a tool-chain for analysing systems using BCF.
2. Using the tool-chain to analyse purpose written specifications based on typical system scenarios in which data leakage is a known issue.
3. Carrying out the following types of tests.
   a) Multiple tests that show that analysing a system using BCF confirms that the confidentiality requirements are respected in a given specification, if there were no contradictions in the system specification.
   b) A test that shows that BCF correctly flags an issue that is not apparent with a seemingly correct specification.
   c) A test that shows that BCF correctly flags an issue with a specification that has an artificially inserted inconsistency within its functionality and confidentiality requirements.
4. Comparing the time taken to analyse systems using the tool-chain and comparing it with manual application to show the value of the mechanisation.
5. Demonstrating the practical applicability of the mechanisation by showing that confidentiality requirements related to data leakage through legitimate channels can be generalised into patterns that supports tool based analysis.

1.6 Contributions

Major contributions of this thesis are:

1. Proposing a practical approach for using Banks's Confidentiality Framework (BCF), to reason about the conformance of a system to a given set of data leakage related confidentiality requirements, by developing a mechanisation for BCF (contribution from *Chapter 4*).

2. Identifying and extracting generalized patterns of confidentiality requirements from literature, where these requirements are related to data leakage in systems through overt channels (contribution from *Chapter 5*).

3. Demonstrating the value of the proposed mechanisation by using it to analyse systems with data leakage related confidentiality requirements. This includes:

   a) Carrying out a comparison of execution times during the manual vs. mechanised application of BCF (contribution from *Chapter 4*).

   b) Reviewing the time consumed for the mechanised application of BCF on hand-crafted systems with varying degrees of complexity, with a confidentiality requirement that reflects a generalized pattern (contribution from *Chapter 6*).

1.7 Thesis structure

The structure of the thesis is as follows.

Chapter 2 presents a discussion of the preliminary knowledge that is required to follow this thesis.

Chapter 3 presents the mechanisation of BCF. The chapter discusses ways in which a practically applicable approach can be developed for BCF.

Chapter 4 presents a discussion on the approach which has been followed in this research to evaluate the mechanisation of BCF.

Chapter 5 presents a systematic literature search for confidentiality related discussions in order to identify common recurring patterns of confidentiality requirements. Further, an approach for deriving generalized patterns of confidentiality requirements is also presented.

Chapter 6 presents a case study analysis where systems with confidentiality requirements, that represent instances of patterns of confidentiality requirements, has been analysed. A formal model has been developed for each system and the results of the mechanised analysis has been presented and compared.

Chapter 7 presents an evaluation of the research in this thesis. Further, this chapter discusses the future directions in which the work pursued in this thesis may be extended. The chapter further summarises the overall contributions, findings and limitations of the work presented in this thesis.

2 Background

2.1 Introduction

The research presented in this thesis establishes a practically applicable approach for the analysis of data leakage in systems with a confidentiality requirement. The approach is based on the mechanisation of BCF (Banks, 2012). BCF is based on Unifying Theories of Programming (UTP) by Hoare and He (1998) and has been instantiated using the *Circus* notation (Oliveira et al., 2009). The denotational semantics of the *Circus* notation is based on UTP. This chapter provides an account of the preliminary knowledge which the user must be equipped with in order to understand the technical content in this thesis.

First, a discussion about the rationale behind selecting BCF for analysing data leakage related confidentiality requirements in systems is presented. This includes a comparison of BCF with research carried out by other researchers in the realm of formal analysis of confidentiality. Next, the chapter introduces the reader to UTP, discusses how the concept of BCF is captured in UTP, introduces the *Circus* notation and explains how UTP forms the basis for the notation, describes how systems are modelled using the *Circus* notation, describes how BCF is instantiated for *Circus* and discusses how BCF in *Circus* can be used to analyse data leakage related confidentiality requirements in systems.

2.2 Analysing systems with a confidentiality requirement

This section reviews some existing formal approaches for analysing systems with a confidentiality requirement. The Figure 2.1 shows the stage of the system development where each approach is utilised. These approaches will be discussed later in this section. The approaches discussed include PROMELA and the SPIN model checker (Holzmann, 1997), SecureUML (Basin et al., 2003), Secure Tropos (Bresciani et al., 2004), CoNaN tool (Cerny and Alur, 2009a), InDico (Accorsi and Wonnemann, 2010), CONCHITA using KAOS (De Landtsheer and Van Lamsweerde, 2005), TEES framework (Howitt, 2008) and Confidentiality properties and the B Method (Onunkun, 2012).

In addition, the Figure 2.1 includes the techniques *abuse case* and UML-RT to *Circus* transformation. Even though these techniques are not used for analysing confidentiality in systems, *abuse case* is included in Figure 2.1 to show that there is a possible alternative to the existing KAOS technique used in CONCHITA, whereas UML-RT to *Circus*, which is discussed later in Section 2.5.2, is included to show the stage of the system development process where UML-RT to *Circus* is utilised.

This section presents a critical analysis of BCF by discussing the comparative advantages and limitations of BCF with respect to other proposed approaches shown in Figure 2.1.

Abuse case. McDermott and Fox (1999) define *abuse case* as a complete interaction between an actor and the system that is harmful to the system, one of the actors or to one of the stakeholders of the system. McDermott and Fox (1999) introduced the notion of *abuse case* to enable engineers to model possible harmful scenarios of system interactions in such a way that the artefact could be understood by both the user as well as the customer.

Abuse case and KAOS shown in Figure 2.1 are both goal-oriented requirement engineering approaches that can be used for deriving security requirements from security goals. However, they differ in how they derive and model security requirements.

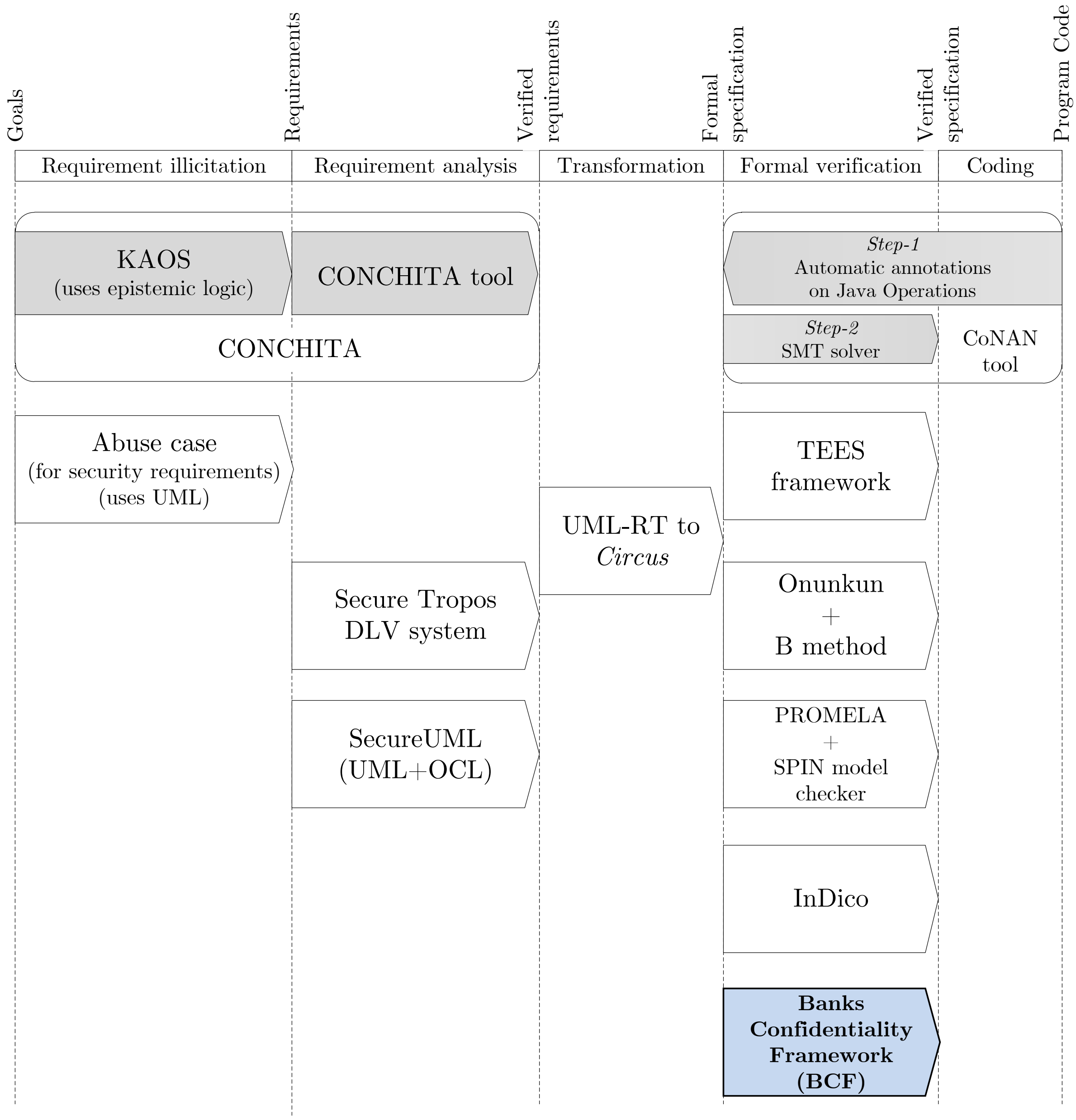


Figure 2.1: Approaches for eliciting, analysing, transforming and formally verifying confidentiality properties in systems

- Knowledge Acquisition in autOmated Specification (KAOS) specification language contains formal definitions in temporal first-order logic for components of the system meta-model (Black, 2009, p. 22). These components include system goal, agents, actions, entities and the relationships between them. KAOS addresses security requirements by way of anti-goals (Lamsweerde, 2004).
- *Abuse case* uses the UML (Rumbaugh et al., 2004) approach for modelling possible harmful scenarios of system interactions.

> "*In the requirement phase, the abuse case helps in gaining better understanding of system security between stakeholders, especially users and customers. Any security design trade-offs can be made easily*"
> (Srivatanakul, 2005, p. 76).

PROMELA and the SPIN model checker. The Protocol/Process Meta Language (PROMELA) (Holzmann, 1997) is a language for modelling finite state machines. It allows a user to model concurrent processes. PROMELA supports embedded C code. Communication between the processes are established through channels defined for message passing. The Simple Promela INterpreter (SPIN) (Holzmann, 1997) analyses the logical consistency of concurrent systems. SPIN supports the PROMELA modelling language. A PROMELA model consists of a number of processes templates with at least one instantiation (Holzmann, 1997). The SPIN model checker translates each template into a finite automaton. The global system behaviour or state space of the system is represented by computing asynchronous interleaving of all the finite automaton. Security properties are modelled as claims in Linear Temporal Logic (LTL). SPIN converts the encoded security properties to a Büchi automaton[1] (Büchi, 1960) and computes the synchronous product of this

[1] The Büchi automata extends the theory of finite automata on finite words to languages over infinite words. "While finite runs of finite automata are accepting if an accepting state is visited at the end of the run, an infinite run of a Büchi automaton is accepting if a final state is visited (or a final transition is taken) infinitely many times during the course of the run. The Büchi acceptance condition thus specifies a set of states (or transitions) that have to be visited (respectively, taken) infinitely often" (Varghese, 2014, p. 1).

automaton and the automaton representing the global state space. The model checker visits every reachable state and also remembers all the states it has visited (Wang et al., 2000, p. 50). The memory requirement to store this information and resources required to traverse the state space depends on the size of the state and the number of reachable states and can be resource intensive depending on the given system specification. Edelkamp et al. (2001) combined SPIN with HSF (Edelkamp, 1999) heuristic search workbench to develop the LISP SPIN tool that can traverse large state spaces more efficiently than SPIN.

The model checker either validates the given security property or else a counter example is produced that shows how the violation can take place. Some other researchers have used SPIN to model and analyse confidentiality properties of systems as described below.

Dabaghchian and Abdollahi Azgomi (2015) used embedded C code in PROMELA to model a variant of the observational determinism confidentiality property. Observation determinism ensures confidentiality in concurrent programs by assuring that public variables and private variables are kept independent during the execution of a program.

Ahmed and Tripathi (2003) used SPIN to model and verify confidentiality properties of a Computer Supported Cooperative Work (CSCW) system. They re-modelled the course activity case study by Foley and Jacob (1995). In this thesis, the same system has been modelled and analysed using BCF (Banks, 2012).

Having to remember every visited state is the biggest limitation of SPIN. Further, the specifications that can be written using PROMELA are restricted to the available PROMELA templates. However, BCF is defined using the UTP framework and can be instantiated for a range of UTP theories as shown by Banks (2012). Therefore a broad set of features can be supported by instantiating BCF on relevant UTP theories than in SPIN+PROMELA.

SecureUML - Integrating UML based process modelling and RBAC. Basin et al. (2003) proposed an approach to integrate RBAC based security policies into formal system models by using OCL constraints in UML. The resulting UML based language is called SecureUML. The RBAC policies imposed by OCL constructs are used to derive the precondition for every action in a UML class. Further, they integrate SecureUML with a process modelling language by defining a dialect that identifies process elements as protected resources. The semantics of this dialect uses a form of weakest pre-condition computation to decide whether a user is allowed to execute a particular process element. The process models are translated to implementations of controller objects for multi-tier applications. They evaluate their approach by generating prototypes using an extended version of a tool called ArcStyler[2] (Basin et al., 2003, p. 8).

SecureUML integrates security into formal models of systems. However they do not provide an approach for verifying those models. The fundamental objective of BCF is to provide an approach for verifying confidentiality integrated formal models of systems.

Secure Tropos - Secure requirements engineering with reasoning. Tropos (Bresciani et al., 2004) is an agent based software engineering methodology. Tropos lacks the ability to capture the functionality and security features of an organisation at the same time. Giorgini et al. (2004) extended Tropos by defining predicates that represent properties of actors and trust properties between actors. These predicates are combined to form security properties in the form of axioms. These axioms are formalized as a datalog[3] logic program and analysed using the DLV system (Leone et al., 2006). Consistency checks guarantee that the security specification is not self contradictory (Giorgini et al., 2004).

[2] ArcStyler "provides a transformation function for converting UML classes and state machines into controller classes for web applications, executed in a Java Servlet environment" (Basin et al., 2003, p. 8).

[3] Abiteboul et al. (1995, p. 273) give an introduction to the datalog language.

Secure Tropos utilizes a graphic model of a system whereas BCF utilizes a formal specification based model of a system. It is not clear how a formal specification of a Secure Tropos based model can be derived so that the specification can be refined to an eventual implementation. However, with certain instantiations of BCF, this is possible.

ConAn tool - Automated confidentiality analysis. Automated program checking for confidentiality by Cerny and Alur (2009a) presents a notion of confidentiality based on possibilistic reasoning. The tool supports a subset of Java that includes boolean variables, integer variables, data variables and variables that range over an infinite domain. However, only equality tests on data variables are supported.

A program execution produces an observation with respect to a condition *cond*. If two executions exist where, in one execution a confidentiality predicate *secret* holds and in another execution the same confidentiality predicate *secret* does not hold, then the two executions will be indistinguishable to the observer, hence achieving confidentiality.

The proposed ConAn tool takes in a program in Java bytecode, a condition *cond*, a confidentiality predicate *secret* and some other required parameters. The tool automatically inserts annotations to the Java program that record user observations based on program execution. The tool generates formal scripts compatible with the Yices SMT solver (Dutertre, 2014). The Yices SMT solver decides satisfiability of the resulting formulae.

Automated program checking for confidentiality related to data leakage is specific to a subset of Java constructs whereas BCF is defined at a higher level since BCF is based on a formal notation and not specific to any programming language.

The approach for verification does not start from a formal specification but rather reverse engineers a program to derive a set of formal scripts which then get evaluated. Data leakage in *Circus* models can be verified using BCF and subsequently those models can be refined to be implemented in any supported programming language. The ConAn tool based approach is limited to restricted Java based implementations of systems, whereas since BCF supports verification of system models at the formal specification level, this limitation does not exist.

InDico - Automated analysis of business processes for confidentiality. Accorsi and Wonnemann (2010) proposed an approach for information flow analysis in business processes. First, a formal model of a business process is developed. For example, the Business Process Model and Notation (BPMN) (White, 2004) can be used for this. The model is mapped to a coloured Petri Net (Jensen, 1987). Next, the activities of the resulting IFnet's[4] are labelled with security labels. Analysis of the IFnet relies on a manual verification process. The first step is to inspect the IFnet for structured patterns that might leak information. The second step is to check whether the identified patterns are reachable within a run of the system. This is a state space explosion problem when processes have non-trivial number of states. Therefore, the approach is not practical for non-trivial processes and also has scalability issues due to a manual analysis approach. Further, this approach supports only non-interference properties.

In comparison to InDico, BCF is not limited by state explosion and scalability because BCF validates a system based on predicates which can be machine evaluated.

CONCHITA framework. The CONfidentiality CHecker for Incremental Threat Analysis (CONCHITA) by De Landtsheer and Van Lamsweerde (2005) is a reasoning framework based on bounded model checking and constraint solving techniques. Formal system models are defined using the goal oriented software requirements engineering methodology called KAOS (Van Lamsweerde et al., 1991). The knowledge of agents at specific states in the system are captured using epistemic constructs. These epistemic constructs are combined with LTL (Linear Temporal Logic) (Pnueli, 1977) to define axioms that capture the interaction between

[4] An IFnet is a specialization of coloured petri nets for work-flow modelling and information flow analysis (Accorsi and Wonnemann, 2010, p. 195).

knowledge and time. A set of templates that represent specification patterns for confidentiality requirements are given. Specifiers must utilize one of these templates to define their confidentiality claims. CONCHITA propositionalizes the input specification and confidentiality claims. The resulting propositions are converted into non-temporal logic versions by defining the length of the trace as a given bound. The confidentiality verification problem is translated to a constraint satisfaction problem by quantifying confidentiality patterns over the user agent's finite bound of knowledge of the system. The resulting constraint is analysed using the Oz constraint solver (Henz et al., 1993) which presents a counter example if the knowledge of a user agent contradicts with the quantified confidentiality claim.

CONCHITA depends on a limited set of templates that can be used to define confidentiality requirements whereas BCF does not have this limitation. Further, BCF uses the *Circus* notation that represents system entities and state variables more closely than epistemic logic used in CONCHITA.

TEES confidentiality model. The TEES confidentiality model (Howitt, 2008) is an authorisation model that utilizes both Role-Based Access Control (RBAC) (Ferraiolo and Kuhn, 1992) and Identity-Based Access Control (IBAC) that includes override. The model is based on a state machine approach and is formalized using the B notation and verified using the Rodin B-toolkit (Butler and Hallerstede, 2007). TEES concentrates on the antecedent of a conditional confidentiality requirement[5] where TEES defines the condition under which the confidentiality of a state variable must be maintained. However, BCF is more flexible in that BCF can additionally define the degree of confidentiality of a state variable. For example, consider a set S that represents the set of bids in an auction. BCF can be used to define a confidentiality property where either all values of S can be kept secret or a defined subset of values of S can be kept secret.

[5] A conditional confidentiality requirement is equivalent to a conditional information flow, a flow of information that only occurs when some condition is met at runtime (Tschantz and Wing, 2008, p. 108).

Confidentiality Properties and the B Method. Onunkun (2012) proposes a framework to reason about information flow security in B machines. The framework is restricted to Multi Level Security properties. In this framework, state variables are mapped to security classes in a security flow lattice. The framework extends the flow logic analysis approach proposed by Clark et al. (2002). Reasoning about the information flow is based on predicates computed based on this extension. Even though the B machines were checked with Atelier-B (2017) for consistency, it is not clear from Onunkun (2012) as to how the described information flow violations were detected using the custom tool which Onunkun (2012) had developed.

BCF detects information flow violations through inconsistencies in a computed predicate similar to that in Onunkun's method. However, BCF is not restricted to Multi Level Security properties only.

As can be seen from Figure 2.1 , the approaches based on Secure Tropos and SecureUML are utilized in the requirement analysis phase. However, there is little research on how the requirements phase is reconciled with the formal specification phase (Nakagawa et al., 2007, p. 531). The work by Nakagawa et al. (2007) is an attempt towards bridging this gap by proposing an approach to generate formal specifications based on VDM++ (Durr and van Katwijk, 1992) from KAOS models.

None of the above approaches support the analysis of a concrete formal specification of a system where confidentiality requirements can be modelled using constraints on the channels through which a system communicates with its environment. However, the instantiation of BCF (Section 2.6) discussed in thesis supports supports such constraints. The features in Table 2.1 are considered as critical criteria based on which BCF has been selected for analysing systems with a confidentiality requirement.

Table 2.1 identifies at least one limitation of each approach in comparision to the BCF approach for analysing data leakage related confidentiality requirements in systems.

Feature	BCF	PROMELA	SecureUML	Secure Tropos	CoNaN	InDico	CONCHITA	TEES
Not restricted by templates	✓	×			×		×	
Supports formal analysis of confidentiality properties in system models	✓		×	×				
Not limited by state explosion problem	✓					×		
Not restricted by Multi-Level Security properties	✓							×

Table 2.1: Features supported by the various approaches for analysing confidentiality requirements

A tick (✓) denotes that the particular feature is available in the related formal approach. A cross (×) denotes that the particular feature is not available in the related formal approach. A blank denotes that the author has not verified the availability of the particular feature in the related formal approach. It is not necessary to identify all the features supported by each approach as the intention of this table is to show that none of the approaches except BCF support all the features listed in the table.

2.3 Banks's confidentiality framework (BCF)

Banks (2012) introduced BCF for the formal analysis of confidentiality requirements in systems related to data leakage. BCF uses the general Unifying Theory of Programming (UTP), and BCF has been instantiated (but not automated) for the *Circus* notation (Oliveira et al., 2009). Hereafter, the phrase "BCF in *Circus*" will be used when referring to this instantiation. BCF combines functionality and confidentiality requirements within a formal framework to allow the specification of systems that are secure-by-design (Banks and Jacob, 2011).

As per Kerckhoffs' Principle, 'security through obscurity' is considered bad practice in the design of a system (Kerckhoffs, 1883). In line with Kerckhoffs' Principle, BCF assumes that the adversary who wants to learn confidential information from the system may have knowledge about the complete source code of the system.

Section 2.4 introduces UTP, describes the concept of BCF in UTP and discusses some of the challenges that arise in automating a framework based on UTP. Section 2.5 gives a brief introduction to the *Circus* notation, discusses how BCF has been instantiated for the *Circus* notation and outlines some of the advantages of using *Circus* models in detecting data leakage in systems.

2.3.1 The conceptual basis for BCF

The development of information flow security theories has been a gradual process. Denning (1976) proposed a lattice model of secure information flow and provided a formal semantics for the formal verification of information flow in program specifications. Other notable information flow properties discussed in the literature include Goguen and Meseguer's Non-Interference (Goguen and Meseguer, 1982), Sutherland's Non-Deducibility (Sutherland, 1986), Jacob's Inference function (Jacob, 1988), McCullough's Generalized Non-Interference (Mccullough, 1988), O'Halloran's Non-inference (O'Halloran, 1990), McLean's Generalized Non-inference (McLean, 1994) and Zakinthinos's Perfect Security Property (Zakinthinos and Lee, 1997).

BCF is loosely based on the user inference function proposed by Jacob (1988). Further, BCF adapts the idea of Morgan's *shadow* semantics (Morgan, 2009). Both Jacob's inference function and Morgan's *shadow* semantics are described below.

Jacob's User Inference. Sometimes a system might only require hiding the occurrences of certain properties of *high*[6] events, rather than all *high* events and the knowledge about the occurrence of other *high* events are considered acceptable. To cater for

[6] Events executed by a user in a higher security level than an ordinary user of the system.

such scenarios, there was a need for a formal approach to calculate how much a group of users can infer about the events executed by another group of users in a system.

Jacob (1988) proposed the inference function to carry out such calculations. The inference function calculates how much a user U can infer about the interactions of other users in a system S, by carrying out an interaction allowed for the user U. This is an observation based approach where the set of all possible observations which the user U can make by interacting with S is syntactically written as $S@U$ and is called the *projection* of U onto S (Jacob, 1988, p. 15). The set of all traces in the system S is denoted by τS. For any trace t, where $t \in \tau S$, U can only observe parts of t that is visible to U through its window which is defined as $t \upharpoonright U$. The *projection* of U onto S is defined as follows.

$$S@U \mathrel{\widehat{=}} \{t \upharpoonright U \mid t \in \tau S\}$$

After observing the output X of an interaction l with the system S, the user U can calculate all possible traces which could have generated the observation X. This is a general approach suitable for calculating the amount of knowledge a user can obtain by interacting with the system.

Morgan's *shadow* semantics. Classical refinement does not preserve ignorance[7] related properties. This phenomenon commonly known as the *refinement paradox* was first identified by Jacob (1988). Morgan's approach (Morgan, 2009) consists both in resolving the *refinement paradox* as well as maintaining the uncertainty during the refinement of sequential programs.

A system state might have a visible as well as a hidden state space based on the security policy requirements of the system. A variable h whose observations are to be kept secret is part of the hidden state space. In addition, Morgan

[7] An observer's ignorance of data is his/her uncertainty about the parts of the program state which he/she cannot see (Morgan, 2009, p. 2).

> introduces a third (set valued) variable to the hidden state space called the *shadow*, which consists of all potential values of the variable h in the hidden state space, including the current value of h. Consider the scenario where an adversary has the complete knowledge of the source code, can view the visible part of system state (based on his authorisation) as well as have the knowledge of the program flow. However because of the uncertainty about the hidden state space due to atomic non-determinism (introduced by the *shadow*), the adversary cannot deduce for sure, the exact value of the variable h in the hidden state space.

Banks (2012) borrowed the concept of *shadow* variables from Morgan (2009). In BCF, the concept of *shadow* variables is established by introducing the concept of a *shadow* system, where the variables in the *shadow* system reflects the same from the original system, under certain user observations. BCF in *Circus* also borrows the concept of the *inference function* from Jacob (1988). BCF in *Circus* provides an inference function that can be used to calculate the possible observations a user can make about the state space of a system by his/her interactions. BCF in *Circus* assumes that the calculated observation of the state space of a system is always a reflection of the state space of the associated *shadow* system.

2.3.2 Advantages and limitations of BCF

The following are some of the advantages of BCF.

BCF being based on UTP. Since BCF is based on UTP, the underlying concept can be specialised for other UTP theories. Banks described how BCF can be specialised for the *theory of designs* (Banks, 2012, p. 35) and the *theory of reactive processes* (Banks, 2012, p. 40). Banks has also instantiated BCF using the *Circus* notation as stated before in page 53. In this thesis, this instantiation has been used in analysing data leakage in systems with a confidentiality requirement.

BCF based analysis involves a comprehensive search of the state space. BCF uses logical expressions to capture the knowledge about the entire state space of a program at any given state.

The following are some of the limitations of BCF.

Weak notion of confidentiality. BCF reasons about the existence of at least one alternative explanation when hiding the value of a state variable. This is a weak notion of confidentiality when compared to Caroll Morgan's *shadow* semantics (Morgan, 2009). In the *shadow* semantics, a set of other possible alternative explanations exist for each hidden value.

Tedious, time consuming and error-prone calculations required in BCF. The calculations required to analyse a system using BCF is tedious, time consuming and error-prone since the probability of human errors exists in any activity related to manually manipulating large blocks of formulae text (Verma, 2011, p. 11).

Requirements must be written specific to a given system. When using BCF, confidentiality requirements must be written specific to a given system and cannot be expressed in a more abstract or generalized manner.

2.4 Unifying Theories of Programming (UTP)

BCF is a generic formal approach defined in Unifying Theories of Programming (UTP). UTP is a unified framework for formal program semantics, which can be used to formally specify systems (Hoare and He, 1998). UTP is a mathematical treatment of computer programming using the simple non-deterministic programming language introduced by Dijkstra (1975).

In the UTP semantics, all the possible observations of executing a program are captured in a predicate (Hoare and He, 1998). Each variable in the predicate models an attribute of the system. The following example describes a universal observation of a system where an attribute x of the system is defined to be greater than 0 and another attribute

y is defined to be greater than x.

$$x > 0 \wedge y > x \tag{2.1}$$

Valid observations of the system may include ($x = 5$ & $y = 6$) or ($x = 12$ & $y = 13$). However, as per the predicate in Equation (2.1), observations such as ($x = 0$ & $y = 1$) or ($x = 3$ & $y = 2$) are not valid. Such observations cannot exist in practice.

2.4.1 UTP theories

A unified theory in UTP is comprised of *alphabets*, *signatures* and *healthiness conditions*[8]. In addition to the observational variables in a system, a UTP theory may contain other variables which are also called auxiliary variables (Foster and Payne, 2013; Oliveira et al., 2009; Verma, 2011) that record certain properties about the execution of a program. The *alphabet* of a program conforming to such a UTP theory includes these auxiliary variables. A *signature* of a UTP theory for a programming language consists of a set of operators and atomic components that represent the constructs of a programming language (Hoare and He, 1998, p. 12). A set of basic *signature*s common to a range of programming language theories are listed in Table 2.2. *Healthiness conditions* are idempotent functions[9] that define the subset of predicates that satisfy a given UTP theory. The *theory of relations* (Hoare and He, 1998), the *theory of designs* (Hoare and He, 1998), the *theory of reactive processes* (Wei, 2013, p. 3) and the *theory of reactive designs* (Cavalcanti and Woodcock, 2006) are UTP theories that form the foundation of the *Circus* theory (Oliveira et al., 2009), the semantic basis for the *Circus* notation. The build up to the theory of *Circus* from the *theory of relations* is shown in Figure 2.2. The following is a brief introduction to each of those theories.

[8] Healthiness conditions of a UTP theory are higher order predicates, that select only some predicates as meaningful in that particular UTP theory. Healthiness conditions are often written as fixed point equations such as $P{=}H(P)$, where P represents a predicate and H is a predicate transformer.

[9] "An idempotent function is a function f, where $f(f(x)) = f(x)$ for all x" (Gormish et al., 1997, p. 8).

Operation	Syntax	Semantics	Description
Assignment	$a := e$	$a' = e \wedge x' = x$	state variable a is assigned the value of e and all other variables (denoted by x) remain unchanged
Sequential composition	$P\,;\,Q$	$\exists\, x_0 \bullet P[x_0/x'] \wedge Q[x_0/x]$	sequential composition between the programs P and Q is the relational composition of their intermediate state
Conditional	$P \lhd b \rhd Q$	$(b \wedge P) \vee (\neg\, b \wedge Q)$	a program that behaves like P if b is true, or like Q if b is false. b is a truth function without dashed variables.
Skip	Π	$x' = x$	does not change the program state in any way and all state variables (denoted by x) remain unchanged
Non-determinism	$P \sqcap Q$	$P \vee Q$	the greatest lower bound between the programs P and Q

Table 2.2: A set of basic *signatures* common to a range of programming language theories

Theory of relations. In the UTP *theory of relations* (Hoare and He, 1998), every programming construct is formalised as a relation between an initial observation and an intermediate or a final observation of a system. Any variable in a program predicate can also be decorated with a prime ($'$) to denote the value of the same variable immediately after the execution of the program. The undecorated counterpart represents the value of the observation before the execution of the program. The observations made before and after the execution of the program can be combined to form a UTP *relation* which describes the relationship between the initial and intermediate or final observation of the system.

For example, assume that the initial observation of the system in Equation (2.1) is such that $x = 3$ and $y = 16$. Now, run the program statement:

$$x := x * 5 \tag{2.2}$$

The following UTP *relation* represents the initial and final observation resulting from executing the program statement in Equation (2.2).

$$x = 3 \wedge x' = 15 \wedge y = 16 \wedge y' = 16$$

The *theory of relations* does not distinguish between terminating and non-terminating programs (Cavalcanti et al., 2006, p. 210).

Theory of designs. A program statement written with preconditions and postconditions and which respects certain *healthiness conditions* is called a *design*. The theory of designs introduces two observation variables where:

- *ok* indicates that the program has started.
- *ok'* indicates that the program has terminated.

The subset of relations that conform to the *theory of designs* (Hoare and He, 1998) must respect the healthiness conditions **H1** and **H2** (Hoare and He, 1998, p. 281).

$$\textbf{H1}(P) \mathrel{\widehat=} ok \Rightarrow P$$

$$\textbf{H2}(P) \mathrel{\widehat=} P \; ; \; ((ok \Rightarrow ok') \wedge v' = v)$$

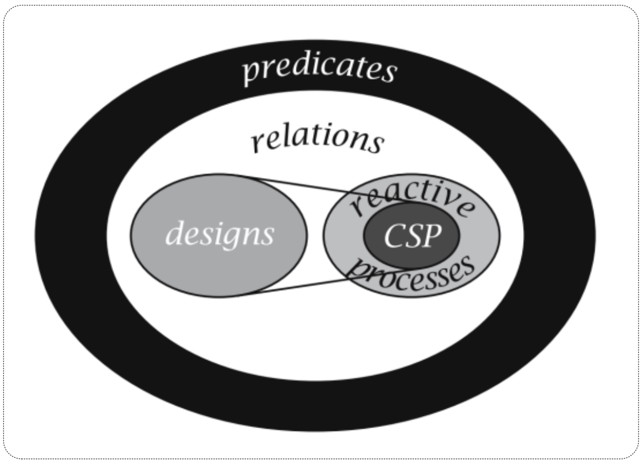
where P is a relation with the alphabet $\{ok, ok', v, v'\}$ and v represents all state variables of the system except ok and ok'. If P is **H1** healthy then any observation on P can only be made after the program has started. If P is **H2** healthy then the program must always terminate.

Theory of reactive processes. A reactive process is a program which may engage with its environment and whose behaviour might depend on these interactions (Wei, 2013, p. 3). In addition to ok and ok', the theory of reactive processes introduces the variables $wait$, tr and ref and their primed counterparts where:

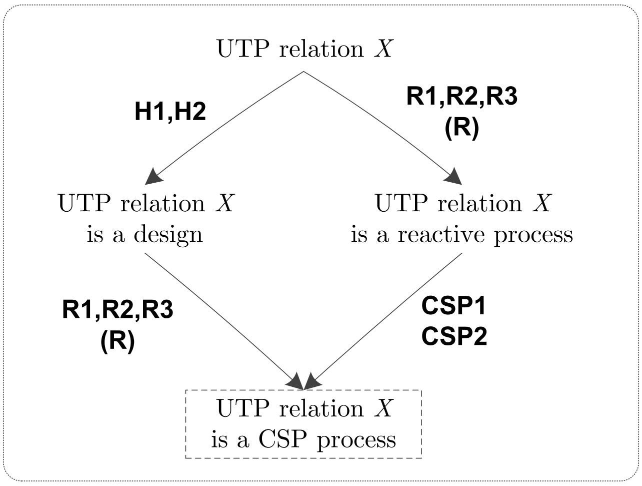
- if $wait'$ is **True** then P is in an intermediate state.
- if $wait'$ is **False** then P has successfully terminated.
- if ok' is **True** then the state of P depends on $wait'$.
- if ok' is **False** then P has diverged.
- tr - sequence of events that have occurred up to the start of P.
- tr' - sequence of events that have occurred after the start of P, to the point when the subsequent observation is made.
- ref - events that P may have refused to participate in, up to the start of P.
- ref' - events that P may have refused to participate in after the start of P, to the point when the subsequent observation is made.

where P is a process. The undashed variables ok and $wait$ represents the similar states of the predecessor of P.

A reactive process P must satisfy the healthiness conditions **R1**, **R2** and **R3** where



UTP theories



Healthiness conditions of UTP theories

syntax	semantics
Z notation	as UTP relations
CSP notation	
Djkstra's guarded commands	
Morgan's specification statements	

The theory of *Circus*

Figure 2.2: UTP theories, healthiness conditions and the theory of *Circus*

R1 states that P must never change history, **R2** states that tr has no influence on the behaviour of P and **R3** states that P has no effect on the observation before it starts execution (Wei, 2013, p. 4). A reactive process is a fixed point on the function composition **R** where:

$$\mathbf{R}(P) \mathrel{\widehat{=}} \mathbf{R1} \circ \mathbf{R2} \circ \mathbf{R3}(P)$$

Theory of reactive designs. The *theory of reactive designs* (Oliveira et al., 2009) combines the valuable qualities of both the *theory of designs* (Hoare and He, 1998) and the *theory of reactive processes* (Cavalcanti and Woodcock, 2006, p. 240) where:

> the ability to model programs in terms of preconditions and postconditions in the *theory of designs*

is combined with,

> the ability to capture the intermediate behaviour of programs in the *theory of reactive processes*.

"The space of *reactive designs* is a sub-space of the *reactive processes*, which is derived by applying **R** to the space of designs" (Banks, 2012, p. 14).

Theory of CSP. Hoare and He (1998) and Cavalcanti and Woodcock (2006) extend the *theory of reactive designs* to give a UTP semantics to CSP processes (Banks, 2012, p. 15). The space of CSP processes is a sub-space of the space of *reactive designs* that also satisfies the healthiness conditions **CSP1** and **CSP2**. **CSP1** states that if a given process P diverges, then the only guarantee is the extension of the trace. **CSP2** states that a given process P cannot require non-termination.

Even though each of the above theories has a different syntax, the semantics of all those theories are based on UTP. An important advantage of a formalised program semantics such as UTP is being able to formally reason about a program. How can one ensure that the developed program is consistent against its specification? This can be answered using program correctness.

2.4.2 Program correctness

A program is correct if every observation made of every possible run of the program results in values that satisfy the original specification (Hoare, 1997, p. 7). For example, consider the specification S and a possible observation Q made from running a program $P1$ that correctly implements S.

$$S \mathrel{\widehat{=}} (l' < m' \land l > 0 \land m' < 100)$$
$$Q \mathrel{\widehat{=}} (l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90)$$

To formalise the notation that the observation Q satisfies the specification S, we state that the specification is implied by the observation.

$$(l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90) \Rightarrow (l' < m' \land l > 0 \land m' < 100)$$

Further, program correctness states that this implication is **true** for all possible values of the observable variables, if $P1$ correctly implements S.

$$\begin{aligned} \forall\, l, m, l', m' \bullet ((&l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90) \\ &\Rightarrow (l' < m' \land l > 0 \land m' < 100)) \end{aligned}$$

This universal quantification can also be written as $[Q \Rightarrow S]$, using the conventional square brackets by Dijkstra and Scholten (1990). The square brackets is an abbreviation for the universal closure of the implication over all the variables in the alphabet.

$$[(l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90) \Rightarrow (l' < m' \land l > 0 \land m' < 100)]$$

The universal quantification of $Q \Rightarrow S$ must be **true** if $P1$ is a correct implementation of

S. In this case:

$$
\begin{aligned}
& \forall\, l, m, l', m' \bullet ((l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90) \\
& \qquad\qquad \Rightarrow (l' < m' \land l > 0 \land m' < 100)) \\
\equiv & \hspace{20em} \text{(Leibniz)} \\
& \forall\, l, m, l', m' \bullet ((l = 5 \land l' = l \times 5 \land m' = 90 \land m = 90) \\
& \qquad\qquad \Rightarrow (25 < 90 \land 5 > 0 \land 90 < 100)) \\
\equiv & \hspace{20em} \text{(simplify)} \\
& \mathbf{true}
\end{aligned}
$$

The above calculation shows that $P1$ is a correct implementation of S. Now, consider an observation R that is made from running another program $P2$.

$$R \mathrel{\widehat{=}} (l = 5 \land l' = l \times 20 \land m' = 90 \land m = 90)$$

In this case:

$$
\begin{aligned}
& \forall\, l, m, l', m' \bullet ((l = 5 \land l' = l \times 20 \land m' = 90 \land m = 90) \\
& \qquad\qquad \Rightarrow (l' < m' \land l > 0 \land m' < 100)) \\
\equiv & \hspace{20em} \text{(Leibniz)} \\
& \forall\, l, m, l', m' \bullet ((l = 5 \land l' = l \times 20 \land m' = 90 \land m = 90) \\
& \qquad\qquad \Rightarrow (125 < 90 \land 5 > 0 \land 90 < 100)) \\
\equiv & \hspace{20em} \text{(simplify)} \\
& \mathbf{false}
\end{aligned}
$$

The above calculation shows that $P2$ is not a correct implementation of S.

Different theories have been proposed to facilitate reasoning about the correctness of programs. Next, a discussion of such theories are presented.

2.4.2.a Theories of program correctness

Formal program verification is proving properties of a program using logic and mathematics. Hoare logic (Hoare, 1969) and Dijkstra's *weakest precondition* (Dijkstra, 1975) are two well-known calculi for the formal verification of programs. BCF utilises a form of *weakest precondition* computation to reason about confidentiality in systems.

Hoare logic. Hoare logic (Hoare, 1969) is a calculus that gives a set of inference rules and axioms to reason about program correctness. A precondition is a boolean expression that must be satisfied before the execution of the program. A postcondition is a boolean expression that must be satisfied immediately after a program has completed its execution. A precondition and postcondition assert a subset of acceptable states on the initial and final states of a program. Hoare uses such assertions to reason about certain programming constructs in UTP. If a program Q starts in a state that satisfies P and completes its execution then the program will reach a state that satisfies R.

$$P\{Q\}R \tag{2.3}$$

This structure is called the Hoare triple (Hoare, 1969, p. 577).

Weakest pre-condition. Dijkstra (1975) used Hoare style assertions (Hoare, 1969) to define a different construct for program development called the *weakest precondition*.

The *weakest precondition* function **wp** is a predicate transformer that maps a post condition Q of a program statement S to a precondition P. Dijkstra (1975) states that if the program S is executed with its initial state satisfying P, the program is guaranteed to reach a state satisfying the post condition Q.

$$P = \mathbf{wp}(S, Q)$$

Figure 2.3 shows the post condition and the resulting *weakest precondition* of an ePurse payment operation where *ePurseBalance* is the existing balance in the ePurse and *cost* is the amount to be deducted from the ePurse for the sale of items. In this case $\mathbf{wp}(S, Q) \equiv (ePurseBalance - cost) > 0$, or $ePurseBalance > cost$.

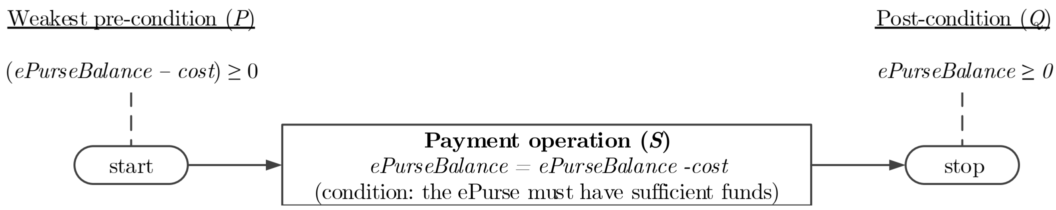


Figure 2.3: Weakest pre-condition and post condition of an ePurse payment operation

2.4.3 Refinement

Refinement is the verifiable transformation of an abstract specification of a system to a more concrete one. If an abstract specification R is refined by a more concrete specification S, the statement is formally written as $R \sqsubseteq S$. Both of these specifications as well as the relation between the two must be formally defined in order to prove that the concrete specification is a "correct realisation" of the abstract specification (Potter et al., 1996a). Program refinement is the process of applying such a set of correctness-preserving transformations on an abstract specification eventually to produce executable code (Back and Wright, 1998, p. 20).

Refinement Calculus. A Refinement Calculus is a framework for reasoning about the correct derivation of programs using refinement. One approach for deriving such correct programs is through stepwise refinement (Wirth, 1971). Back (1980) used Dijkstra's *weakest precondition* calculus (see Section 2.4.2.a) as a basis when formalizing stepwise refinement in a refinement calculus. The refinement calculus proposed by Morgan (1998) is an alternative approach where specifications and executable code are regarded equally as programs. A third approach has been proposed by Morris (1987). The approach by Morris (1987) is directly based on that of Back (Cavalcanti et al., 1998, p. 1).

2.4.4 BCF in UTP

BCF allows a user to validate the consistency of the requirements in a system by comparing the state space of the original system P and an isomorphic state space of a possible copy of the system $\widetilde{P}$. From now on, this possible copy of the system, having the possible copy of the state space, will be called the *twin* system and its state space the *twin* state space. Banks called the *twin* state space the *fog* space (Banks and Jacob, 2014, p. 4). However, the word *twin* brings clarity to the concept of the *fog* space by emphasizing that BCF assumes that there is exactly one alternative copy of the state space and that the composition of the *fog* space is similar to that of the original system state space. This composition implies that:

if a user is uncertain about the value of a state variable in the original system state space based on his/her knowledge about the program counter

then the user will also be uncertain about the value of its *twin* counterpart in the *twin* state space

The user's knowledge about the program counter depends on what functions the user is allowed to perform using the system. This in turn is defined by the functional requirement of the system. Retrospectively, a confidentiality requirement defines what a user must not learn from his/her interactions with a system. To achieve this, it must be made sure that the user is uncertain about the value of the particular state variable which the confidentiality requirement demands to be hidden or concealed. This uncertainty can be achieved by restricting the user's knowledge about the program counter at the state where the value of that particular variable needs to be secured. To achieve this restriction, a separation between the two state spaces must be enforced and this can be specified by defining a predicate that uses variables from both the original as well as the *twin* system.

2.4.5 Possible *twin* state space

Identifying the state space of a system and subsequently introducing a possible *twin* copy of the state space of the system, reflecting a possible copy of the system are pre-requisites for using BCF. Banks uniquely identified the variables of the *twin* system using the tilde decoration. In his thesis (Banks, 2012, p. 56), the *twin* variable for every variable x is written as $\tilde{x}$.

The *twin* system always exists in tandem with the original system. The predicate that represents the combined state space of the the original system and the *twin* system is derived using the predicate transformer **U** (Banks, 2012, p. 56). The predicate transformer **U** is defined as:

$$\mathbf{U}(S) \mathrel{\widehat{=}} S \wedge \widetilde{S}$$

where S represents a relational predicate that defines a system, $\widetilde{S}$ denotes $S[\widetilde{x},\widetilde{x}'/x,x']$, that is, S with each variable x and x' systematically renamed to $\widetilde{x}$ and $\widetilde{x}'$. Every state variable in the original system S has a *twin* variable in the *twin* system $\widetilde{S}$. The combined state space represented by the relation $S \wedge \widetilde{S}$ is called a *lifted relation* (Banks, 2012, p. 56).

For example, consider the relational predicate S that represents a system.

$$S \equiv x > 3 \wedge y \leq 100$$

The combined predicate that represents the system S in the lifted state space is:

$$\begin{array}{ll} & \mathbf{U}(S) \\ \equiv & \hfill \text{(definition of } \mathbf{U}\text{)} \\ & S \wedge \widetilde{S} \\ \equiv & \hfill \text{(definition of } S \text{ and } \widetilde{S}\text{)} \\ & x > 3 \wedge y \leq 100 \wedge \widetilde{x} > 3 \wedge \widetilde{y} \leq 100 \end{array}$$

where $\widetilde{x}$ and $\widetilde{y}$ are *twin* state space variables introduced by renaming the alphabetised relational state variables x and y in the relational predicate S. The variable $\widetilde{x}$ is a copy of x with the same value domain[10]. Likewise, $\widetilde{y}$ is a copy of y having the same value domains.

[10] "A value domain is defined as the permissible values for a data element" (American National Standard Institute (ANSI), 1999, P. 27). Here, the term 'value domain' is used to refer to the set of values a variable might assume through out all the stable states of a system.

2.5 *Circus*: a formal specification language

Banks (2012, p. 85) illustrates BCF by instantiating BCF using the *Circus* notation (Freitas, 2005; Oliveira et al., 2009; Woodcock and Cavalcanti, 2002). *Circus* is a formalism that combines a state based formalism called the Z notation (Spivey, 1989) and a process-oriented formalism called CSP (Roscoe, 1995; Schneider, 1999) using the underlying UTP semantics of the languages. In addition, *Circus* uses Dijkstra's guarded command notation (Dijkstra, 1997) and Morgan's refinement calculus (Morgan, 1998). Since *Circus* combines both Z and CSP (Woodcock and Cavalcanti, 2002), *Circus* utilizes the syntactic structures from both the Z and the CSP notations.

2.5.1 Advantages of *Circus*

The state of a *Circus* process is hidden except for communications through channels through which values of specified state variables may be observed (Cavalcanti and Gaudel, 2014, p. 416) . Data security policies may be captured in a *Circus* specification by introducing constraints on the data that can be communicated through defined channels. Further, *Circus* supports complex data structures (Mahony and Dong, 1998). The *Circus* notation has a strong formal semantics that is based on UTP, a framework that unifies programming theories across many different computational paradigms (Oliveira et al., 2005, p. 1). The refinement strategy for *Circus* by Sampaio et al. (2003) allow the stepwise refinement of *Circus* specifications to code in a calculational way. The underlying relational model of the *Circus* notation has proved convenient for reasoning (Ramos et al., 2005, p. 100).

> "*We can benefit from the use of the Circus refinement calculus to model a system at different abstraction levels, and, by using its refinement laws, verify the consistency of the different refinement levels with the help of formal proofs*."
> (Gomes, 2012, p. 5)

2.5.2 Uses of *Circus*

The *Circus* notation by Woodcock and Cavalcanti (2001a) has benefited from active development from the academic community since its introduction in 2001. Work has been done to both illustrate the suitability of the *Circus* notation as a modelling language as well as to extend the formalism to support a richer set of system characteristics.

The work by Sherif and Jifeng (2002), Wei et al. (2010) and Wei et al. (2011) proposed different timed models for *Circus* for studying the properties of timed programs in the untimed model, *OhCircus* by Cavalcanti et al. (2003) extended *Circus* with object-oriented features (classes, inheritance and dynamic binding), *SCJ-Circus* by Miyazawa and Cavalcanti (2015) supported the specification and verification of Safety-Critical Java[11] (SCJ) models (Henties et al., 2009).

Oliveira et al. (2004) presented a refinement strategy for industrial scale systems in *Circus*. They illustrated this strategy by refining a *Circus* specification for an industrial fire control system. They further stated that the illustration is an empirical evidence that the strategy is applicable to large systems.

Freitas and Cavalcanti (2006) described a tool that uses a translation strategy for converting a *Circus* specification to a Java program. Later, Cavalcanti et al. (2011) extended her work (Cavalcanti et al., 2005) by proposing a semantics for automatically deriving *Circus* specifications from a subset of Ada programs[12] and proving that such an Ada implementation of a control law diagram is correct.

Cavalcanti et al. (2005) proposed a semantics for control law diagrams[13] using *Circus*.

[11] "The Safety-Critical Java (SCJ) specification is designed to enable the creation of safety-critical applications using a safety-critical Java infrastructure and using safety-critical libraries that are amenable to certification under DO-178B, Level A and other safety-critical standards" (Henties et al., 2009, p. 3).

[12] Wegner (1980) gives a brief history including characteristics of the Ada programming language.

[13] "In a control law diagram, systems are modelled by directed graphs of blocks connected by wires. Roughly speaking, wires carry signals, and blocks represent functions that determine how outputs are calculated from the inputs. In a continuous-time model, signals vary continuously; in a discrete model, signals are sampled at fixed time intervals, so that input and output take place in cycles." (Cavalcanti et al., 2011, p. 467)

They use extended versions of existing tools to translate a control law diagram to both Z and CSP specifications respectively, capturing the state and reactive models of a system as required. Finally, they proposed a translation strategy to derive a *Circus* specification from the generated Z and CSP specifications.

Ramos et al. (2005) proposed a semantics for UML Realtime (UML-RT)[14] via mapping the realtime objects of the UML-RT into *Circus*. They proposed and proved a decomposition law for those realtime objects to illustrate that the proposed model transformation from UML-RT to *Circus* is sound (Ramos et al., 2005, p. 109).

Gomes (2012) presented a *Circus* specification for the Integrated Modular Avionics (IMA) architecture[15] for aircraft systems. In compliance with the ARINC 653 standard (Prisaznuk, 2006), the formalisation focuses on modelling the temporal partitioning of the application layer[16] of the IMA architecture, that prevents the direct communication between applications running on that layer. The *Circus* specification is validated by deriving a CSP specification from the *Circus* specification and using the Failures-Divergence Refinement (FDR) tool (Goldsmith et al., 2005) on the resulting CSP specification.

2.5.3 Challenges of using the *Circus* notation

The absence of a single common BNF for the *Circus* notation is one of the challenges of using the notation for the formal specification of systems. Further, the absence of a dedicated tool for specifying and type checking the resulting *Circus* specification is another barrier that hinders researchers from using the *Circus* notation for developmental

[14] "The UML Real-Time Profile (UML-RT) addresses modeling concepts that have proven suitable for modelling the run-time architectures of complex real-time systems in application domains such as telecommunications, aerospace, and industrial control" (Cheng and Garlan, 2001, p. 104)

[15] "The IMA architecture consists of a distributed system, where many aircraft applications can be executed in the same hardware module, sharing computing resources, communications and input and output devices." (Gomes, 2012, p. 3)

[16] "The operating system of the IMA architecture is designed in such a way to prevent, through the concept of partitioning, direct communication among applications. It ensures that none of the partitions can share the same memory area or processing time slice." (Gomes, 2012, p. 4)

research. Even though CZT (Malik and Utting, 2005) can be used for type checking a *Circus* specification, it does not show helpful error messages making it difficult to type check a *Circus* specification.

2.6 BCF using *Circus*

This section illustrates how BCF is instantiated using the *Circus* notation. Recall from Section 2.3 that this instantiation is referred as 'BCF in *Circus*' throughout the rest of this thesis.

2.6.1 User inference through observation

The *Circus* specification notation provides constructs called **channel**s that allow external actors to interact with a system through inputs and outputs. Through the aforementioned communications and combined with the knowledge about the source code of the system, users may learn information about the values assumed by certain state variables in a particular state or states. This information obtained by a user is termed a *user observation* of that particular state or states of the system. If a user does not know the exact value of a variable in a particular state, the user will be uncertain about the exact value of that variable in that particular state.

Consider the trivial system in Figure 2.4 that maintains a secret number. Figure 2.5 shows how the inference of two users Alice and Bob differ based on the channels they can access from the system in Figure 2.4.

Naming convention used in *Circus* specifications

All *Circus* specifications presented in this thesis follow the naming convention presented in Table 2.3. This convention has been inspired by the naming convention used by Barden et al. (1995) for presenting specifications using the Z notation. The names used in the example column of the Table 2.3 are borrowed from the *Circus* specification in Figure A.1, except in the case of Free data type.

Circus construct	Naming convention used	Example
Basic data type	Written with all caps.	*CUSTOMER*
Free data type	The data type name is written with all caps. The elements of the free type are written using all lowercase letters. For example, *STAFF* is a free type with elements *no* and *yes*.	$STAFF ::= no \mid yes$
State variable	Written using all lowercase letters. If the state variable name is a combined word then starting from the second word, capitalize the first letter of each word.	*spent* *currentCustomer* *buyItem*
Channel	Written using all lowercase letters. If the channel name is a combined word then starting from the second word, capitalize the first letter of each word. Add the postfix '*In*' at the end of the channel name if the channel is used for inputting data into the system. Add the postfix '*Out*' at the end of the channel name if the channel is used for outputting data from the system.	*buyItemIn*
Channel set, Action, Schema	Capitalize the first letter and use lowercase letters afterwards. If the name is a combined word then capitalize the first letter of each word and use lowercase letters afterwards.	*Customer* *RecordMyRecipt* *State*

Table 2.3: Naming convention used for *Circus* specifications

$$\begin{array}{|l}\hline \textit{State} \\ n : 1..9 \\ \hline\end{array}$$

channel $xIn, xOut : 1..9$
channelset $Alice == \{\!|\ xIn, xOut\ |\!\}$
channelset $Bob == \{\!|\ xOut\ |\!\}$

process $SecretNumber \mathrel{\widehat=}$ **begin**
  state $State$
  $RecordSecret \mathrel{\widehat=}$ **var** $x : 1..5 \bullet xIn?x \longrightarrow n := x?$
  $ShowSecret \mathrel{\widehat=} xOut!(n \bmod 2) \longrightarrow \mathbf{Skip}$
  $\bullet\ RecordSecret\ ;\ ShowSecret$
end

Figure 2.4: *Circus* specification of the secret number system

	Alice		Bob	
Initial observation	$n \in \{1..9\}$		$n \in \{1..9\}$	
when executing				
RecordSecret				
channel *xIn* visible	Yes		No	
can observe	x	(through *xIn*)	$x \in \{1..5\}$	(from spec)
can infer about n	$n = x$	(from spec)	$n \in \{1..5\}$	(from spec)
ShowSecret				
channel *xOut* visible	Yes		Yes	
can observe	$n \bmod 2$	(through *xOut*)	$n \bmod 2$	(through *xOut*)
can infer about n	already know value of x and that $n = x$		if $n \bmod 2$ is 1 then $n \in \{1, 3, 5\}$ if $n \bmod 2$ is 0 then $n \in \{2, 4\}$	
certainty about the value of n	**certain**		**uncertain**	

Figure 2.5: Inferences of Alice and Bob from system observations

Alice In the post state of *ShowSecret*, Alice knows the exact value of n because she knows the exact value of x and $n = x$. In this case, the value of the *twin* variable $\widetilde{n}$ is the same as the value of the variable n as follows.

$$
\begin{aligned}
& \mathbf{U}(n = x) \\
= \quad & && \text{(definition of } \mathbf{U}\text{)} \\
& n = x \wedge \widetilde{n} = x \\
= \quad & && \text{(predicate logic)} \\
& n = \widetilde{n}
\end{aligned}
$$

Bob In the post state of *ShowSecret*, Bob only knows that the value of n is such that either $n \in \{1,3,5\}$ or $n \in \{2,4\}$. Assume that Bob figures out that $n \in \{2,4\}$. In this case the value of $\widetilde{n}$ in the *twin* system will be such that $\widetilde{n} \in \{2,4\}$ as shown below.

$$
\begin{aligned}
& \mathbf{U}(n \in \{2,4\}) \\
= \quad & && \text{(definition of } \mathbf{U}\text{)} \\
& n \in \{2,4\} \wedge \widetilde{n} \in \{2,4\}
\end{aligned}
$$

If a user observes the exact value of a state variable n in a particular state then the value of the *twin* variable in that particular state is such that $\widetilde{n} = n$ as we have seen from Alice's inference. We call this the *coercion of observation*. In the case of Bob's inference, the uncertainty around the value of the variable n makes it possible for n and $\widetilde{n}$ to have different values in the state immediately after the operation *ShowSecret*. BCF captures the notion of information secrecy based on this uncertainty as discussed in Section 2.6.2.

The indistinguishability relation. The indistinguishability relation $\mathbf{I}(\mathcal{L})$ (Banks, 2012, p. 87) codifies the observable behaviour of the *Circus* process[17] P in the original system and the *Circus* process $\widetilde{P}$ in the *twin* system as indistinguishable to a user, having *window* $\mathcal{L}$ to a system, when:

[17] "Each *Circus* process has a state and accompanying actions that define both the internal state transitions and the changes in control flow that occur during execution." (Sampaio et al., 2002, p. 451)

- the two processes have the same values for the auxiliary variables (*ok*, *wait*, etc).
- the projection[18] of the traces (Banks, 2012, p. 24) through $\mathcal{L}$ are the same.
- the refusal sets are the same, as long as the behaviour has not terminated.

Here, the user's *window* $\mathcal{L}$ is defined as "the set of events communicated by a reactive process which are visible to the user" (Banks, 2012, p. 40). The indistinguishability relation $\mathbf{I}(\mathcal{L})$ is defined as follows:

$$\mathbf{I}(\mathcal{L}) \mathrel{\widehat{=}} \left(\begin{array}{c} ok = \widetilde{ok} \wedge ok' = \widetilde{ok'} \\ \wedge\ wait = \widetilde{wait} \wedge wait' = \widetilde{wait'} \\ \wedge\ (tr' - tr) \upharpoonright \mathcal{L} = (\widetilde{tr'} - \widetilde{tr}) \upharpoonright \mathcal{L} \\ \wedge\ wait' \Rightarrow ref' \cap \mathcal{L} = \widetilde{ref'} \cap \mathcal{L} \end{array} \right)$$

By lifting the semantics of the *Circus* action A using the construct $\mathbf{U}$(A) and enforcing $\mathbf{I}(\mathcal{L})$ on the resulting relation, we confine the observational capabilities of the user to the user's *window*. This process is captured using the predicate transformer **UC**.

$$\mathbf{UC}(\mathcal{L}, A) \mathrel{\widehat{=}} \mathbf{U}(A) \wedge \mathbf{I}(\mathcal{L})$$

Banks models a user's *window* as the subset of the channels in a *Circus* process (Banks, 2012, p. 114). Such a channel set (Oliveira et al., 2009, p. 5) that contains only the set of events visible to a particular group of users reflects the user *window* of those users to the system.

[18] A projection is an observable trace of a process in relation to a particular user window $\mathcal{L}$, where $\mathcal{L}$ is a channelset through which the user access a system.

Blocks. A block is a syntactic structure of BCF in *Circus* that can be used to specify how *Circus* actions should be translated to lifted state space. A block is defined as:

$$\langle L : A \rangle \triangleq (\mathbf{UC}\ (\mathcal{L}, a) \lhd \ell = L \rhd A)$$

where L is a channelset, A is a *Circus* action and ℓ is a *window* label.

Blocks delineate the boundaries between *lifted actions* explicitly. BCF in *Circus* assumes that a system user can only learn information about the program counter at these boundaries. Further, the information that the user can learn at these boundaries depends on the channels which the user can access from L. BCF in *Circus* formalizes the information the user can learn at these delineated boundaries by proposing back propagation laws. Each back propagation law is proposed for a particular type of *Circus* action A and is used to calculate a predicate that represents the information that the user can learn immediately after the execution of the action A. The back propagation laws discussed later in Table 2.4 show how these formal predicates can be calculated from blocks.

Blocks provide a systematic structure to extend the state space of a given *Circus* action A while the indistinguishability relation allows us to identify the distinguishable knowledge that can be learnt by observing A through a given channelset L. The objective of a confidentiality requirement in the context of a system environment is to limit this knowledge someone can obtain by observing the system through the same channelset L. To address this objective, an approach for formalizing the confidentiality requirements of a system is required, so that those formalized requirements can be integrated into a formal specification in such a way that the resulting system specification can be analysed for consistency.

2.6.2 Formalising a confidentiality requirement

Confidentiality requirements demand constraints on the information that can be revealed to a user through the user's interactions with a system. BCF captures confidentiality requirements by maintaining a user's uncertainty about the value assumed by a state variable, based on his/her observation of the state space of the system. For example, a confidentiality requirement is defined such that $x \neq \widetilde{x}$, where x is a variable in a system. In this case all values of $\widetilde{x}$ that are different from the current value of x serve as cover stories (Banks, 2012, p. 61) or alternative possible values for x. By combining variables from the original system and its *twin* counterpart as in $x \neq \widetilde{x}$, BCF encapsulates a relation between the two when defining a confidentiality requirement. The resulting predicate defines a coercion between a variable in a particular state and its *twin* counterpart.

The confidentiality predicate must be associated with a channelset to define the scope of the system communications on which the confidentiality predicate can be enforced. For example, the construct $\langle L \mid x \neq \widetilde{x} \rangle$ encodes that the confidentiality predicate $x \neq \widetilde{x}$ must be enforced on all the communications through the channels that are included in the channelset L.

A confidentiality annotation (CA) (Banks, 2012, p. 105) is a structure similar to a block (see Section 2.6.1) where a logical predicate *confidentiality_predicate* that encapsulates a confidentiality requirement is associated with a set of channels *channelset* as in Equation (2.4).

$$\langle \mathit{channelset} \mid \mathit{confidentiality\_predicate} \rangle \tag{2.4}$$

The CA defined in Equation (2.4) mandates that if the user observing a system at a particular state has access to a channel in the set of channels *channelset* then the confidentiality constraint defined by the predicate *confidentiality_predicate* must be enforced on that state. Confidentiality is a 'relative' phenomena whereby confidentiality may be conditional on several attributes such as who to conceal the information from and under which other conditions[19] the information must be concealed. These constraints may be applied as part of the antecedent of a confidentiality predicate.

Since confidentiality requirements in a system can now be formalized and integrated into a formal system specification, the *back propagation* approach (Section 2.7) provided in BCF in *Circus* can now be utilized.

2.7 Analysing confidentiality requirements using BCF in *Circus*

BCF contains a predicate transformer **bw** that derives a predicate from a *Circus* specification S that may contain both *Circus* actions A as well as a confidentiality predicate[20] $Conf$. The predicate transformer **bw** calculates the weakest precondition of A. The derived predicate is used to reason about the consistency of the requirements in S.

$$S \mathrel{\widehat=} \langle A \rangle \; ; \; \langle Conf \rangle$$

The specification S embeds the requirement whereby the confidentiality predicate $Conf$ must be satisfied immediately after the execution of A. To validate whether this requirement is satisfied, we calculate the weakest precondition of A such that the post state of A can satisfy $Conf$. This calculation can be done using the function $\mathbf{bw}(A, \theta)$ whereby it calculates the weakest precondition of A such that the post state of A can satisfy θ, where θ is a predicate.

If the action was a sequential composition of two or more actions, then the weakest precondition calculation is carried out iteratively starting from the right most action. Consider the specification $S1$.

$$S1 \mathrel{\widehat=} \langle B1 \; ; \; B2 \rangle \; ; \; \langle Conf \rangle$$

[19] Tschantz and Wing (2008) describes a requirement as a *conditional confidentiality requirement* if it contains a *conditional information flow* where information flow occurs only when some condition is met at runtime (Tschantz and Wing, 2008, p. 108). The same has been highlighted later in Section 6.2.4.

[20] It must be noted that many confidentiality predicates can be integrated into a single specification.

To observe whether *Conf* is respected immediately after the action $\langle B1\,;\ B2\rangle$ we first calculate the weakest precondition of the action $\langle B2\rangle$ using the formula $\mathbf{bw}(\langle B2\rangle, \langle \mathit{Conf}\rangle)$ and use the resulting predicate when calculating the weakest precondition of $\langle B1\rangle$. Hence the overall weakest precondition of the system is defined as:

$$\mathbf{bw}(\langle B1\,;\ B2\rangle, \langle \mathit{Conf}\rangle) \ \equiv\ \mathbf{bw}(\langle B1\rangle, \mathbf{bw}(\langle B2\rangle, \langle \mathit{Conf}\rangle)) \tag{2.5}$$

In BCF in *Circus* terminology, calculating the weakest precondition of a *Circus* action in this manner is called *back propagation*. Banks (2012, p. 138) has provided a set of *back propagation* laws to compliment BCF in *Circus*. These laws facilitate the calculation of the weakest precondition for certain atomic actions and composite constructs defined using the *Circus* notation as shown in Table 2.4.

2.7.1 Back propagation laws

The process of back propagation proposed in BCF in *Circus* uses a collection of *back propagation laws* (Banks, 2012, p. 138). Later in this thesis, some of the *back propagation laws* are used to analyse specifications of systems modelled using the *Circus* notation. The definitions of these *back propagation laws* are presented in Table 2.4. The back propagation approach for validating the consistency of the requirements in a system specification involves:

- back propagating the specification of the system to generate a resulting predicate that can be used to reason about the consistency of the requirements in the system specification.
- simplifying the generated predicate to reveal whether the predicate is satisfiable.

According to BCF in *Circus*, a satisfiable predicate indicates that the specification respects all the confidentiality properties coded in the specification whereas if the predicate has a contradiction, this indicates that there is an inconsistency in the specification.

Action	Syntax	BCF in *Circus*
Assign	$a := E$	$\mathbf{bw}(\langle L : a := E\rangle, \theta) = \theta[E, \widetilde{E}/a, \widetilde{a}]$
Output	$c!E \longrightarrow \mathbf{Skip}$	$\mathbf{bw}(\langle L : c!E \longrightarrow \mathbf{Skip}\rangle, \theta) = \begin{cases} \theta \wedge E = \widetilde{E} & \text{if } c \in L \\ \theta & \text{if } c \notin L \end{cases}$
Input	$c?e : P$	$\mathbf{bw}(\langle L : c?e : P \longrightarrow e := e?\rangle, \theta) = \begin{cases} \forall\, e : \delta(c) \bullet P(e) \Rightarrow \theta[e/\widetilde{e}] & \text{if } c \in L \\ \forall\, e : \delta(c) \bullet P(e) \Rightarrow \exists\, \widetilde{e} : \delta(c) \bullet P(\widetilde{e}) \wedge \theta & \text{if } c \notin L \end{cases}$
Guard	$g\ \&\ B$	$\mathbf{bw}(g\ \&\ B, \theta) = (\mathbf{bw}(B, \theta) \wedge \mathbf{U}(g)) \vee \mathbf{U}(\neg\, g)$
External choice	$B_1 \square B_2$	$\mathbf{bw}(B_1 \square B_2, \theta) = \mathbf{bw}(B_1, \theta) \wedge \mathbf{bw}(B_2, \theta)$
Scope	$\mathbf{var}\, a : T \bullet B$	$\mathbf{bw}(\mathbf{var}\ a : T \bullet B, \theta) = \forall\, a : T \bullet \exists\, \widetilde{a} : T \bullet \mathbf{bw}(B, \forall\, a : T \bullet \exists\, \widetilde{a} : T \bullet \theta)$

Table 2.4: A subset of back propagation laws of BCF in *Circus* by Banks (2012)

2.8 Limitations of BCF in *Circus*

In addition to the limitations of BCF, highlighted in Section 2.3.2, below are some of the limitations specific to BCF in *Circus*.

BCF in *Circus* does not have a mechanizable law for parallel processes. Banks (2012, p. 145) provides a discussion on how to back propagate a CA through a parallel construct. However, this approach involves manual intervention to 'reform' (Banks, 2012, p. 147) the parallel process and so cannot be mechanised. Therefore, further research is required to define a systematic approach and possibly a restricted parallel construct for *Circus* that can be mechanised.

BCF in *Circus* has not been applied to a real system. Banks (2012) demonstrated the practical application of BCF by using BCF in *Circus* to analyse the confidentiality requirements of a small fictitious auction system. However, he used a heuristic approach when doing the necessary BCF calculations rather than doing them from first principles (Banks, 2012, p. 135). Further, he did not apply BCF in *Circus* to a real problem.

Back propagation laws has not been machine verified. While all back propagation laws of BCF in *Circus* has been derived and justified by hand proofs, some of these derivations include non-trivial and lengthy manual calculations.

> "*All theorems, lemmas and laws presented in this thesis have been justified by hand proof. Nevertheless, it would be expedient to verify their correctness by encoding their proofs in a theorem prover*" (Banks, 2012, p. 187).

Therefore, it would be strongly advisable to machine verify the correctness of these laws before using them. For example, the "**bw** specification statement" has been derived through such lengthy manual calculations. During the current research, an error with "**bw** input prefix" law was identified and the correct definition of the law was proposed (see Section 3.3).

2.9 Summary

The main objective of this chapter is to present a preliminary description of the background material that is required to follow the discussions in the remaining chapters of this thesis. It must be recalled that the intention of this research is to develop a practically applicable approach for analysing data leakage related confidentiality requirements in systems using BCF.

Similar to Banks (2012), the intention is to use the instantiation of BCF in *Circus* for modelling systems. The definition of a practically applicable approach in the current context is a mechanisation where system models can be written and type checked using a tool, extracting the predicate from BCF analysis on the system model can be automated and the simplification of the derived predicate can be automated.

In this chapter:

- a brief description of UTP including the theory of relations, the theory of design, weakest precondition, program correctness and refinement was presented.
- a brief description of the *Circus* notation was presented.
- a detailed description of BCF was presented.
- other formal and semi-formal approaches that have been proposed by other researchers for analysing confidentiality properties related to data leakage in systems with a confidentiality requirement were reviewed.

3 Mechanisation of BCF

3.1 Introduction

The core objective of this thesis is to produce a practically applicable approach for reasoning about confidentiality in systems using BCF in *Circus*. While working on achieving this objective, we were also determined to extend the value of BCF in *Circus* for the research community. Therefore, while designing a practically applicable and suitable mechanisation, the efficiency of the mechanisation was also considered. Figure 3.1 shows the benefits derived from the mechanisation that has extended the value of BCF in *Circus*. Further, they can be considered as high-level criteria for evaluating the mechanisation produced in this thesis. The benefits derived from the mechanisation are described below.

Practicality explore the development of a practically applicable approach that uses BCF in *Circus* for analysing systems with a confidentiality requirement. During this exercise, we have fixed an erroneous law in BCF.

Suitability evaluate the suitability of the mechanisation for analysing the different types of confidentiality requirements, as identified in page 149 under Section 5.2.5.

Efficiency explain one possible approach for determining the efficiency of the mechanisation. Compare the efficiency achieved with mechanisation when compared to the manual process.

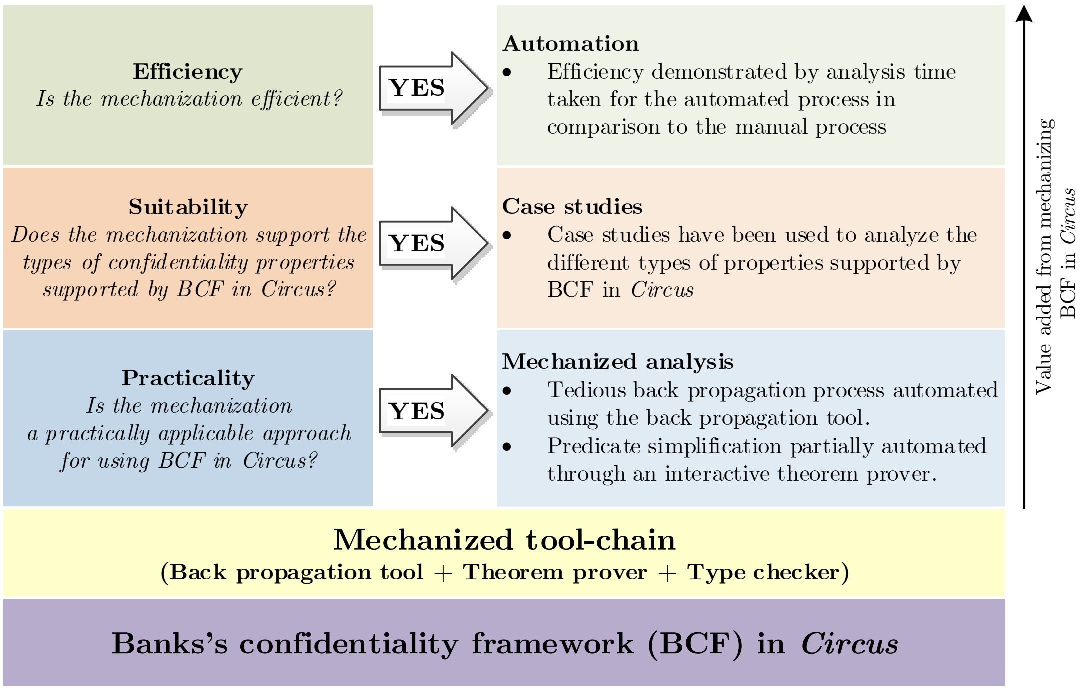


Figure 3.1: Value added from mechanising BCF in *Circus*

The above criteria demand the adoption of a combination of design and development research (Ellis and Levy, 2010) and case study research (Easterbrook et al., 2008). In this context, the design and development research involves developing a solution that is practically applicable for analysing systems with a confidentiality requiremet, using BCF in *Circus*. The practicality of the mechanisation has been been evaluated through a number of case studies. Case studies for this analysis has been selected through an explicit framework as advised by Easterbrook et al. (2008).

The following subsection discuss how the mechanisation helps in achieving a practically applicable approach for analysing a system using BCF in *Circus*. After that, the subsequent subsections discuss why the mechanisation is suitable for analysing different types of confidentiality properties supported by BCF in *Circus* and how the relative efficiency of the mechanisation in comparison to the manual approach can be determined.

3.2 Practicality

The practical use of BCF has been hindered by the following issues:

1. The application of BCF is lengthy and hence, tedious and error prone.
2. Because of the state explosion problem, the back propagation of a system specification results in a huge logical predicate spanning multiple pages. Manually simplifying such huge predicates is error prone.

> "*Manual proofs are time-consuming, error-prone and often not economically viable*" (Cao and Yu, 2012, p. 48).

Therefore, the application of BCF can only be viable if it is done through a software tool. Further, to mitigate manual errors and to be economically viable, the evaluation of lengthy predicates should be automated or machine assisted so that the users can enjoy the luxury of both "time and precision" when using BCF.

3.2.1 Rationale for a custom tool for mechanising BCF in *Circus*

Currently, there are no tools that support the mechanised application of BCF. However, mechanising the application of BCF and subsequently automating the simplification of the generated predicate will remove the complex, time-consuming and error prone exercise demanded during the use of BCF. Since BCF is based on the *Circus* notation, one would be tempted first to try and extend an existing tool that supports the *Circus* notation, to reduce the development life cycle for the required tool. A custom tool development should only be considered if an extendible candidate cannot be found. Tool support for the *Circus* notation is limited. To the author's knowledge, the only tools that provide any form of support for specifying systems using the *Circus* notation are

Symphony IDE[1] (Coleman et al., 2014) supporting the COMPASS Modelling Language (CML) (Woodcock and Miyazawa, 2012), CZT (Malik and Utting, 2005) and *CRefine* (Oliveira et al., 2008). A detailed look into the architecture of these three tools (see Appendix A.2) revealed that the work required to modify any of these tools to support an extension to the *Circus* notation is not viable within the realm of this doctoral research.

Since there was no viable platform that could be adopted and extended to support BCF in *Circus*, a decision was made to develop a simple tool for the same purpose. The tool has been named the 'Confidentiality Framework Application Tool' (CFAT). And subsequently, the notation supported in this tool is referred as the CFAT notation. Even though BCF has been instantiated for the *Circus* notation in BCF in *Circus*, CFAT notation is a non-LaTeX notation. Later, in Section 3.2.3 under the title "**CFAT notation**", a discussion is presented that details the reasons for adopting a non-LaTeX notation for modelling systems for the purposes of this thesis.

3.2.2 The proposed mechanisation of BCF in *Circus*

The proposed mechanisation for analysing systems using BCF in *Circus* is centred on a tool-chain that contains the CFAT tool developed by the author, Isabelle theorem prover for theorem proving and CZT for type checking *Circus* specifications. The CFAT tool generates the necessary input that is required by each of the other two tools. Figure 3.2 shows the overall architecture and flow in the proposed mechanisation.

[1] COMPASS Modelling Language (CML) is a language designed for modelling and analysing systems of systems (Woodcock and Miyazawa, 2012). CML is based on VDM (Gulati and Singh, 2012), CSP (Hoare, 1980) and *Circus* (Oliveira et al., 2006). Symphony IDE (Coleman et al., 2014) is a tool that utilizes CML models to generate theorem files to reason about certain properties of these models. The generated theorem files are based on the Isabelle/UTP framework (Woodcock et al., 2015). Isabelle/UTP is a deep embedding of UTP notation in the Isabelle theorem prover (Nipkow et al., 2014).

3.2.2.a The process of analysing a system for data leakage using BCF in *Circus*

The process of analysing a system for data leakage using BCF in *Circus* includes four stages as shown in Figure 3.3. They are the *Specification stage*, the *Back propagation stage*, the *Predicate simplification stage* and the *Conclusion stage* as described below.

Specification stage

A formal model of the system is developed at this stage. Further, the confidentiality requirements of the system are integrated in to the formal model.

- In the case of the manual analysis, the system and the confidentiality requirements are modelled using BCF in *Circus*.
- In the case of the proposed mechanisation, a model of the system and its confidentiality requirements are developed using the CFAT notation.

Back propagation stage

The back propagation calculation is carried out at this stage.

- In the case of manual analysis, the calculation results in a logical predicate.
- In the case of the proposed mechanisation, a HOL based theory file compatible with the Isabelle theorem prover is generated.

Predicate simplification stage

The simplification of the generated predicate is carried out at this stage.

- In the case of the manual analysis, the simplification of the generated predicate is carried out manually.
- In the case of the proposed mechanisation, the simplification of the generated predicate is carried out using the Isabelle theorem prover.

Conclusion stage

At this stage, a conclusion is drawn from the result of the simplification carried out during the previous stage.

3.2.2.b Why each component of the mechanisation is required

The following is a brief description of each component in the tool chain including the reason why the component is required.

Specification stage

Parser. The system model is supplied to the tool in the CFAT notation. The parser is required to parse the input and build an object model that depicts the components of a *Circus* specification.

LaTeX interpreter. The LaTeX interpreter is required to generate a *Circus* specification from the CFAT object model of the system, derived by the parser.

Community Z tools (CZT). CZT is used to type-check the *Circus* specification of the system, generated by the LaTeX interpreter.

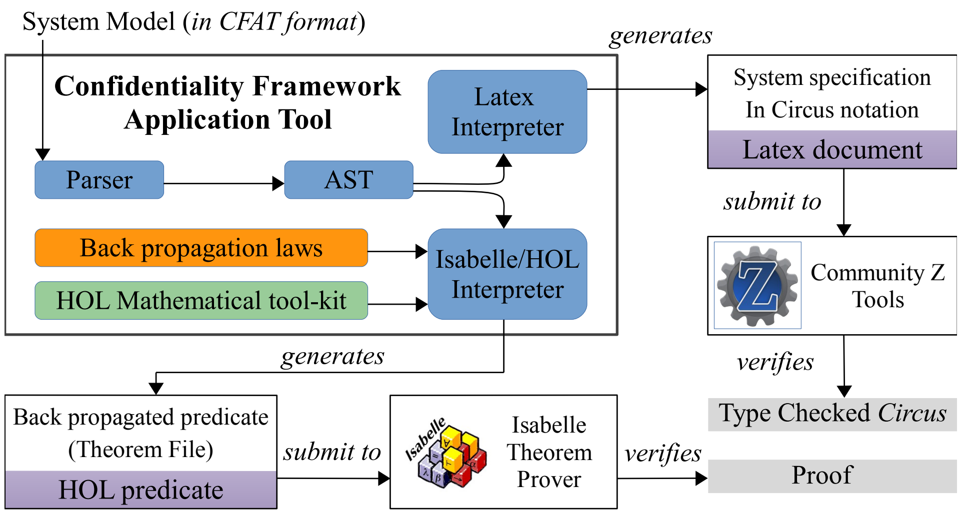


Figure 3.2: The architecture and the flow of the mechanisation of BCF in *Circus* for analysing systems with a confidentiality requirement

Back propagation stage

Back propagation laws. Back propagation laws of BCF are a catalogue of transformation laws for *Circus* actions. It contains algebraic logic that converts *Circus* specification statements of certain patterns to formal predicates in higher order logic. Therefore, back propagation laws are required to generate this predicate that can be used to reason about confidentiality in the related system. Table 2.4 presents a subset of the back propagation laws of BCF.

HiVE mathematical tool-kit. The Z data structures in the generated predicate needs to be mapped to their equivalent implementations in the target platform, that will be used for predicate simplification. Section 3.2.3 discusses possible frameworks that can be used for this mapping and why HiVE was selected for the particular mechanization approach discussed in this thesis. The HiVE tool-kit provides an implementation of Z data structures in the Isabelle/HOL platform, which is used for predicate simplification. The function names defined in HiVE are used for semantic mapping between Z data structures and their HOL equivalent functions, when the HOL compliant back-propagated predicate is generated by the Isabelle/HOL interpreter.

Isabelle/HOL interpreter. The Isabelle/HOL interpreter is responsible for creating HOL definitions for the data types defined in the CFAT model. Further, the interpreter packages these definitions and generates a HOL compliant Isabelle theorem prover theory file which contains the back-propagated predicate and the data type definitions in HOL. The interpreter also creates other supporting theorem files as required. The

Isabelle/HOL interpreter is required because it generates all the necessary theorem files that are required for analysing confidentiality in a given system.

Predicate simplification stage

Isabelle theorem prover. The Isabelle theorem prover is required to machine assist the simplification of the back-propagated predicate, generated by the Isabelle/HOL interpreter.

3.2.3 Design decisions

Decisions were made in selecting specific tools for building the mechanised tool chain. The following is an explanation of what features about the specific tools influenced the design decisions.

Parser. The CFAT tool uses a grammar based on ANTLR 4 (Parr, 2013) for parsing specifications of systems submitted to the CFAT tool. Some other potential parsers include yacc (Johnson, 1975) and JavaCUP (Hudson et al., 1998). The grammar file for yacc is difficult to read because both the grammar rules as well as the instantiations are in the same file. In comparison, ANTLR keeps the grammar rules and the visitor classes[2] in seperate files. Further, to the author's knowledge there is no GUI tool that supports yacc. However, there is GUI support for ANTLR through the standalone tool ANTLRWorks (Bovet and Parr, 2008) as well as through plugins for NetBeans (Salter and Dantas, 2014), Eclipse (Burnette, 2005) and IntelliJ (JetBrains, 2017). The GUI support for ANTLR is very useful in debugging a grammar. In addition, the visitor classes are generated in Java, the same language used for CFAT tool development.

The parsed system model can subsequently be used for generating the proof files containing the HOL predicates that are then submitted to a theorem prover for simplification. The parsed system model can also be used for generating *Circus* specifications

[2] A visitor class is an interface that computes and returns values by walking the parse tree (Parr, 2013, p. 40).

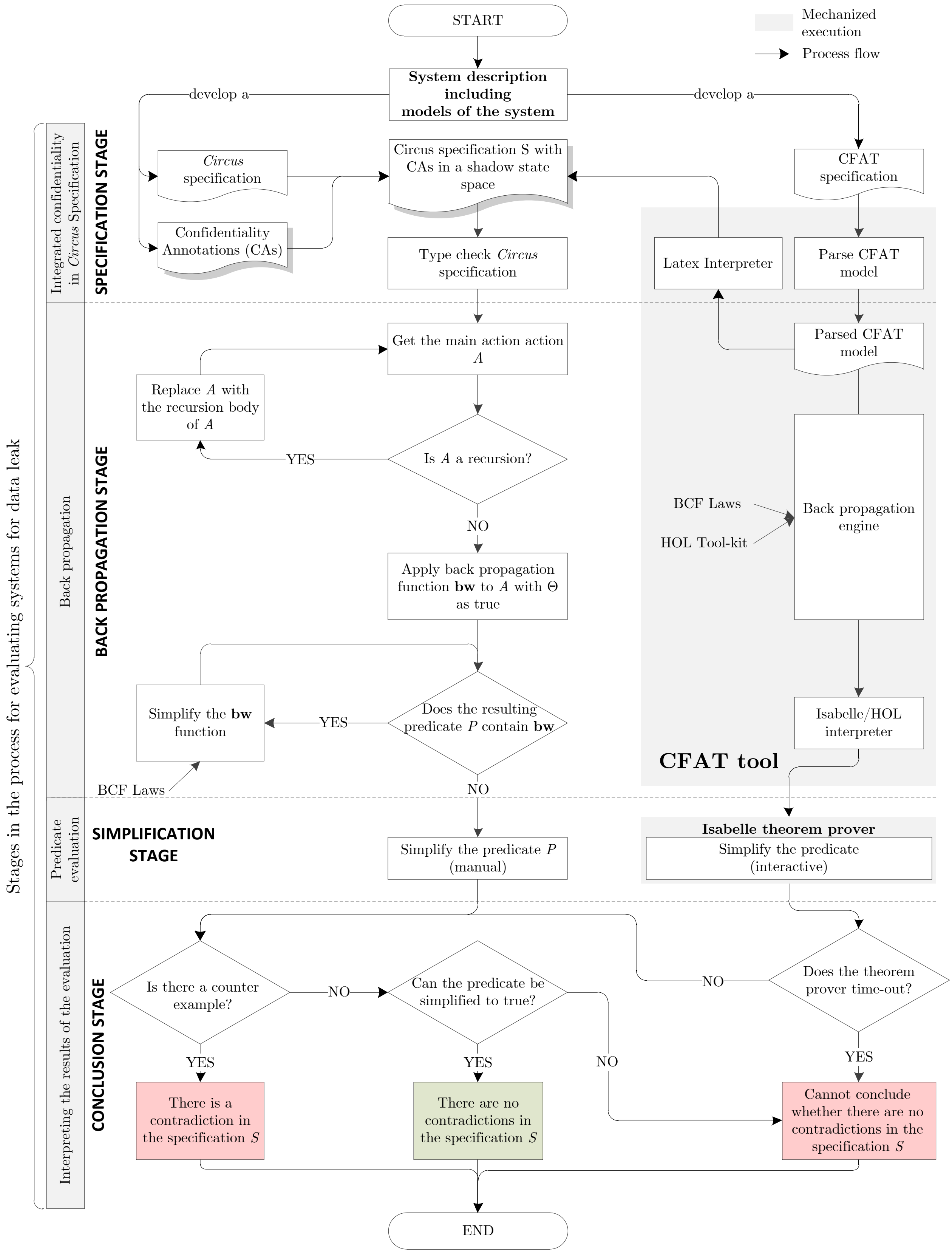


Figure 3.3: The process for evaluating a system with a confidentiality requirement requirement using the manual approach as well as using the Confidentiality Framework Application Tool

in LaTeX that can be type checked using the CZT tool to assure that the CFAT tool correctly transforms the given CFAT specification to the *Circus* LaTeX syntax.

CFAT notation. One concrete syntax of the *Circus* notation is compatible with LaTeX. However, inspired by the non-LaTeX approach adopted by *CRefine* (Oliveira et al., 2008), *Perfect Developer* (Crocker, 2003) and *Symphony IDE* (Coleman et al., 2014) (that is discussed in Appendix A.3), a decision was made to support a simple and concise notation in our tool, that closely resemble the structure of *Circus* specifications, but also one that can easily be transformed using a preprocessor into data structures that collectively represent a system model.

Formal definition of the *Circus* notation

To the author's knowledge, there is no official BNF for the *Circus* notation. However, there is a need to decide on a clear definition of the *Circus* notation, before BCF in *Circus* can be mechanized. Moreover, since our *Circus* specifications will be type checked using the CZT (Malik and Utting, 2005), it was logical to follow the *Circus* BNF presented in Leonardo Freitas's doctoral thesis "Model Checking *Circus*" (Freitas, 2005); the preliminary work that integrated *Circus* type checking as part of the CZT tool.

Isabelle theorem prover. The earlier design decision to build a custom tool to carry out the back propagation process (see Section 3.2.1) further required a decision on a platform that will be used to evaluate the predicate resulting from the back propagation. The critical criteria when selecting a platform for evaluating this predicate is its support for the Z data structures. In this regard, the theorem prover extensions Isabelle/HiVe (Mahony et al., 2009), Isabelle/ZF, ProofPower-Z (Lemma 1 Ltd., 2006, p. 1), Z/EVES (Freitas, 2004) and the translation tool Z2SAL (Derrick et al., 2011) are suitable since they all contain an encoding of the Z data structures.

Isabelle theorem prover is a LCF style interactive theorem prover (Nipkow et al., 2014). It has a fixed set of core axioms to which all proofs must conform. ProofPower-Z

(Lemma 1 Ltd., 2006, p. 40) extends ProofPower (Lemma 1 Ltd., 2006, p. 1) and supports specification and proofs in Z. ProofPower is also an LCF style interactive theorem prover (Lemma 1 Ltd., 2006, p. 6). Z/EVES is an extension to the EVES proof engine and supports specification and proofs in Z (Freitas, 2004, p. 1). Z2SAL (Derrick et al., 2011) is a translation tool for model checking Z specifications by translating Z specifications to SAL input language (Moura et al., 2003) to be used by tools in the SAL tool suit.

Hands-on experience of some academics with Z2SAL has revealed that they have run into difficulty in running the SAL simulator because of the state explosion problem which is related to model checking (Siregar et al., 2014, p. 230). This is not a limitation when using theorem proving. This persuaded the adoption of an approach based on theorem proving, to simplify the predicate.

Z/EVES has a handful of tactics[3] available for dispatching proofs whereas ProofPower has over thousand tactics (Freitas, 2004). However, support for automatic theorem provers (ATPs) and satisfiability-modulo-theories (SMT) solvers in the Isabelle theorem prover lifts the Isabelle theorem prover platform to a whole new level in automating the proof dispatch process. As stated by Blanchette and Paulson (2016), the sledgehammer tool in the Isabelle theorem prover provides support for ATPs such as AgsyHOL (Lindblad, 2014), Alt-Ergo (Bobot et al., 2008), E (Schulz, 2002), E-SInE (Hoder and Voronkov, 2011), iProver (Korovin, 2008), iProver-Eq (Korovin and Sticksel, 2010), LEO-II (Benzmüller et al., 2008), Satallax (Brown, 2012), SNARK (Stickel et al., 1994), SPASS (Weidenbach et al., 2009), Vampire (Riazanov and Voronkov, 2002), Waldmeister (Hillenbrand et al., 1997) and Zipperposition (Cruanes, 2015) and SMT solvers such as CVC3 (Barrett and Tinelli, 2007), CVC4 (Barrett et al., 2011), veriT (Bouton et al., 2009), and Z3 (Böhme and Weber, 2010). In addition, the Isabelle theorem prover has other automatic proof dispatch tools such as *auto* and *blast* (Blanchette and Paulson, 2016, p. 24). The decision to select an encoding based on the Isabelle theorem prover has been supported further by the fact that Isabelle theorem prover is a stable and mature

[3] "A tactic is an ML function which, when applied to a goal, reduces the goal to a list of subgoals and provides a 'proof function' which justifies why solving the subgoals will solve the goal" (Cant, 1992, p. 30).

theorem prover (Feliachi et al., 2013) and has been utilised in many projects. Further, its has a huge on-line community base and is constantly under development.

The author was not able to find a comparison between Isabelle/ZF and Isabelle/HiVe in the publicly accessible literature. And so, the preference to use HiVe tool-kit was purely based on the "possible" quality of the tool-kit. Isabelle/HiVe has been sanctioned by a government body[4] whereas the the code-base of Isabelle/ZF has been maintained at the University of Cambridge by interested researchers. It may be assumed that Isabelle/HiVe would have gone through a rigorous audit process for a clean and accurate code but this maybe less true for Isabelle/ZF.

HOL mathematical toolkit. A mathematical tool-kit is required for the semantic representation of data structures that are translated from *Circus* to Isabelle/HOL. Data structures in the *Circus* notation are defined as per the Z notation (Z Standards Panel, 2000) where the semantics of the Z notation is based on the Zermelo-Fraenkel set theory (Spivey, 1988). The HiVe mathematical toolkit by Mahony et al. (2009) and the HOL-Z 2.0 tool-kit by Brucker et al. (2003), both encode the mathematical data structures of the Z notation in the Isabelle/HOL. HiVe was selected rather than the HOL-Z 2.0 because the publicly available version of the HiVe toolkit supports Isabelle 2013-2 whereas the HOL-Z 2.0 is much older and was written in 2003 raising compatibility issues with Isabelle 2013-2 and further is not available publicly. A subset of the definitions from the HiVe tool-kit has been used to encode the mathematical structures of Z using Isabelle theorem prover data structures. From now on, the HiVe mathematical toolkit maybe referred as the 'mathematical toolkit'. Some of the mathematical notations being used in this thesis is include in Appendix A.4.

Community Z Tools (CZT). Community Z Tools by Malik and Utting (2005) supports the parsing of *Circus* specifications. In spite of the the many limitations (see Section 7.6), CZT is the only available tool for type checking *Circus* specifications. Therefore, CZT was utilized for this function.

[4] Australian Department of Defence (Mahony et al., 2009).

3.2.4 Requirements of the major components in the architecture

Input/output format and the content type. A number of integration challenges resulted from the architectural decisions that were considered while designing the tool chain, as shown in Figure 3.2. The main three components of the tool chain are the CFAT tool, Isabelle theorem prover and the CZT tool. Table 3.1 shows the input and output file format and content and the additional components required by each major component in the tool chain to perform its function.

Component	Input file format and content type	Output file format and content type	Additional components required for the component to function
CFAT tool	System specification in CFAT format	- theorem file generated with .thy extension - *Circus* specification file generated in LaTeX format with .tex extension	- Back propagation laws of BCF in *Circus*
Isabelle theorem prover	Isabelle theorem prover theory file format (extension .thy)	Result of the simplification is shown in the results pane of the theorem prover. (No output file is produced.)	- HiVe mathematical tool kit - Typing files generated by CFAT tool
CZT tool	*Circus* specification of a system in the LaTeX format (extension .tex)	Result of type checking is shown on the editor pane of CZT. (No output file is produced.)	- LaTeX type setting package 'circus'

Table 3.1: The input and output format of each major component of the architecture of the mechanisation of BCF in *Circus*

Syntactic renaming. The input and output variables in the *Circus* notation have the postfix decorations '?' and '!' respectively. Likewise the same postfixes are attached to similar variables in the CFAT notation. The Isabelle theorem prover does not accept these decorations. Hence, a syntactic renaming of the input and output variables are carried out before generating the Isabelle theorem files, one of which contains the back propagated predicate. When generating the predicate, the input and output variables are renamed whereby the "?" and "!" decorations are replaced with "_i" and "_o" respectively.

Each variable of the *twin* state in BCF in *Circus* (see Section 2.4.5) is decorated with a tilde such as $\widetilde{x}$ where x is a state variable. This decoration is not supported by either CZT or by the Isabelle theorem prover. Therefore, when writing the confidentiality annotation using the CFAT notation, each *twin* variable in the confidentiality annotation is written with a '**Z**' prefix. The '**Z**' prefix represents the twidle decoration on the *twin* variable.

When generating the theorem file for analysis using the Isabelle theorem prover, every *twin* variable reference $\widetilde{x}$ has been renamed by prefixing the variable with a 'Z' such as Zx in place of $\widetilde{x}$.

When generating the predicate for the Isabelle theorem prover, the *twin* variables continue to have the '**Z**' prefix in their variable name. However, when generating the *Circus* specification file for type checking with CZT, the '**Z**' prefix is removed from each each *twin* variable $\boldsymbol{Zx}$ in the CFAT specification followed by decorating the same variable with a subscript such as $\boldsymbol{x_9}$. The subscript integer 9 or the prefix '**Z**' are arbitrary choices that do not clash with anything else provided that the restrictions on naming variables are followed as specified next.

Restrictions on variable names. In the current development of the CFAT tool, variables of the *twin* state are identified using the prefix 'Z', input variables are identified using the suffix '_i' and output variables are identified using the suffix '_o'. Therefore, the following restriction have been applied to any specification submitted via the CFAT tool editor interface.

- A variable name cannot have the letter 'Z' as the first letter.
- A variable name cannot end with the suffix '_i' or '_o'.

The above restrictions are specific to the current version of the tool and does not hinder the functionality of the tool. In a future iteration of the tool, these literal identifiers can be replaced with other identifiers outside the letters of the alphabet.

Transforming CFAT notation to constructs of the *Circus* notation and Isabelle/HOL. The CFAT notation provides support for a limited number of constructs which can be used to specify variables, relations, actions and schemas of a *Circus* specification. The structures must be converted from the original CFAT specification to the target notation using constructs from the target notation that represent the structures of the CFAT notation. Two different types of files are generated by the CFAT tool.

- For type checking purposes, the LaTeX based *Circus* specification generated has the same system model as the submitted CFAT model.
- For theorem proving purpose, the file generated contains a logical predicate and has no system model. However, the predicate uses data structures from the original CFAT specification. Therefore, the data objects specified using the CFAT notation must be represented using the host notation in the Isabelle theorem prover. The data objects of the CFAT notation themselves represent Z data structures. Appendix A.4 describes how this can be achieved. It is important to note here that Appendix A.4 does not represent a translation from Z to HOL. But rather, Appendix A.4 discusses how type definitions, variable definitions and relation definitions specified using the CFAT notation, that represents their equivalent Z data structures, can be represented using the host language in the Isabelle theorem prover.

```
CFAT System Specification
#freetypes
     PERSON ::= eve | dave | carol | bob | alice
endfreetypes

#schema-State
     highestBidvalue      : nat
     managers        : \finset PERSON
     cashiers        : \finset PERSON
     customers       : \finset PERSON
     loggedIn        : \finset PERSON
     loginUser       : PERSON
predicate
     (customers ∩ cashiers ∩ managers)={}
     loggedIn ⊆ (customers ∪ cashiers ∪ managers)
     loginUser ∈ loggedIn
endschema

action_code-RecordHighestBid
     var recordBid?: nat
     guarded: ((loginUser ∈ cashiers) ∨ (loginUser ∈ managers)) ==>
          assign: highestBidvalue := recordBid?
endaction_code

action_code-ShowHighestBid
     chan showLastBidOut: nat
     guarded: ((loginUser ∈ cashiers) ∨ (loginUser ∈ managers))  ==>
          output: showLastBidOut!highestBidvalue
endaction_code

#confproperty-HideHighestBidModified
     chan:CustomerY
     liftedvar: ZhighestBidvalue
     (
          (loginUser ∉ (cashiers ∪ managers))
          \implies
          (highestBidvalue ≠ ZhighestBidvalue)
     )
endconfproperty
```

Figure 3.4: The CFAT editor window

Figure 3.4 contains part of the CFAT specification of the *Circus* specification in Figure 6.8. A parser built using ANTLR is used to parse the CFAT specification. The labels in blue color resemble structures of a *Circus* specification. Predicates can be presented with the same syntactic notation as written using *Circus*. The keywords var, guarded, assign, output are special keywords in CFAT notation to identify the type of action and chan is used to specify a channel or channelset depending on whether you associate a datatype to it. Liftedvar defines the variables on the *twin* system.

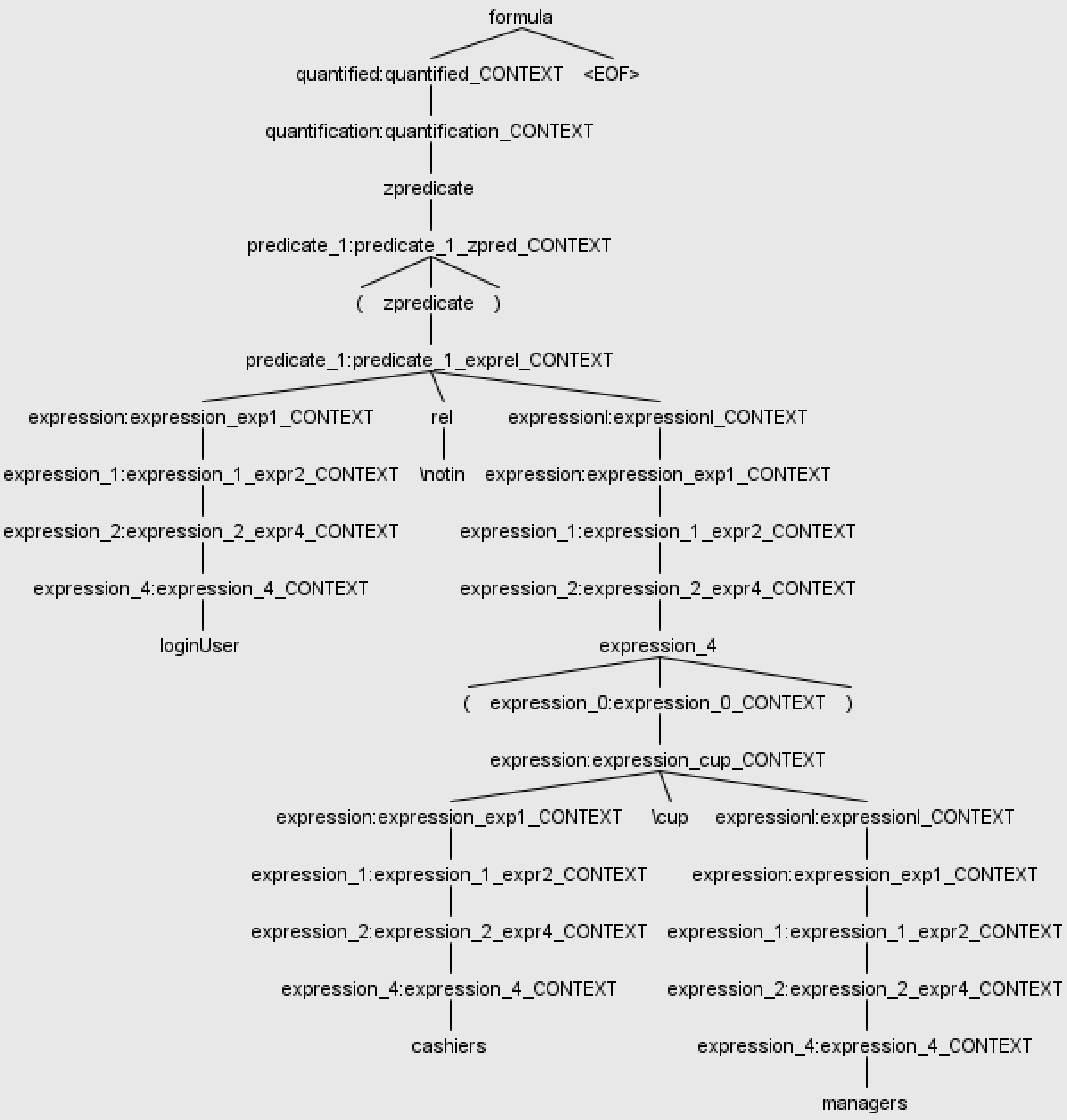


Figure 3.5: How the predicate ($loginUser \notin (cashiers \cup managers)$) is parsed using the CFAT tool

Figure 3.5 shows how the predicate ($loginUser \notin (cashiers \cup managers)$) is parsed using the in-built parser in the CFAT tool. How to read the parse tree in Figure 3.5 can be found in the ANTLR Reference Manual (Parr, 2013).

3.2.5 The mechanised analysis process

Once a confidentiality integrated CFAT specification is developed from a system description, the consistency of the confidentiality and functionality requirements captured in that specification can be analysed using the mechanised tool chain proposed in this chapter. Figure 3.6 shows the steps which must be followed during this analysis. The following is a description for each step.

❶ **Develop a CFAT specification of the system based on the description and use cases of the system**

Based on the descritpion and models of a system, a CFAT specification for the system is generated. There is no formal translation between the system model or system description to the CFAT specification. The requirement for this translation has been highlighted in Section 7.8 as a potential area of further research that can add value to the mechanised evaluation process.

❷ **Feed the specification into the mechanised tool**

Next, the CFAT specification of the system is fed into the CFAT tool. This is done by typing the specification into the editor interface of the CFAT tool.

❸ **Generate the back propagated predicate and typing files**

The CFAT tool has an interface button called 'Generate'. When the user presses this button, the tool executes the back propagation of the submitted specification as shown in Figure 3.3. This execution generates theorem files for both the back propagated predicate and the data types defined in the specification. Both these files utilize Z data constructs from the HiVe Mathematical Toolkit by Mahony et al. (2009). The files are generated in a format compatible with the Isabelle theorem prover.

❹ **Feed the theorem files into the Isabelle theorem prover**

The theorem file generated in step ❸ for the back propagated predicate is opened in the Isabelle theorem prover. During preprocessing of the file, the

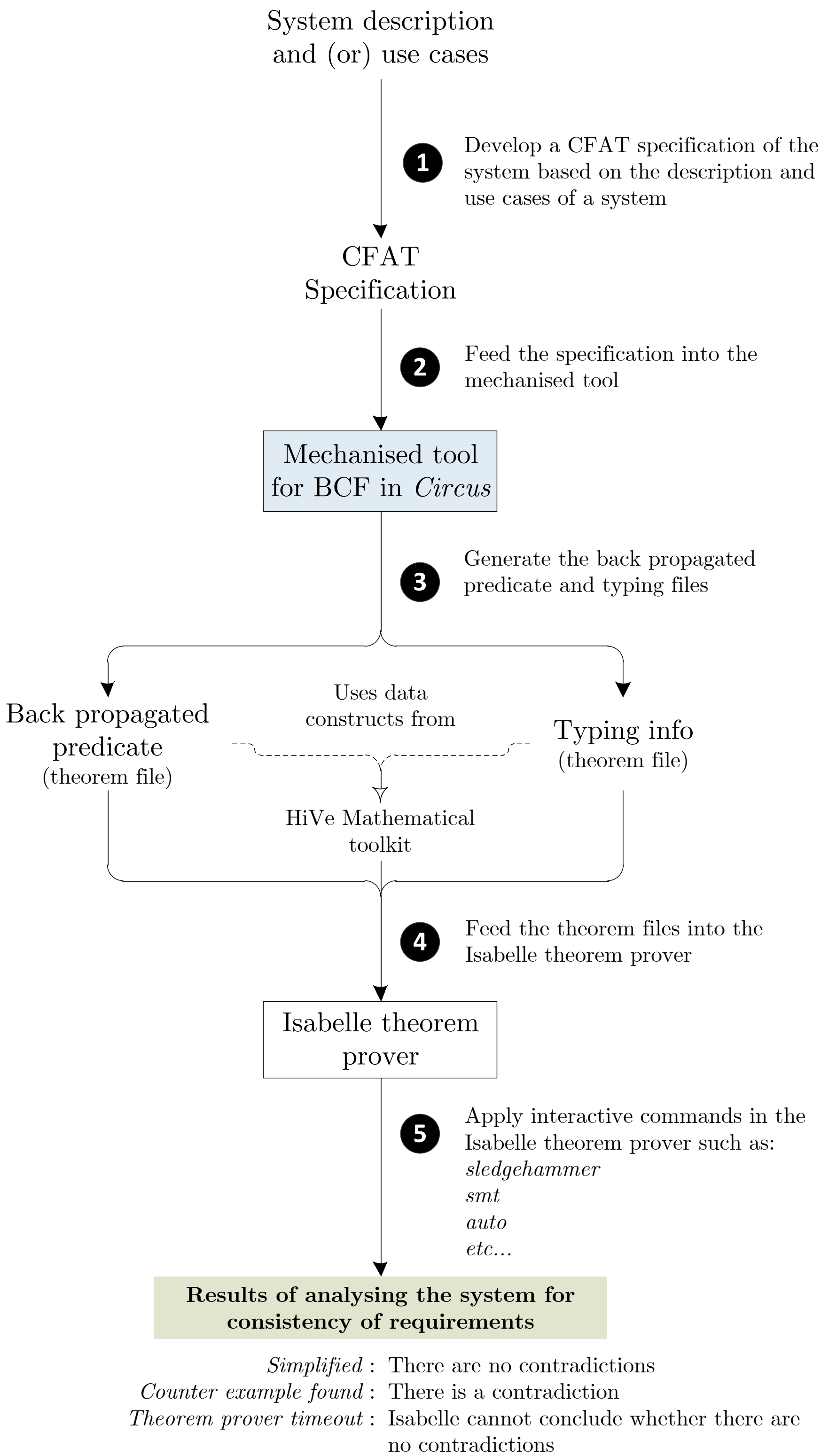


Figure 3.6: The mechanised analysis process

Isabelle theorem prover loads all the necessary dependencies. In this case, it includes loading the HiVe Mathematical Toolkit theory package (Mahony et al., 2009) and the theorem files generated for the types defined in the system.

5 **Apply interactive commands in the Isabelle theorem prover**
Relevant commands in the Isabelle theorem prover are then used at the provided interactive interface to simplify the predicate.

3.2.6 Interpreting the result of a mechanised analysis

Once the Isabelle theorem prover theory files, generated as per 3 in Figure 3.6, is submitted to the Isabelle theorem prover, as per step 4 in Figure 3.6, the user can use interactive theorem proving commands on the theorem prover, as per 5 in Figure 3.6, to simplify the predicate in the theorem file.

The final result of the simplification may identify one or more contradictions in the predicate. This may be as a result of contradictions between the functional requirements in the system or between the functional requirements and the confidentiality requirements of the system. At the end of the analysis, three possible outcomes can be expected as shown in Figure 3.3. They are:

Simplified — If the predicate could be simplified to **true**, then according to BCF in *Circus*, there are no contradictions in the system model being analysed.

Counter example found — If the theorem prover identifies a counter example, then according to BCF in *Circus*, there might be a possible contradiction in the system model being analysed. Page 250 shows the automatic generation of a counter example while analysing a specification using the mechanisation developed in this chapter.

Theorem prover time-out If the theorem prover cannot reach a conclusion on simplifying the predicate but rather times-out, then nothing can be concluded about the presence or absence of contradictions in the specification. Therefore the predicate could be true or false. This may be a limitation of the mechanisation proposed in this thesis. In some cases, even though the tool has timed out, it may be possible to manually demonstrate whether the predicate is 'true' or 'false'.

3.3 Fixing the input prefix law

During the mechanisation process it was identified that the **bw** input prefix law (Banks, 2012, p. 140) was erroneous. Banks presented the following *Circus* input action

$$\mathbf{bw}(\langle L : c?e : P \longrightarrow e := e? \rangle, \theta) \tag{3.1}$$

and described his encoding of the input prefix law as follows.

> "A prefixing which accepts an input value $e?$ from the environment on channel c reveals the exact value of $e?$ to Low, provided Low can observe c. Conversely, if Low cannot observe c, Low can still infer that $e?$ has the type $\delta(c)$ and that $P(e?)$ holds" (Banks, 2012, p. 140).

The expression P defines a set of values that represent the type of the variable $e?$. However, P may also be defined in terms of one or more state variables of the system. For example, consider a system with a state variable called *bal* and a *Circus* action called *CheckBalance*, where *PERSON* is a set of identifiers for customers.

$$\begin{array}{lll} bal : PERSON \twoheadrightarrow \mathbb{N} & & \\ CheckBalance & \mathrel{\widehat=} & c?e : (\mathrm{dom}\, bal) \longrightarrow e := e? \end{array}$$

In *CheckBalance*, the type P of the variable $e?$ is represented by the expression $\operatorname{dom} bal$. In the lifted state space, the equivalent $\widetilde{e}?$ will have the type $\widetilde{P}$ with the expression $\operatorname{dom} \widetilde{bal}$. In the system state space the typing constraint $P(e)$ must hold and in the lifted state space the typing constraint $\widetilde{P}(\widetilde{e}?)$ must hold. Which means, if Low cannot observe c, Low can still infer that $\widetilde{e}?$ has the type $\delta(c)$ and that $\widetilde{P}(\widetilde{e}?)$ holds. Based on this discussion, the corrected input prefix law is defined in Definition 3.1.

Definition 3.1. bw Input prefix law (corrected). A prefixing which accepts an input value $e?$ from the environment on channel c reveals the exact value of $e?$ to Low, provided Low can observe c. Conversely, if Low cannot observe c, Low can still infer that $\widetilde{e}?$ has the type $\delta(c)$ and that $\widetilde{P}(\widetilde{e}?)$ holds.

$$\mathbf{bw}(\langle L : c?e : P \longrightarrow e := e? \rangle, \theta)$$
$$= \begin{cases} \forall\, e : \delta(c) \bullet P(e) \Rightarrow \widetilde{P}(e) \land \theta[e/\widetilde{e}] & \text{if } c \in L \\ \forall\, e : \delta(c) \bullet P(e) \Rightarrow \exists\, \widetilde{e} : \delta(c) \bullet \widetilde{P}(\widetilde{e}) \land \theta & \text{if } c \notin L \end{cases}$$

In comparison, the existing **bw** input prefix law (Banks, 2012, p. 140) proposed in BCF is:

$$\mathbf{bw}(\langle L : c?e : P \longrightarrow e := e? \rangle, \theta)$$
$$= \begin{cases} \forall\, e : \delta(c) \bullet P(e) \Rightarrow \theta[e/\widetilde{e}] & \text{if } c \in L \\ \forall\, e : \delta(c) \bullet P(e) \Rightarrow \exists\, \widetilde{e} : \delta(c) \bullet P(\widetilde{e}) \land \theta & \text{if } c \notin L \end{cases}$$

Examining the issue with the existing bw input prefix law

Consider the *Circus* action *ShowBalance* and the channelset *cashier*.

channelset *cashier* $== \{\!|\ c, nout\ |\!\}$

$$ShowBalance \quad \widehat{=} \quad c?e : (\operatorname{dom} bal) \longrightarrow nout!bal\ e? \longrightarrow \mathbf{Skip}$$

Assume that a confidentiality annotation CA is back propagated through *ShowBalance* where *ShowBalance* is lifted through the channelset *cashier*.

$$\langle cashier \mid ShowBalance \rangle\ ;\ \langle CA \rangle$$

The application of BCF is as follows.

$$\begin{array}{ll}
 & \langle ShowBalance \rangle\ ;\ \langle CA \rangle \\
= & \hfill \text{(definition of } ShowBalance\text{)} \\
 & \langle c?e : (\operatorname{dom} bal) \longrightarrow nout!bal\ e? \longrightarrow \mathbf{Skip} \rangle\ ;\ \langle CA \rangle \\
= & \hfill \text{(decomposing the prefix)} \\
 & \langle c?e : (\operatorname{dom} bal) \longrightarrow \mathbf{Skip} \rangle\ ;\ \langle nout!bal\ e? \longrightarrow \mathbf{Skip} \rangle\ ;\ \langle CA \rangle \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ sequence)} \\
 & \langle c?e : (\operatorname{dom} bal) \longrightarrow \mathbf{Skip} \rangle\ ;\ \mathbf{bw}(\langle nout!bal\ e? \longrightarrow \mathbf{Skip} \rangle, \langle CA \rangle) \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ output, } nout \in cashier\text{)} \\
 & \langle c?e : (\operatorname{dom} bal) \longrightarrow \mathbf{Skip} \rangle\ ;\ \langle bal\ e? = \widetilde{bal}\ \widetilde{e?} \wedge CA \rangle \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ sequence)} \\
 & \mathbf{bw}(\langle c?e : (\operatorname{dom} bal) \longrightarrow \mathbf{Skip} \rangle, \langle bal\ e? = \widetilde{bal}\ \widetilde{e?} \wedge CA \rangle) \\
= & \hfill \text{(definition of the existing } \mathbf{bw} \text{ input prefix law , } c \in cashier\text{)} \\
 & \forall e? \bullet e? \in \operatorname{dom} bal \Rightarrow bal\ e? = \widetilde{bal}\ e? \wedge CA
\end{array}$$

Looking at the resulting predicate, we see that there is not enough information in the predicate to determine if $e? \in \operatorname{dom} \widetilde{bal}$. If this is the case, $\widetilde{bal}\ e?$ might be undefined for certain values of $e?$.

Now, the same calculation is carried out again, but with the new input prefix law proposed in Definition 3.1.

$$
\begin{aligned}
& \langle \mathit{ShowBalance} \rangle \ ; \ \langle \mathit{CA} \rangle \\
= & \hfill \text{(definition of } \mathit{ShowBalance}\text{)} \\
& \langle c?e : (\mathrm{dom}\, \mathit{bal}) \longrightarrow \mathit{nout}!\mathit{bal}\ e? \longrightarrow \mathbf{Skip} \rangle \ ; \ \langle \mathit{CA} \rangle \\
= & \hfill \text{(decomposing prefix)} \\
& \langle c?e : (\mathrm{dom}\, \mathit{bal}) \longrightarrow \mathbf{Skip} \rangle \ ; \ \langle \mathit{nout}!\mathit{bal}\ e? \longrightarrow \mathbf{Skip} \rangle \ ; \ \langle \mathit{CA} \rangle \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ sequence)} \\
& \langle c?e : (\mathrm{dom}\, \mathit{bal}) \longrightarrow \mathbf{Skip} \rangle \ ; \ \mathbf{bw}(\langle \mathit{nout}!\mathit{bal}\ e? \longrightarrow \mathbf{Skip} \rangle, \langle \mathit{CA} \rangle) \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ output, } \mathit{nout} \in \mathit{cashier}\text{)} \\
& \langle c?e : (\mathrm{dom}\, \mathit{bal}) \longrightarrow \mathbf{Skip} \rangle \ ; \ \langle \mathit{bal}\ e? = \widetilde{\mathit{bal}}\ \widetilde{e}? \land \mathit{CA} \rangle \\
= & \hfill \text{(definition of } \mathbf{bw} \text{ sequence)} \\
& \mathbf{bw}(\langle c?e : (\mathrm{dom}\, \mathit{bal}) \longrightarrow \mathbf{Skip} \rangle, \langle \mathit{bal}\ e? = \widetilde{\mathit{bal}}\ \widetilde{e}? \land \mathit{CA} \rangle) \\
= & \hfill \text{(definition of the new } \mathbf{bw} \text{ input prefix law , } c \in \mathit{cashier}\text{)} \\
& \forall\, e? \bullet e? \in \mathrm{dom}\, \mathit{bal} \Rightarrow e? \in \mathrm{dom}\, \widetilde{\mathit{bal}} \land \mathit{bal}\ e? = \widetilde{\mathit{bal}}\ e? \land \mathit{CA}
\end{aligned}
$$

The result of the above calculation shows that $e? \in \mathrm{dom}\, \widetilde{bal}$ and so $\widetilde{bal}\ e?$ has been defined for all possible values of $e?$.

3.4 Suitability

The usefulness of the mechanisation of BCF in *Circus* can be evaluated in terms of its suitability for the intended purpose. For this, there is a need to check if the types of confidentiality analysis supported by BCF in *Circus* can be carried out using the using the mechanisation.

3.4.1 Types of data leakage supported by BCF in *Circus*

Recall from Section 1.3 that Shabtai et al. (2012, p. 5) describe data leakage as the intentional or unintentional distribution of private or sensitive data to an unauthorised entity. Following are some types of data leaks that BCF in *Circus* can be used to reason about.

Data leakage through direct communication. One way data might leak is through direct communication to the environment. This may happen if a function communicates the value of a state variable x to the environment, while x has already been declared as confidential by a confidentiality requirment in the same system. BCF in *Circus* can identify such contradictions. For example, the *Circus* action *ShowX* in Equation (3.2) outputs the value of x through the channel *out*. The confidentiality requirement *ConfX* in Equation (3.3) states that x must never be revealed through the channelset L. Assume that $out \in L$.

$$ShowX \triangleq \langle L \mid out!x \longrightarrow \mathbf{Skip} \rangle \tag{3.2}$$

$$ConfX \triangleq \langle L \mid x \neq \widetilde{x} \rangle \tag{3.3}$$

The contradiction between the functionality *ShowX* and the confidentiality *Conf* is brought to light with the following calculation.

$$\begin{aligned}
& \langle ShowX \rangle \,;\, \langle ConfX \rangle \\
= \; & \mathbf{bw}((\langle ShowX \rangle \,;\, \langle ConfX \rangle), \mathbf{True}) && \text{[Back propagation]} \\
= \; & \mathbf{bw}(\langle ShowX \rangle, \mathbf{bw}(\langle ConfX \rangle, \mathbf{True})) && \text{[Law 6.32 - } \mathbf{bw} \text{ } \textit{sequence}\text{]} \\
= \; & \mathbf{bw}(\langle ShowX \rangle, \langle x \neq \widetilde{x} \rangle)) && \text{[Law 6.18 - } \mathbf{bw} \text{ CA]} \\
= \; & x = \widetilde{x} \wedge x \neq \widetilde{x} && \text{[Law 6.34 - } \mathbf{bw} \text{ } \textit{output}\text{]} \\
= \; & \mathbf{False} && \text{[Simplify]}
\end{aligned}$$

Given a particular user u with a user role having access to the channels in the channelset L, if u cannot observe the channel *out* then the value of x will not be revealed to u. This can be possible if $out \notin L$. Such role based access control restrictions can be implemented using BCF in *Circus*.

Data leakage through inference. One of the ways in which a data leakage may occur is through inference. A data leakage through inference is where a legal functionality allows an authorised user to deduce something about a part of the system state to which they do not have access rights. The challenge in addressing such a data leakage is called an inference problem (Farkas and Jajodia, 2002).

> "*The inference problem is denoted as the compromise or increased probability of compromise by deduction of unauthorized information due to combinations of the possession, known existence, known absence, chronology and location of authorized information*" (Hubbard et al., 1986, p. 23).

In the context of software systems, access control mechanisms regulate the access which subjects (users or other processes) have on the objects (state variables) of a system (Denning, 1999). However, access control cannot capture the flow of information.

> "*Access control checks place restrictions on the release of information but not its propagation*" (Sabelfeld and Myers, 2003, p. 5).

The philosophy of BCF "for protecting the confidentiality of information is to regulate the information flow from systems to their users" (Banks, 2012, p. 54). Therefore, BCF in *Circus* maintains knowledge about the origin of the information that is communicated to the environment through a particular state variable x rather than just knowing the value of x that is communicated to the environment. By bundling this capability with an RBAC implementation[5] in BCF in *Circus*, engineers can address some inference problems in *Circus* specifications.

---

[5] Role Based Access Control (RBAC) can be modelled in *Circus* specifications by regulating user access to channels used in a specification.

How BCF in *Circus* can track the flow of information is demonstrated using the following example. For example, the *Circus* action *AssignX* in Equation (3.4) assigns the value of the state variable y to the state variable x. The confidentiality requirement *ConfY* in Equation (3.5) states that y must never be revealed through any channel in the channelset L. Assume that $out \in L$.

$$AssignX \triangleq \langle L \mid x := y \rangle \tag{3.4}$$
$$ConfY \triangleq \langle L \mid y \neq \widetilde{y} \rangle \tag{3.5}$$

Consider the program fragment $\langle AssignX \rangle ; \langle ShowX \rangle ; \langle ConfY \rangle$. From an access control point of view, the fragment does not have a contradiction because the only output action *ShowX* in the fragment does not reveal the state variable y, that is required to be kept confidential by *ConfY*. However, the indirect flow of confidential information in y through the channel *out* is revealed if the fragment is analysed using BCF in *Circus*, as shown in the following calculation.

$$\begin{aligned}
& \mathbf{bw}((\langle AssignX \rangle \ ; \ \langle ShowX \rangle \ ; \ \langle ConfY \rangle), \mathbf{True}) & \\
&= \mathbf{bw}((\langle AssignX \rangle \ ; \ \langle ShowX \rangle), \mathbf{bw}(\langle ConfY \rangle, \mathbf{True})) & [\text{Law 6.32 - } \mathbf{bw} \ \textit{sequence}] \\
&= \mathbf{bw}((\langle AssignX \rangle \ ; \ \langle ShowX \rangle), \langle y \neq \widetilde{y} \rangle) & [\text{Law 6.18 - } \mathbf{bw} \text{ CA}] \\
&= \mathbf{bw}(\langle AssignX \rangle, \mathbf{bw}(\langle ShowX \rangle, \langle y \neq \widetilde{y} \rangle)) & [\text{Law 6.32 - } \mathbf{bw} \ \textit{sequence}] \\
&= \mathbf{bw}(\langle AssignX \rangle, \langle x = \widetilde{x} \wedge y \neq \widetilde{y} \rangle) & [\text{Law 6.34 - } \mathbf{bw} \ \textit{output}] \\
&= \langle x = \widetilde{x} \wedge y \neq \widetilde{y} \rangle [y, \widetilde{y} / x, \widetilde{x}] & [\text{Law 6.31 - } \mathbf{bw} \ \textit{assignment}] \\
&= \langle y = \widetilde{y} \wedge y \neq \widetilde{y} \rangle & [\text{Renaming}] \\
&= \mathbf{False} & [\text{Simplify}]
\end{aligned}$$

In summary, BCF in *Circus* can be used to analyse systems to reason about the:

- direct communication of values of state variables to the environment, that are required to be kept confidential as per a confidentiality requirement.
- indirect communication of a confidential data to the environment through a state variable authorised for that particular user.

3.4.2 Analysing data leakage through indirect communication using BCF in *Circus*

How the mechanised analysis proposed in this chapter detects a possible data leakage through direct communication is demonstrated later in Section 6.2.1. In this section, data leakage through indirect communication is demonstrated using the results of a mechanised analysis carried out on a fictitious hand crafted specification.

The system has two bidders defined by the free type *BIDDER* where the bidder can either *Alice* or *Bob*. The system maintains the highest bidder of a round of bidding using the state variable *highestBidder* and the last bidder who has proposed a bid for the same round using the state variable *lastBidder*. The channelsets *Clerk*,*CustomerX* and *CustomerY* represents user roles where a person having that user role can observe communications through any channels included in that channelset. A detailed discussion of user roles and their importance in the data leakage analysis carried out in this thesis is presented in Section 6.2.3.d. The channel *recordBidderIn* is used to submit the name of a bidder to the system while *showOnlyLastBidderOut* and *showLastBidderOut* are used to output the name of a bidder to the environment. The *Circus* action *RecordHighestBidder* is used to record the name of the highest bidder of a bidding round, *ShowLastBidder* and *ShowLastBidderOnly* are used to output the name of the last bidder who has submitted a bid for the current round and finally, the *Circus* action *HideHighestBidder* (through the schema *HideHighestBidder*) defines a confidentiality property where the value of the highest bidder must never be revealed. To keep the example small, it is assumed that a value for *lastBidder* has already been recorded.

The possible interpretations of the results of a mechanised analysis are considered in Section 3.2.6. Table 3.2 discusses the possible reasons for the results of the mechanised analysis of *HideHighestBidder*. The results show that the mechanisation is suitable for identifying data leakage through indirect flow of confidential data.

$BIDDER ::= Alice \mid Bob$

$$
\begin{array}{|l}
\multicolumn{1}{l}{\textit{State}} \\
\hline
lastBidder, highestBidder : BIDDER \\
\hline
\end{array}
$$

$$
\begin{array}{|l}
\multicolumn{1}{l}{\textit{HideHighestBidder}} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad highestBidder \neq highestBidder_9 \\
\hline
\end{array}
$$

channel $recordBidderIn, showOnlyLastBidderOut, showLastBidderOut : BIDDER$

channelset $Clerk == \{\!| recordBidderIn |\!\}$
channelset $CustomerX == \{\!| showOnlyLastBidderOut |\!\}$
channelset $CustomerY == \{\!| showLastBidderOut |\!\}$

process $Secret\_Highest\_Bidder \mathrel{\widehat=}$ **begin**

state $State$

$$
\begin{array}{lcl}
RecordHighestBidder & \mathrel{\widehat=} & \mathbf{var}\ recordBidder : BIDDER \bullet \\
& & \quad recordBidderIn?recordBidder \longrightarrow \\
& & \qquad highestBidder := recordBidder? \\[1ex]
ShowLastBidder & \mathrel{\widehat=} & lastBidder := highestBidder; \\
& & \quad showLastBidderOut!(lastBidder) \longrightarrow \mathbf{Skip} \\[1ex]
ShowOnlyLastBidder & \mathrel{\widehat=} & showOnlyLastBidderOut!(lastBidder) \longrightarrow \mathbf{Skip} \\[1ex]
HideHighestBidder & \mathrel{\widehat=} & HideHighestBidder
\end{array}
$$

$$
\bullet\ \mu X \bullet \left(\left(\begin{array}{ll} & \langle RecordHighestBidder \rangle \\ \Box & \langle ShowLastBidder \rangle \\ \Box & \langle ShowOnlyLastBidder \rangle \end{array} \right) ; \ \langle HideHighestBidder \rangle \ ; \ X \right)
$$

end

Figure 3.7: Specification of Secret Highest Bidder - *code block 1 of 1*

User role	Outcome of the analysis	Reason for the outcome
Clerk	Counter example found	Any user with the user role *Clerk* has access to the channel *highestBidderIn* and therefore the user already knows the highest bidder *highestBidder*. The confidentiality requirement *HideHighestBidder* to maintain the secrecy of the highest bidder from this user role will rightly result in a contradiction as shown from the outcome of the analysis.
CustomerY	Counter example found	The value that represents the highest bidder *highestBidder* is passed to the state variable *lastBidder* through the assignment action in *ShowLastBidder* and therefore the value being revealed in *ShowLastBidder* through the state variable *lastBidder* is not the original value of the last bidder but the value of the highest bidder. Since a user with the user role *CustomerY* has access to the channel *showLastBidderOut* that user will learn the value of the highest bidder. This knowledge contradicts with the confidentiality requirement *HideHighestBidder* where it demands to maintain the secrecy of the highest bidder from all users. The analysis identifies this by producing a counter example.
CustomerX	Simplified	The value that represents the highest bidder is not passed to the state variable *lastBidder* and therefore the value being revealed through the state variable *lastBidder* is the current value that represents the last bidder.

Table 3.2: Analysing data leakage through indirect communication

3.4.3 Confidentiality violation through recursion

The analysis carried out in Section 3.4.2 has been restricted to a single run of the system because BCF in *Circus* and therefore its mechanisation does not support the analysis of recursive constructs in *Circus*. This has been highlighted as an important future area of research (see Section 7.2).

The analysis carried out in Section 3.4.2 is a scenario where the support for recursion in BCF in *Circus* would have revealed the highest bidder to a user with the user role *CurtomerX*, in contradiction to the outcome shown in Table 3.2 . The execution of *ShowLastBidder* would pass the value of the highest bidder *highestBidder* to the state variable *lastBidder* and a subsequent execution of the *ShowOnlyLastBidder* would have reveal the value of the highest bidder that has been recorded in the variable *lastBidder* .

3.5 Efficiency

Efficiency is a measure of the estimated cost which includes the total time taken for executing user procedures (Seffah et al., 2006, p. 164). Efficiency of a process can be measured in relation to the level of effectiveness achieved to the expenditure of resources where a resource can be the time taken for the process, which can be used to give a measure of the temporal efficiency of the process (Bevan and Azuma, 1997, p. 176). The efficiency measure can be used to compare two or more tasks when carried out in an environment where all parameters of the environment are the same except the variable property of the environment that is being studied. The objective is to check the relative efficiency of the mechanised process in comparison to the manual process.

The manual impracticality of both the back propagation as well as the simplification of the generated predicate when analysing a non-trivial system has been the inspiration for this thesis. Therefore, it goes without question that time taken for the manual analysis of non-trivial systems cannot be obtained. However, since the mechanization developed in this chapter is an important contribution of this thesis, it is important to compare the relative efficiency between the manual and the mechanized analysis of a small specification of a system, for which the time taken for the manual analysis can be obtain.

3.5.1 Comparison of efficiency between the manual and the mechanized analysis

Section 4.2 presents a manual analysis of the system specification in Figure 4.1. The time taken for this analysis as well as the analysis of the same system using the mechanization developed in this chapter is shown in Table 3.3. It must be noted here that there are no matrices to accurately measure the manual analysis of a system using BCF in *Circus*. Therefore, the stated time for the manual analysis is an estimate. As stated earlier in Section 3.2.6 , the outcome "Simplified" indicates that there are no contradictions between the functionality and the confidentiality requirements in the system. Bevan and Azuma (1997, p. 176) propose the following formulae to measure temporal efficiency of a process.

$$\text{Temporal Efficiency} = \text{Effectiveness}/(\text{Task Time})$$

It is assumed that the Effectiveness is the same for both the manual as well as the mechanized analysis in this example since the analysis outcome from both are the same as shown in Table 3.3. There is no particular unit of measurement given for the Effectiveness measurement. For example, if we state that in this particular scenario both approaches were 100% effective, then the Temporal Efficiency can be calculated as shown in Table 3.3.

Type of analysis	Analysis outcome	Time taken for the analysis	Temporal Efficiency
Manual	Simplified	3600000 ms	100/3600000 = 0.000027
Mechanized	Simplified	120 ms	100/120 = 0.833333

Table 3.3: Time taken for analysing Figure 4.1 using BCF in *Circus*

For this particular scenario, the ratio of the Temporal Efficiency of the mechanized approach in comparison to the manual approach is 1 : 0.003 as shown below.

$$(\text{Manual efficiency} \;/\; \text{Mechanized efficiency}) = (0.000027/0.833333) = 0.003$$

3.6 Summary

The main contribution of this chapter is the proposition of a mechanisation to make the process of analysing systems using BCF in *Circus* practically applicable. In addition, this chapter discusses the suitability of the proposed mechanisation, for analysing the different types of confidentiality requirements, supported by BCF in *Circus*. Finally, the chapter presents a comparison of efficiency between the manual and the mechanized analysis of a given system.

The proposed mechanisation is a tool chain that consists of a custom tool, Isabelle theorem prover and CZT. The custom tool is used for the mechanized back propagation and generation of a back propagated predicate for a given system. The Isabelle theorem prover is used to simplify the predicate, the result of which is used to reason about confidentiality in the given system. The tool further generates a *Circus* specification of the given system which is type checked using the CZT tool. The mechanisation will be evaluated in Chapter 6.

In this chapter:

- the mechanisation approach that has been adopted in this research, to extend the value of BCF in *Circus*, has been described.
- the types of confidentiality requirements that can be analysed using BCF in *Circus* has been identified.
- the correct definition in place of an erroneous definition of the existing **bw** input prefix law has been proposed.

4 An approach for evaluating the mechanisation of BCF

4.1 Introduction

This chapter presents the approach which has been followed in evaluating the usefulness of the mechanisation of BCF in *Circus*. There is a need to analyse case studies using the mechanisation so that the advantage of the mechanisation can be demonstrated in terms of saving time and detecting the possibility of a data leakage in systems with a confidentiality requirement. Since the function of the mechanisation is to detect data leakage in a given system, every potential case study system chosen mush have one or more distinct confidentiality requirements relating to data leakage so that the case study can be useful in this analysis.

An ideal evaluation would require testing the mechanisation on a range of realistic case studies with different specifications and confidentiality requirements. Such an evaluation can illustrate that the mechanised analysis approach can cope with varied *Circus* specifications having data leakage related confidentiality requirements. However, such realistic case studies can only be carried out using real world requirement specifications of systems. Such requirement specifications maybe obtained from officially published documents of real life systems. However, if such documents are not available, as was the case in this research, we would have to compile them by being in the field and studying the original system and engaging with the real stakeholders. Such an approach was used by Srivatanakul (2005) in conducting a case study on the Baggage Handling System of the Bangkok International Airport in Thailand. However, based on the structure of a given Ph.D. research, such an engagement might not be always possible, given the time limitation as was the case in this doctoral research.

4.2 The advantage of mechanisation over a manual approach

Mechanising the back propagation process can save a lot of resources related to time which otherwise might be required when following manual calculations which needs to be carried out with meticulous detail, to avoid human error. The advantage that this mechanisation brings is self evident in a manual run that involves back propagating a non-trivial *Circus* specification of a system. In this section, a step-by-step walk through for back propagating a small component of a fictitious system is presented.

Figure 4.1 presents the *Circus* specification of the patient details component of a Health Information System where a doctor uses a system to access details of patients who are being treated by that doctor. The descriptions of the types, state variables, state invariants, channels and actions of this specification are included in Table 4.1.

PATIENT	The set of all possible patient identifiers.
PATIENTDETAILS	The set of all possible patient detail identifiers.
treats	The set of people currently being treated at the clinic where the doctor practices.
reqPatient	The identifier of the patient whose patient details is being requested from the system.
patientInfo	A function that identifies the details of a patient, if any.
$treats \subseteq \mathrm{dom}\, patientInfo$	The set of people treated must be from the set of patients whose patient details are recorded in the system.
patientIn	The use of this channel by the system is to input the identifier of the patient whose details are being requested from the system.
detailsOut	The use of this channel by the system is to output the details of the particular patient being requested from the system.
PatientDetails	Allows a person to request the details of a patient, if the identifier of that particular patient is in the set *treats*.
ConfType	Enforces a confidentiality requirement that if the requested patient is not in *treats* then do not reveal the details of the patient.

Table 4.1: Descriptions of the constructs of the Patient details component of the Health Information System

$[PATIENT, PATIENTDETAILS]$

$$
\begin{array}{|l}
\textit{State} \\ \hline
treats : \mathbb{P}\, PATIENT \\
patientInfo : PATIENT \pinj PATIENTDETAILS \\
reqPatient : PATIENT \\ \hline
treats \subseteq \operatorname{dom} patientInfo \\ \hline
\end{array}
$$

$$
\begin{array}{|l}
\textit{HidePatientDetails} \\ \hline
\Xi State \\ \hline
\exists\, \widetilde{State} \bullet \\
\quad reqPatient \notin treats \Rightarrow \\
\qquad (patientInfo\ reqPatient \neq \widetilde{patientInfo}\ \widetilde{reqPatient}) \\ \hline
\end{array}
$$

$\mathbf{channel}\ patientIn : PATIENT$

$\mathbf{channel}\ detailsOut : PATIENTDETAILS$

$\mathbf{channelset}\ All == \{\!|\ detailsOut, patientIn\ |\!\}$

$\mathbf{process}\ PatientSystem \mathrel{\widehat=} \mathbf{begin}$

$Init \mathrel{\widehat=} [State']$

$$
\begin{aligned}
PatientDetails \mathrel{\widehat=} \mathbf{var}\ patient : PATIENT \bullet \\
& patientIn?patient \longrightarrow reqPatient = patient?; \\
& (patient? \in treats \land patient? \in \operatorname{dom}\ patientInfo)\ \& \\
& \qquad detailsOut!(patientInfo\ patient?) \longrightarrow \mathbf{Skip})
\end{aligned}
$$

$ConfType \mathrel{\widehat=} HidePatientDetails$

$\bullet\ \langle Init \rangle\ ;\ \langle PatientDetails \rangle\ ;\ \langle ConfType \rangle$

$\mathbf{end}$

Figure 4.1: Specification of the patient details component of a Patient information system

Assume that the state variables *patientInfo* and *treats* have already been populated. The following is a step-by-step back propagation of the specification in Figure 4.1.

$$
\begin{array}{ll}
& \mathbf{bw}((\langle Init\rangle \ ; \ \langle PatientDetails\rangle \ ; \ \langle ConfType\rangle), \mathbf{True}) \\
= & \hfill [\text{Law 6.32 - } \mathbf{bw}\ \mathit{sequence}] \\
& \mathbf{bw}((\langle Init\rangle \ ; \ \langle PatientDetails\rangle), \mathbf{bw}(\langle ConfType\rangle, \mathbf{True})) \\
= & \hfill [\text{Law 6.18 - } \mathbf{bw}\ \text{CA}] \\
& \mathbf{bw}((\langle Init\rangle \ ; \ \langle PatientDetails\rangle), \langle ConfType\rangle) \\
= & \hfill [\text{Law 6.32 - } \mathbf{bw}\ \mathit{sequence}] \\
& \mathbf{bw}(\langle Init\rangle, \mathbf{bw}(\langle PatientDetails\rangle, \langle ConfType\rangle))
\end{array}
$$

The following is the back propagation calculation for $\mathbf{bw}(\langle PatientDetails\rangle, \langle ConfType\rangle)$.

$$
\begin{array}{ll}
& \mathbf{bw}(\langle PatientDetails\rangle, \langle ConfType\rangle) \\
= & \hfill [\text{definition of } \mathit{PatientDetails}] \\
& \mathbf{bw}(\langle \mathbf{var}\ patient : PATIENT \bullet \\
& \quad patientIn?patient \longrightarrow reqPatient := patient?; \\
& \quad (patient? \in treats \land patient? \in \operatorname{dom}\ patientInfo\ \& \\
& \qquad\qquad detailsOut!(patientInfo\ patient?) \longrightarrow \mathbf{Skip})\rangle, \\
& \qquad\qquad\qquad \langle ConfType\rangle)
\end{array}
$$

$$
\begin{aligned}
= \quad & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad [\text{Law 6.27 - } \mathbf{bw} \text{ scope}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}((\langle patientIn?patient \longrightarrow reqPatient := patient? \rangle; \\
& \qquad \langle (patient? \in treats \land patient? \in \operatorname{dom}\ patientInfo\ \& \\
& \qquad\qquad detailsOut!(patientInfo\ patient?) \longrightarrow \mathbf{Skip}) \rangle), \\
& \qquad\quad \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType) \\
= \quad & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad [\textbf{Lemma 5.23}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}((\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle; \\
& \qquad \langle reqPatient := patient? \rangle; \\
& \qquad \langle (patient? \in treats \land patient? \in \operatorname{dom}\ patientInfo\ \& \\
& \qquad\qquad detailsOut!(patientInfo\ patient?)) \longrightarrow \mathbf{Skip} \rangle), \\
& \qquad\quad \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType) \\
= \quad & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad [\text{Law 6.32 - } \mathbf{bw}\ \mathit{sequence}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle; \\
& \qquad \langle reqPatient := patient? \rangle, \\
& \qquad\quad \mathbf{bw}(\langle (patient? \in treats \land patient? \in \operatorname{dom}\ patientInfo\ \& \\
& \qquad\qquad detailsOut!(patientInfo\ patient?)) \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad\qquad\quad \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType))
\end{aligned}
$$

$$
\begin{aligned}
= \quad & \quad [\text{Law 6.33 - } \mathbf{bw}\ \textit{guard}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle; \\
& \qquad \langle reqPatient := patient? \rangle, \\
& \qquad\quad (\mathbf{bw}(\langle detailsOut!(patientInfo\ patient?) \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad\qquad \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType) \\
& \qquad\quad \wedge\ \mathbf{U}(patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo)) \\
& \qquad \vee\ \mathbf{U}(\neg\ (patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo))) \\
= \quad & \quad [\text{Law 6.34 - } \mathbf{bw}\ \textit{output}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle; \\
& \qquad \langle reqPatient := patient? \rangle, \\
& \qquad\quad (((\forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType \wedge \\
& \qquad\qquad (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient}?)) \\
& \qquad\quad \wedge\ \mathbf{U}(patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo) \\
& \qquad \vee\ \mathbf{U}(\neg\ (patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo)))) \\
= \quad & \quad [\text{Law 6.32 - } \mathbf{bw}\ \textit{sequence}] \\
& \forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad (\mathbf{bw}(\langle reqPatient := patient? \rangle, \\
& \qquad\quad (((\forall\, patient : PATIENT \bullet \exists\, \widetilde{patient} : PATIENT \bullet ConfType \wedge \\
& \qquad\qquad (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient}?)) \\
& \qquad\quad \wedge\ \mathbf{U}(patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo)) \\
& \qquad \vee\ \mathbf{U}(\neg\ (patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo)))))
\end{aligned}
$$

$$
\begin{array}{ll}
= & \text{[Law 6.31 - } \mathbf{bw} \textit{ assignment}] \\
& \forall patient : PATIENT \bullet \exists \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad (((\forall patient : PATIENT \bullet \exists \widetilde{patient} : PATIENT \bullet ConfType \land \\
& \qquad\quad (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient?})) \\
& \qquad \land \mathbf{U}(patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo)) \\
& \qquad \lor \mathbf{U}(\neg\ (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo)))) \\
& \qquad\qquad [reqPatient, \widetilde{reqPatient} / patient?, \widetilde{patient?}] \\
= & \text{[Definition of } \textit{ConfType}] \\
& \forall patient : PATIENT \bullet \exists \widetilde{patient} : PATIENT \bullet \\
& \quad \mathbf{bw}(\langle patientIn?patient \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad (((\forall patient : PATIENT \bullet \exists \widetilde{patient} : PATIENT \bullet \\
& \qquad\quad (reqPatient \notin treats \Rightarrow \\
& \qquad\qquad patientInfo\ reqPatient \neq \widetilde{patientInfo}\ \widetilde{reqPatient}) \\
& \qquad \land (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient?})) \\
& \qquad \land \mathbf{U}(patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo)) \\
& \qquad \lor \mathbf{U}(\neg\ (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo)))) \\
& \qquad\qquad [reqPatient, \widetilde{reqPatient} / patient?, \widetilde{patient?}]
\end{array}
$$

$$
\begin{aligned}
= \quad & \qquad\qquad\qquad\qquad\qquad\qquad [\text{Renaming } \mathit{reqPatient}, \widetilde{\mathit{reqPatient}}] \\
& \forall\, \mathit{patient} : \mathit{PATIENT} \bullet \exists\, \widetilde{\mathit{patient}} : \mathit{PATIENT} \bullet \\
& \quad \mathbf{bw}(\langle \mathit{patientIn}?\mathit{patient} \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad (((\forall\, \mathit{patient} : \mathit{PATIENT} \bullet \exists\, \widetilde{\mathit{patient}} : \mathit{PATIENT} \bullet \\
& \qquad\quad (\mathit{patient}? \notin \mathit{treats} \Rightarrow \\
& \qquad\qquad \mathit{patientInfo}\ \mathit{patient}? \neq \widetilde{\mathit{patientInfo}}\ \widetilde{\mathit{patient}}?) \\
& \qquad\quad \wedge (\mathit{patientInfo}\ \mathit{patient}? = \widetilde{\mathit{patientInfo}}\ \widetilde{\mathit{patient}}?)) \\
& \qquad\quad \wedge \mathbf{U}(\mathit{patient}? \in \mathit{treats} \wedge \mathit{patient}? \in \operatorname{dom}\ \mathit{patientInfo})) \\
& \qquad \vee \mathbf{U}(\neg\ (\mathit{patient}? \in \mathit{treats} \wedge \mathit{patient}? \in \operatorname{dom}\ \mathit{patientInfo})))) \\
= \quad & \qquad\qquad\qquad\qquad\qquad\qquad [\text{remove quantifiers - no bound variable}] \\
& \forall\, \mathit{patient} : \mathit{PATIENT} \bullet \exists\, \widetilde{\mathit{patient}} : \mathit{PATIENT} \bullet \\
& \quad \mathbf{bw}(\langle \mathit{patientIn}?\mathit{patient} \longrightarrow \mathbf{Skip} \rangle, \\
& \qquad\quad (((\mathit{patient}? \notin \mathit{treats} \Rightarrow \\
& \qquad\qquad \mathit{patientInfo}\ \mathit{patient}? \neq \widetilde{\mathit{patientInfo}}\ \widetilde{\mathit{patient}}?) \\
& \qquad\quad \wedge (\mathit{patientInfo}\ \mathit{patient}? = \widetilde{\mathit{patientInfo}}\ \widetilde{\mathit{patient}}?) \\
& \qquad\quad \wedge \mathbf{U}(\mathit{patient}? \in \mathit{treats} \wedge \mathit{patient}? \in \operatorname{dom}\ \mathit{patientInfo})) \\
& \qquad \vee \mathbf{U}(\neg\ (\mathit{patient}? \in \mathit{treats} \wedge \mathit{patient}? \in \operatorname{dom}\ \mathit{patientInfo}))))
\end{aligned}
$$

$$
\begin{aligned}
= \quad & \hspace{20em} [\text{Law 6.36 - } \textbf{bw} \textit{ input prefix}] \\
& \forall\, patient? : PATIENT \bullet \exists\, \widetilde{patient}? : PATIENT \bullet \\
& \quad ((\forall\, patient? : PATIENT \bullet \\
& \qquad\qquad (((patient? \notin treats \Rightarrow \\
& \qquad\qquad\qquad patientInfo\ patient? \neq \widetilde{patientInfo}\ \widetilde{patient}?) \\
& \qquad\qquad \wedge (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient}?) \\
& \qquad\qquad \wedge \mathbf{U}(patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo)) \\
& \qquad\quad \vee \mathbf{U}(\neg\ (patient? \in treats \\
& \qquad\qquad\quad \wedge patient? \in \operatorname{dom}\ patientInfo))))[patient?/\widetilde{patient}?]) \\
= \quad & \hspace{20em} [\text{Law 6.33 - definition of } \mathbf{U}] \\
& \forall\, patient? : PATIENT \bullet \exists\, \widetilde{patient}? : PATIENT \bullet \\
& \quad ((\forall\, patient? : PATIENT \bullet \\
& \qquad\qquad (((patient? \notin treats \Rightarrow \\
& \qquad\qquad\qquad patientInfo\ patient? \neq \widetilde{patientInfo}\ \widetilde{patient}?) \\
& \qquad\qquad \wedge (patientInfo\ patient? = \widetilde{patientInfo}\ \widetilde{patient}?) \\
& \qquad\qquad \wedge (patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo) \\
& \qquad\qquad \wedge (\widetilde{patient}? \in \widetilde{treats} \wedge \widetilde{patient}? \in \operatorname{dom}\ \widetilde{patientInfo})) \\
& \qquad\quad \vee (\neg\ (patient? \in treats \wedge patient? \in \operatorname{dom}\ patientInfo) \\
& \qquad\qquad \wedge \neg\ (\widetilde{patient}? \in \widetilde{treats} \wedge \widetilde{patient}? \in \operatorname{dom}\ \widetilde{patientInfo})))) \\
& \hspace{24em} [patient?/\widetilde{patient}?])
\end{aligned}
$$

$$
\begin{array}{ll}
= & \hfill [\text{Renaming}] \\
& \forall\, patient? : PATIENT \bullet \exists\, \widetilde{patient}? : PATIENT \bullet \\
& \quad (\forall\, patient? : PATIENT \bullet \\
& \qquad (((patient? \notin treats \Rightarrow \\
& \qquad\quad patientInfo\ patient? \neq \widetilde{patientInfo}\ patient?) \\
& \qquad \land (patientInfo\ patient? = \widetilde{patientInfo}\ patient?) \\
& \qquad \land (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo) \\
& \qquad \land (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \widetilde{patientInfo})) \\
& \qquad \lor (\neg\, (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo) \\
& \qquad \land \neg\, (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \widetilde{patientInfo})))) \\
= & \hfill [\text{Eliminate outer existential quantifier}] \\
& \forall\, patient? : PATIENT \bullet \\
& \quad (\forall\, patient? : PATIENT \bullet \\
& \qquad (((patient? \notin treats \Rightarrow \\
& \qquad\quad patientInfo\ patient? \neq \widetilde{patientInfo}\ patient?) \\
& \qquad \land (patientInfo\ patient? = \widetilde{patientInfo}\ patient?) \\
& \qquad \land (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo) \\
& \qquad \land (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \widetilde{patientInfo})) \\
& \qquad \lor (\neg\, (patient? \in treats \land patient? \in \mathrm{dom}\ patientInfo) \\
& \qquad \land \neg\, (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \widetilde{patientInfo}))))
\end{array}
$$

$$
\begin{aligned}
= \quad & \hspace{20em} \text{[Combine outer universal quantifiers]} \\
& \forall\, patient? : PATIENT \bullet \\
& \qquad (((patient? \notin treats \Rightarrow \\
& \qquad\qquad patientInfo\ patient? \neq \widetilde{patientInfo}\ patient?) \\
& \qquad \wedge (patientInfo\ patient? = \widetilde{patientInfo}\ patient?) \\
& \qquad \wedge (patient? \in treats \wedge patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad \wedge (patient? \in \widetilde{treats} \wedge patient? \in \mathrm{dom}\ \ \widetilde{patientInfo})) \\
& \quad \vee (\neg\ (patient? \in treats \wedge patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad \wedge \neg\ (patient? \in \widetilde{treats} \wedge patient? \in \mathrm{dom}\ \ \widetilde{patientInfo})))
\end{aligned}
$$

Continuing the back propagation from page 125;

$$
\begin{aligned}
& \mathbf{bw}(\langle Init \rangle, \mathbf{bw}(\langle PatientDetails \rangle, \langle ConfType \rangle)) \\
= \quad & \hspace{12em} [\text{simplification of } \mathbf{bw}(\langle PatientDetails \rangle, \langle ConfType \rangle)] \\
& \mathbf{bw}(\langle Init \rangle, \\
& \quad (\forall\, patient? : PATIENT \bullet \\
& \qquad (((patient? \notin treats \Rightarrow \\
& \qquad\qquad patientInfo\ patient? \neq \widetilde{patientInfo}\ patient?) \\
& \qquad \wedge (patientInfo\ patient? = \widetilde{patientInfo}\ patient?) \\
& \qquad \wedge (patient? \in treats \wedge patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad \wedge (patient? \in \widetilde{treats} \wedge patient? \in \mathrm{dom}\ \ \widetilde{patientInfo})) \\
& \quad \vee (\neg\ (patient? \in treats \wedge patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad \wedge \neg\ (patient? \in \widetilde{treats} \wedge patient? \in \mathrm{dom}\ \ \widetilde{patientInfo})))))
\end{aligned}
$$

$$
\begin{array}{ll}
= & \hfill \text{[No change in state in } \langle\ \mathit{Init}\ \rangle\text{]} \\
& \forall\, patient? : PATIENT \bullet \\
& \quad (\quad (\quad (patient? \notin treats \Rightarrow \\
& \qquad\qquad\qquad patientInfo\ patient? \neq \widetilde{patientInfo}\ patient?) \\
& \qquad\qquad \land\ (patientInfo\ patient? = \widetilde{patientInfo}\ patient?) \\
& \qquad\qquad \land\ (patient? \in treats \land patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad\qquad \land\ (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \ \widetilde{patientInfo})) \\
& \qquad \lor\ (\neg\ (patient? \in treats \land patient? \in \mathrm{dom}\ \ patientInfo) \\
& \qquad\qquad \land\ \neg\ (patient? \in \widetilde{treats} \land patient? \in \mathrm{dom}\ \ \widetilde{patientInfo}))) \\
= & \hfill \text{[Predicate calculus]} \\
& \mathbf{true}
\end{array}
$$

The above manual back propagation of the specification in Figure 4.1 took approximately one hour to complete whereas the mechanised back propagation of the same specification using the tool (see Chapter 3) developed in this research took 120 milliseconds to complete. This shows a time-saving advantage of the mechanised back propagation approach over the manual approach. In addition, the amount of human errors that could be avoided through this mechanised calculation approach is self evident.

4.3 Value of the mechanisation

During the case study analysis carried out as part of this research, we were able to verify the consistency of the requirements in a specification where a real issue with the formalisation of the confidentiality requirement was not apparent at first glance. However, later it was noticed that specification was seemingly incorrect. Upon further review, it was identified that we had circumvented the weakness in the specification of the system by strengthening the formalisation of the confidentiality requirement, that allowed us to verify the consistency of the requirements in the system. In this thesis, such a specification is called a 'weak specification'.

Weak specification. For the purposes of this research, a specification is referred as a 'weak specification' if the specification is seemingly incorrect but the mechanised analysis of the specification using BCF in *Circus* results in a predicate that can be simplified to **true**, thereby verifying the consistency of the requirements.

This experience with a 'weak specification' is discussed and demonstrated in Section 6.2.7 using a fictitious hand-crafted system. The discussion further demonstrates the value of the mechanisation. This is because the analysis did not verify the consistency of the requirements until the confidentiality requirements were strengthened.

4.4 Benchmark for evaluation

To the author's knowledge, there is no existing literature that defines a "benchmark set" of case studies that can be used to evaluate a potential tool for analysing systems with a confidentiality requirement. However, many papers that cover a broad range of systems especially in the domain of information flow theories, security and privacy discusses various confidentiality properties. And so, deriving an initial catalogue of case studies that can be used for evaluating the mechanisation of BCF in *Circus* or other similar mechanisations of security related tools as well as that can be extended by other researchers would be a useful contribution. Such a catalogue is proposed in the next chapter. Later in this thesis, this catalogue is used for evaluating the mechanisation of BCF in *Circus*.

4.5 Limitations of the catalogue approach for evaluation

The papers identified in Chapter 5 discuss confidentiality requirements that are required in certain system contexts. However, none of the identified papers contain any description or formal specification of these systems. Therefore, in order to analyse each identified confidentiality pattern **CP**, the following activities were carried out.

- Select a confidentiality requirement from Table 5.3 that reflects the pattern **CP**.
- Hand-craft a set of system requirements for a typical system for which **CP** has been identified as a confidentiality requirement.
- Develop a formal specification by interpreting the hand-crafted system requirements for the system.

It is a limitation of this research that specifications for case studies had to be developed based on hand-crafted system requirements. However, if there was at least a full description of a system in the identified papers, the system description could have been re-written using a Controlled Natural Language (CNL)[1]. An unambiguous and structured system description that follows a CNL can systematically be translated to formal specifications that can be used for analysing those systems for data leakage.

Cabral and Sampaio (2008) have produced a tool that can translate a specification written in a particular CNL to CSP. CSP being the reactive notation used in the *Circus* notation, such an approach can directly map reactive characteristics from a requirement document to a formal specification in the *Circus* notation. Since a CNL can be used

[1] "CNLs are engineered subsets of natural languages whose grammars and vocabularies have been restricted in a systematic way in order to reduce both the ambiguity and complexity of full NLs (e.g. English, French, etc.)" (Feuto Njonko et al., 2014, p. 68).

in such translations, further research can be carried out as to how the data structures can be mapped from a similar CNL to the Z notation, where the Z notation is used to encode data structures using the *Circus* notation. An effort in this direction is the work by Becker (2007) who proposed the use of Cassandra[2] to formalise policy specifications. Translating specifications written in a particular CNL to the *Circus* notation might be appropriate as a further extension to the mechanisation presented in this thesis.

[2] Cassandra is a policy specification language that is based on Datalog (Abiteboul et al., 1995) with constraints.

4.6 Evaluation plan

The evaluation of the tool will be carried out using the following steps.

1. Identify a set of patterns recurring in the catalogue of confidentiality requirements that has been derived from literature, where these requirements are related to data leakage.
2. Present a case study example for each identified confidentiality requirement pattern. The case study example will involve:
   - hand-crafting an unambiguous description of the system.
   - developing an appropriate *Circus* specification of the system.
   - encoding the confidentiality requirements using BCF in *Circus*.
   - using the mechanisation of BCF in *Circus* to analyse the formalized system for data leakage by executing the back propagation process and simplifying the resulting predicate using the Isabelle theorem prover.
3. Demonstrate how the weakness in a specification can be circumvented to make it verifiable when analysed using BCF in *Circus*.
4. Demonstrate how a contradiction in a specification can be detected when a system specification is analysed using BCF in Circus by introducing a contradiction purposely in the specification.
5. Demonstrating positive tests where specifications in the above case studies without a contradiction are verified when analysed using BCF in *Circus*.
6. Use the time taken for executing the back propagation process using the tool and the time taken for simplifying the generated predicate as parameters, to compare the relative resource utilization when different specifications are analysed using the proposed mechanisation on a common platform.

The objective of the evaluation is to show that the mechanisation correctly identifies the specifications that contain an inconsistency within the specification and specifications that do not. As you may recall from Section 2.7.1 on page 82, BCF concludes that a system may leak data if the predicate generated by back propagating the specification of a system contains a contradiction. Similarly, if the predicate generated does not contain a contradiction, then BCF concludes that the system will not leak data. Here, a contradiction reflects a logical inconsistency within the formal definitions of the functional and confidentiality requirements in a system specification.

Types of specifications analysed

During the evaluation, the following different types of specifications have be analysed.

Positive specification For the purposes of this research, a positive specification is defined as one which is written without any contradictions between the functionality and confidentiality requirements of the system. It is expected that applying the mechanised tool on such a specification will produce a predicate that can be *Simplified* to **true** by the Isabelle theorem prover.

Weak specification Recall from Section 4.3 in page 134 that during the analysis we were able to verify the consistency of the requirements that seemed to be incorrect. However, this verification was possible by circumventing the weakness with the specification using a modified formalisation of the confidentiality requirement. This issue has been demonstrated in Section 6.2.7.

Negative specification For the purposes of this research, a negative specification is defined as one which is written with at least one definite contradiction between the functionality and confidentiality requirements of the system. It is expected that applying the mechanised tool on such a specification will produce a predicate that cannot be *Simplified* by the Isabelle theorem prover. Rather, attempting to simplify the predicate using the Isabelle theorem prover will result in either *Theorem prover time-out* or *Counter example found* as outcomes.

Possible categories of specifications based on analysis outcome

In general, there can be four different categories of specifications as listed below.

positive and *provable* — A *positive specification* that can be proved automatically automatically using proof tactics.

positive and *not provable* — A *positive specification* that cannot be proved automatically using proof tactics. In this case, expert assistance is required for theorem proving. The theorem proving exercise may result in a time-out when some automated theorem proving commands are executed.

negative and *provable* — A *negative specification* for which a counter example can be generated automatically using proof tactics.

negative and not *provable* — A *negative specification* for which a counter example can be generated using automatically using proof tactics. In this case, expert assistance is required for identifying a counter example. The theorem proving exercise may result in a time-out when some automated theorem proving commands are executed.

4.7 Summary

The main objective of this chapter is to layout a plan for evaluating the proposed mechanisation of BCF in *Circus*. This plan has been derived based on both the capabilities of the mechanisation as well as the factors that confine the space where the mechanisation can be utilized.

In this chapter:

- The comparative advantages of the proposed mechanisation over the manual approach has been demonstrated.
- How the proposed mechanisation can be beneficial in identifying weak specifications which otherwise might be overlooked when following the manual approach was demonstrated.
- The limitations that guide and confine the approach that has been taken in mechanising BCF in *Circus* was discussed.
- The plan for evaluating the mechanisation of BCF in *Circus* has been discussed.

5 A systematic literature search for case study material

5.1 Introduction

This chapter presents an approach for compiling a catalogue of confidentiality requirement patterns from the literature. A pattern is a generalized description of a commonly occurring requirement (Dwyer et al., 1999, p. 412). A *pattern catalogue* is a collection of related patterns subdivided into different categories (Hakeem, 2010, p. 23).

In this chapter, a literature search for confidentiality requirements are carried out and the results are analysed to identify recurring patterns in those confidentiality requirements. In the next chapter, system models that contain confidentiality properties based on these patterns will be used in evaluating the practical applicability of the mechanisation of BCF. To the author's knowledge, system models that contain confidentiality properties based on such a pattern catalogue has not been published in the publicly accessible literature to this date. However, such a catalogue is required to evaluate the BCF in *Circus* mechanisation developed through this research. This chapter discusses how such a catalogue has been compiled to address this need. A systematic literature search process is adopted to identify publications that can be included in such a catalogue.

In addition, this chapter includes an approach for extracting generalized formalisations from the formalisations of confidentiality requirement patterns. The result is a set of minimum unique patterns of formalisation required to capture all the identified patterns of confidentiality requirements. Any technique or approach intending to provide support for the catalogue of confidentiality requirements can do so by providing support for this minimum set of generalized formalisations. In this research, this set of generalized formalisations is referred to as the "generalized patterns of confidentiality requirements". Similarly, when designing a software to support the catalogue of confidentiality requirements, we must ensure that the software supports the specification templates that reflect the generalized patterns of confidentiality requirements.

The 'pattern' approach for software engineering became common place in the software development community after Gamma et al. (1995) published the book *Design Patterns: Elements of Reusable Object-oriented Software*. In their book, they used "patterns to capture good solutions to common problems programmers experienced when designing software" (Adolph et al., 2003, p. 7).

5.2 Systematic literature search for case study material

A systematic process is followed in this literature search to enhance the quality and relevance of the resulting dataset.

5.2.1 Research question

The research question addressed in this chapter is:

> What confidentiality properties or requirements have been discussed in software engineering literature?

BCF in *Circus* integrates aspects of secure information flow theories with a formal system development approach. Formal system development is a software engineering approach that aims at delivering reliable software.

"*Software engineering is the establishment and use of sound engineering principles in order to obtain economically software that is reliable and works efficiently on real machines*" (Andreson, 2014, p. 496).

An unambiguous description of a system is required for formal system development. Further, scenarios with a confidentiality requirement or confidentiality property are needed to test secure information flow theories related to confidentiality.

Therefore, the ideal set of testing data for analysing BCF in *Circus* must have unambiguous descriptions of systems with a confidentiality requirement. The above research question confines the literature search to software engineering to limit the search base while maximising the possibility of extracting unambiguous descriptions of systems.

5.2.2 Identification of indexing services

The following phrases were used as a composite search string in Google Scholar to identify the literature that discusses systematic literature review of software engineering.

"systematic literature review" "software engineering"

The first 20 results were considered. The motivation was to categorize the collection of indexing services which each author thought was relevant for software engineering research. Table 5.1 lists the most recurring indexing services which the author used.

Based on the number of papers where the indexing server was mentioned, as shown in Table 5.1 , the indexing services IEEE Explorer, ACM Digital Library, ScienceDirect, SpringerLink and Google scholar were selected as indexing services to based the systematic literature search on. CiteSeer was excluded because it has a smaller digital library than Google Scholar (Khabsa and Giles, 2014, p. 1) even though both had the same number of mentions.

5.2.3 Inclusion criteria

The inclusion criteria for the documents retrieved were as follows.

1. The document must be in English.
2. Do not include repeated copies of the same document.
3. PDF and postscript documents were considered for this collection.
4. Only full documents rather than parts of documents were considered.
5. Only published journal papers, conference papers, thesis and reports were considered.

The collection of documents that conformed to the inclusion criteria is called the *literature base*.

During the preparation for the literature search, the author identified that *privacy* and *confidentiality* were often used in the context of lawyer-client confidentiality, patient privacy and patient-doctor confidentiality. However, sometimes these discussions were not centred on system engineering and design. During the literature search, such papers were therefore not considered. Section 5.2.1 explains how confining the literature search to software engineering may help in getting search results that discusses confidentiality analysis centred on system engineering and design.

5.2.4 Search keywords

The ecosystem of research addressed in this thesis is confidentiality engineering. A keyword map that represents the confidentiality engineering ecosystem is presented in Figure 5.1.

Indexer	# of times mentioned in the 20 papers
IEEE Explorer	16
ACM Digital Library	15
ScienceDirect	11
SpringerLink	9
Google scholar	5
CiteSeer	5

Table 5.1: Relevant catalogues for software engineering research

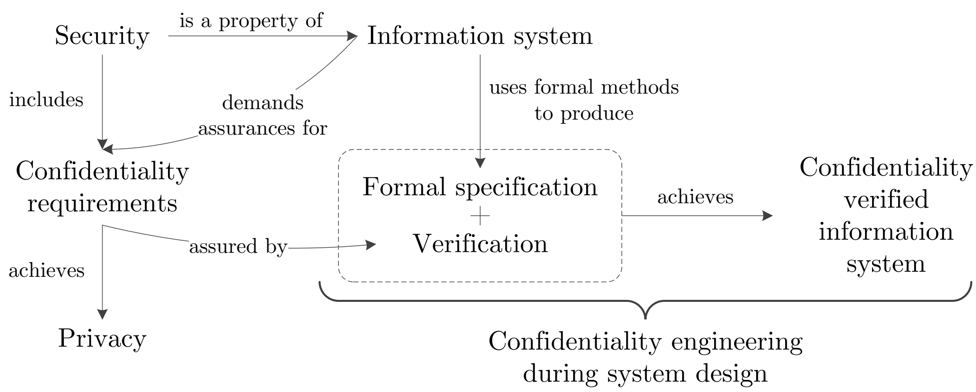


Figure 5.1: Keyword map describing the confidentiality engineering ecosystem

Based on the keyword map in Table 5.1, the following words and phrases were used to search for literature that may discuss confidentiality engineering during system design.

- “confidentiality” and “formal methods”
- “confidentiality” and “system design”
- “confidentiality properties”

- "confidentiality requirements"
- "security engineering"
- "secure by design"
- "privacy[1] by design"

5.2.5 Literature selection

The literature search carried out in this research showed that very few published papers described a complete model of a system. Rather, papers discussed scenarios within the system execution where a confidentiality assurance is required and how to fix it. Therefore, any literature that mentioned the need for confidentiality of information in the context of an information system was included.

Search results revealed 490 articles. All articles were put on a Mendeley catalogue (Mendeley Ltd., 2016). The catalogue was searched using the keyword 'confidential'. The inbuilt search system in Mendeley was used to search for the keyword. If a keyword existed in a paper, Mendeley showed the number of occurrences of that keyword in that paper. Mendeley takes the user directly to each occurrence in the paper through its inbuilt interface. The paragraph, table or diagram where each occurrence of the keyword was reviewed to see if a confidentiality requirement was described. Table 5.3 presents the collection of confidentiality requirements that have been identified following this search process.

Sequential access implementations. The system contexts where some of these confidentiality requirements were described might have been based on systems with concurrent access. However, the systems modelled in this research have been restricted to sequential access implementations because the catalogue of back

[1] As highlighted in the introduction section, the words Privacy and Confidentiality have been used interchangeably by many author's to mean the same thing. Our objective is to cover a broad ground regarding the existing literature that discusses confidentiality assurances required in system design.

propagation laws for BCF in *Circus* does not provide support for parallel processes. This limitation has been discussed in Section 2.8.

Types of data leakage risks considered. As discussed in "On data leakage and the inference problem" on pages 111 - 113 , BCF in *Circus* can be used to reason about the possibility of data leakage through:

- direct communication of values of state variables to the environment, that are required to be kept confidential as per a confidentiality requirement.
- indirect communication of confidential data to the environment through a state variable authorised for that particular user.

Therefore, the confidentiality requirements selected for inclusion in the confidentiality catalogue have been restricted to the above types of requirements.

The importance of analysing patterns of confidentiality requirements. When evaluating a technique that has been proposed for analysing confidentiality requirements in systems, it will be more justifiable to consider candidate requirements from groups of requirements having the same pattern, rather than individual requirements. By using this approach, a broader range of requirements can be addressed during the evaluation of the mechanized analysis technique. Confidentiality requirements take similar forms in many contexts. Such similarities can be the basis for grouping confidentiality requirements. Each resulting group will have confidentiality requirements with the same pattern. The next section presents the derivation of groups of confidentiality requirements, each having a different pattern.

5.3 Patterns of confidentiality requirements

The main objective of this section is to identify and review common patterns that may exist in a collection of confidentiality requirements, which has been extracted from literature. Each confidentiality requirement in this collection has been identified by a unique identifier of the form **CR*X*** where ***X*** represents a unique integer assigned to that particular requirement. A total of 33 **CR**s (**CR1**–**CR33**) were extracted from the literature and these confidentiality requirements are presented in Table 5.3, Section 5.3.1. Table 5.2 presents the patterns that exists in the descriptions of these confidentiality requirements. The table further groups the collection of confidentiality requirements based on which pattern each confidentiality requirement falls under. A pattern reflects data leakage risks of a similar form across many contexts.

Pattern id	Pattern description	Confidentiality requirement where the pattern exists
CP1	do not reveal the relation between x and y in S	**CR3**, **CR4**, **CR5**, **CR6**, **CR7**, **CR8**, **CR9**, **CR11**, **CR12**, **CR13**, **CR18**, **CR23**, **CR27**, **CR29**, **CR33**
CP2	do not reveal whether x is a member of S	**CR10**, **CR14**, **CR20**, **CR21**, **CR22**, **CR24**, **CR25**, **CR26**
CP3	do not reveal the set S	**CR28**, **CR30**, **CR32**
CP4	do not reveal the exact value of x	**CR1**, **CR2**, **CR15**, **CR16**, **CR19**, **CR31**
CP5	do not reveal whether the value of x is lower/higher than a given threshold n	**CR17**

Table 5.2: Patterns of confidentiality requirements

5.3.1 Deriving patterns of confidentiality requirements

Table 5.2 includes the collection of confidentiality requirements, identified from the set of literature, short-listed in Section 5.2.5. It is important to discuss briefly, the process which has been followed in identifying and deriving patterns of confidentiality requirements from this collection. The steps in this process include:

- Extracting a direct quote or paraphrasing the confidentiality requirement discussed in a given paper.
- Rephrasing the extracted description of each confidentiality requirement using a structured statement.
- Categorizing the structured statements based on commonalities in their descriptions.
- Presenting each category as a pattern of confidentiality requirements in Table 5.2.

Table 5.3: A collection of confidentiality requirements from literature

Context scenario	Confidentiality property/goal required
	a structured general definition for the confidentiality requirement
	Context : Sealed bid auction system
	The bid value b and the randomiser r must not be revealed to anyone except the bidder until the bid submission phase. (Viswanathan et al., 2000, p. 416)
CR1	**if** the user is not the bidder of b **then** <u>do not reveal the value</u> of b (which represents the bid value)
CR2	**if** the user is not the bidder of b **then** <u>do not reveal the value</u> of r (which represents the randomiser value)
	Context : Clinical information system
	"personal information about patients must be kept secure and confidential". "identifying information must not be made available to government and health authorities." (Gurses et al., 2005, p. 7,10)
CR3	**if** the user belongs to the government or a health authority **then** <u>do not reveal the association</u> between the patient and his/her medical data

Continued on next page

Table 5.3 – *Continued from previous page*

	"An unauthorized source should never access to the content". No one apart from authorised personal can have access to personal identifiable health information. (Juan et al., 2011, p. 26)
CR4	**if** the user does not have the necessary authorisation **then** <u>do not reveal the association</u> between the patient and his/her medical data
	"The IS shall protect the privacy of patients and their associated medical records. The confidentiality of data shall be guaranteed. Moreover, the database shall be available for allowing the access of patient medical information in case of urgent need". "Focusing on the patient data and its relationship with medical data, a privacy goal is associated with them. However medical data (without its associated relationship with patient data) is not constrained by this privacy goal." (Mayer et al., 2005, p. 2,10)
CR5	**if** the user does not have the necessary authorisation **and** the request is not made under a condition of urgency **then** <u>do not reveal the association</u> between the patient and his/her medical data

Continued on next page

Table 5.3 – *Continued from previous page*

	"For example, a patient typically gives consent to his/her medical record to physicians in a call group (set of physician sharing a practice), however, patients with particular conditions might only give consent to their family physician". Onabajo and Jahnke (2006b)
CR6	**if** the patient has a particular condition **and** the user is not the family physician **then** <u>do not reveal the association</u> between the patient and his/her medical data
	"The context of the confidentiality statement is not only based on the purpose, but also on potential user(s) or stakeholder(s) who require access to data e.g., a patient would normally give access to his/her medical record to a physician for care-delivery, but deny access to non-medical staff". "For example, access to sections of a medical record, such as prescription history, might have potential influence on treatment options, particularly during emergencies". (Onabajo and Jahnke, 2006a, p. 3,4)
CR7	**if** the user is not a physician **then** <u>do not reveal the association</u> between the patient and his/her medical data

Continued on next page

Table 5.3 – *Continued from previous page*

	It is important to preserve individual privacy of the persons in healthcare information systems. (Trouessin, 1999, p. 450)
CR8	**if** the user is not authorized **then** <u>do not reveal the association</u> between the patient and his/her medical data
	"We motivate the need for conditional confidentiality by referring to the doctor example from the introduction. As described before, the system should allow access to the X- ray only if the user is a doctor." (Tschantz and Wing, 2008, p. 111)
CR9	**if** the user is not a doctor **then** <u>do not reveal the association</u> between a patient and his/her x-ray
	"Protection of the integrity and confidentiality of medical images is an issue in the management of patients' medical records. Confidentiality states that unauthorized parties should not be granted to access medical images during transmission". (Ulutas et al., 2011, p. 341)
CR10	**if** the user is not authorized **then** for every given x, do not reveal whether x is a member of the set S (where S contains the set of x-rays)

Continued on next page

Table 5.3 – *Continued from previous page*

	"the specific association between individual patients and their illnesses is sensitive and should be maintained confidential". (De Capitani di Vimercati et al., 2014, p. 214)
CR11	**if** the user is not authorized **then** <u>do not reveal the association</u> between a patient and his/her illness
	"The last kind of attribute is the confidential attribute,the values of which we have to protect". "For example, if the attribute is a HIV test result, then the revelation of a '+' value may cause a serious invasion of privacy". (Wang et al., 2007, p. 257)
CR12	**if** the user is not authorized **then** <u>do not reveal the association</u> between a patient and his/her HIV result

Continued on next page

Table 5.3 – *Continued from previous page*

	Context : e-payment system “Several items in this system may need protection: (i) User’s private information as known to the local host (ii) Account information provided by User to the applet upon form submission (iii) Order information similar to (ii) (iv) The mere fact that User is engaging in a transaction with Merchant (v) Secrets concerning User’s account possessed by Acquirer such as account balance or credit limit.” (Dam and Giambiagi, 2000, p. 235)
CR13	**if** the user is not authorized **then** <u>do not reveal the association</u> between a customer and his/her account balance result

Continued on next page

Table 5.3 – *Continued from previous page*

Context : Phone book

The existence of a particular phone number in a phone book should be kept secret.
"The property to be kept secret for the example is whether a particular string, say '555-55' is in the phone book. Let us denote it by secret. We want to verify that the attacker cannot infer whether the secret holds or not based on her knowledge of the program and observation of the outputs (in this case, the variable message)".

(Cerny and Alur, 2009b, p. 175)

CR14

if the user is not authorized
then for every given x,
do not reveal whether x is a member of the set S
(where S contains the phone numbers in the phone book)

Context : Smart card

The confidentiality of the personal data stored in a smart card must be maintained.
"Due to its particular nature, a major concern of smartcards applications is to guarantee confidentiality and integrity of data".

(Barthe and Dufay, 2005, p. 133,164)

CR15

if the user is not authorized
then <u>do not reveal the value</u> of x
(where x is any personal detail stored in the smart card)

Continued on next page

Table 5.3 – *Continued from previous page*

	Context : e-Purse "In that specific example, agents who are not the card holder should not know that there is at least $v in the e-purse (whatever the value of v is)". "An agent should not know the exact value of some state variable". "An agent should not know that the value of some state variable is below/above some threshold". (De Landtsheer and Van Lamsweerde, 2005, p. 44)
CR16	**if** the agent is not the card holder **then** <u>do not reveal the value</u> of *x*
CR17	**if** the agent is not the card holder **then** do not reveal whether the value *y* is above/below a certain threshold *n*

Continued on next page

Table 5.3 – *Continued from previous page*

Context : Bank information system

The paper uses confidentiality requirements from Chandra and Khan (2010, p. 17), which reads, "Confidentiality protects data/information from unauthorised user access. Security demands that sensitive information should not be disclosed publicly. For example, in a bank account management system, function get balance () shows the current balance amount of user. In this case permission should be granted only for authorised user to see the information".

(Parveen et al., 2015, p. 2)

CR18

if the user is not authorized
then do not reveal the association between
a customer and his/her current balance

"This enables us to check confidentiality properties, e.g., that critical data such as credit card information are shared only with authorized partners". "a driver in trouble must be assured that information about his credit card and his location cannot become available to unauthorized users".

(Lapadula et al., 2008, p. 713,714)

CR19

if the user is not authorized
then do not reveal the value of y
(where y is a credit card information of the card holder)

Continued on next page

Table 5.3 – *Continued from previous page*

	Context : Examination system "No examinee should learn any details of the contents of the examination before the start of the examination". "No examinee should learn any details of the contents of any other examinees answer paper between the start of the paper and the end of the examination". "No examinee should learn any details of the marking until results are posted". (Foley and Jacob, 1995, p. 143)
CR20	**if** the user u is registered in an exam e **and** exam e has not started **then** for every given x, do not reveal whether x is a member of the set S (where S represents the contents of the exam e)

Continued on next page

Table 5.3 – *Continued from previous page*

CR21	**if** the user u currently using the system is not requesting information that belongs to him/her **and** exam e has started and but not ended **then** <u>do not reveal the set</u> S (where S represents the answers recorded by a user other than u in the exam e)
CR22	**if** the user u is registered in an exam e **and** the results of exam e has not been posted **then** for every given x, do not reveal whether x is a member of the set S (where S represents the markings for the exam e)
	The crucial information that is confidential[2] in a computer assisted assessment and diagnosis system includes the testing number, the name of the candidates, title, score and user account amongst others. (Cao and Wang, 2009, p. 292)
CR23	**if** the user is not authorized **then** <u>do not reveal the association</u> between a candidate and his/her candidate details

Continued on next page

[2] Cao and Wang (2009) describes a mechanism that protects the confidential data via encryption.

Table 5.3 – *Continued from previous page*

	Context : Java card
	The confidentiality of data in a multi-application Java card must be guaranteed as per the applet isolation principle. (Andronick et al., 2003, p. 335)
CR24	**if** the applet A is not authorised on the applet B **then** for every given x, do not reveal whether x is a member of the set S (where S represents the set of data in the applet A)
	"Open smart cards let you download code onto cards after their issuance (postissuance)". "One of the main issues when deploying these applications is to guarantee to the customer that these applications will be safe i.e., that their execution will not jeopardise the smart card's integrity or confidentiality.". (Casset, 2002, p. 290)
CR25	**if** the applet A is not authorised on the applet B **then** for every given x, do not reveal whether x is a member of the set S (where S represents the set of data in the applet A)

Continued on next page

Table 5.3 – *Continued from previous page*

	"This objective prevents the objects owned by one applet from being used by another applet without explicit sharing. The isolation between the applets covers two security properties: *confidentiality* and integrity. The confidentiality ensures that during its execution, an applet cannot read the information stored in the other applets". (Chetali and Nguyen, 2008, p. 202)
CR26	**if** the applet A is not authorised on the applet B **then** for every given x, do not reveal whether x is a member of the set S (where S represents the set of data in the applet A)

Continued on next page

Table 5.3 – *Continued from previous page*

	Context : Conference management system The following confidentiality properties are addressed. "A group of users learn nothing about a paper unless one of them becomes an author of that paper or a PC member at the paper's conference. A group of users learn nothing about a paper beyond the last submitted version unless one of them becomes an author of that paper. A group of users learn nothing about the content of a review beyond the last submitted version before the discussion phase and the later versions unless one of them is that review's author. The author's learn nothing about the discussion of their paper". (Kanav et al., 2014, p. 168)
CR27	**if** the user u is not the author of the paper x **and** u is not a PC member at the conference where x is submitted **then** <u>do not reveal the association</u> between the paper x and any details related to that paper

Continued on next page

Table 5.3 – *Continued from previous page*

Context : Broker subscription system

	"Confidentiality is important here because Pubs want to make sure that only paying customers have access to the quotes. We say that a CBPS system provides *publication confidentiality* if Brokers can neither identify the content of the messages published by Pubs nor infer the distribution of *attribute values* of the message". (Ion et al., 2010, p. 134)
CR28	**if** the user *u* is a Broker **then** do not reveal the set *S* (where *S* is the set of contents in the messages published by a publisher)
	"We say that a CBPS system provides *subscription privacy* if Brokers can neither identify what subscriptions **Subs** made nor relate a set of subscriptions to a specific **Sub**". (Ion et al., 2010, p. 134)
CR29	**if** the user *u* is a Broker **then** do not reveal the association between a subscriber and his/her set of subscriptions

Continued on next page

Table 5.3 – *Continued from previous page*

Context : Military information system

"Information about mission plans, strategy, and deployment of troops must remain confidential on the C4I computer system and networks of all type".
"If an adversary gets access to the logistics information stored in a file or database may be used to misguide the army commander in the deployment of troops".

(Alghamdi et al., 2010, p. 131)

CR30	**if** the user *u* is not authorised **then** do not reveal the set *S* (where *S* is the set of logistics information)

Context : Information retrieval system

The confidentiality of the search query as well as the contents of the retrieved documents should be maintained.
"The proposed method maintains the confidentiality of the query as well as the content of retrieved documents".

(Swaminathan et al., 2007, p. 12)

CR31	**if** the user is not authorized **then** do not reveal the value of *x* (where *x* is the search query)
CR32	**if** the user is not authorized **then** do not reveal the set *S* (where *S* is the set of contents in the retrieved documents)

Continued on next page

Table 5.3 – *Continued from previous page*

Context : Human resource

"For example, to maintain the confidentiality of personnel data while handling the requests for HR data, the security requirement shall guarantee that only those requests coming from the members of human resources staff are considered".

(Yu et al., 2015, p. 104)

CR33	**if** the user is not authorized **then** do not reveal the association between an employee and his/her personal details

It is important to identify any commonalities that may exist in the formalisation of the patterns in Table 5.2 using BCF in *Circus*. Such commonalities maybe considered as generalized patterns, as they exist across more than one confidentiality pattern. However, before a confidentiality pattern can be formalized, any vagueness within its description must be removed. In Table 5.3, **CP3** is identified as having a vague description. The next section discusses the possible different interpretations of **CP3** that can be formalised.

5.4 Subtleties in formalizing generic patterns of confidentiality requirements using BCF in *Circus*

Most of the confidentiality requirements presented in Table 5.3 are not described in a clear and concise manner. Therefore, the patterns derived from these confidentiality requirements can be formalised in more than one way. The subtleties with these different formal definitions translate to different upper limits on the information that can be disclosed to an unauthorised audience.

Such subtleties may be required during the system design stage where there are often trade-offs between functional and non-functional requirements (Yu and Liu, 2001, p. 185; Santen, 2006, p. 154). For example, rather than concealing every single bid in a set of bids *Bids* it will be acceptable to conceal at least 1 bid. By doing so, the uncertainty about the highest bid in *Bids* can be maintained as the the concealed bid may be the highest bid.

In this section, we discuss possible different formal definitions of inequality between two sets, as required by pattern **CP3**. The pattern **CP3** states:

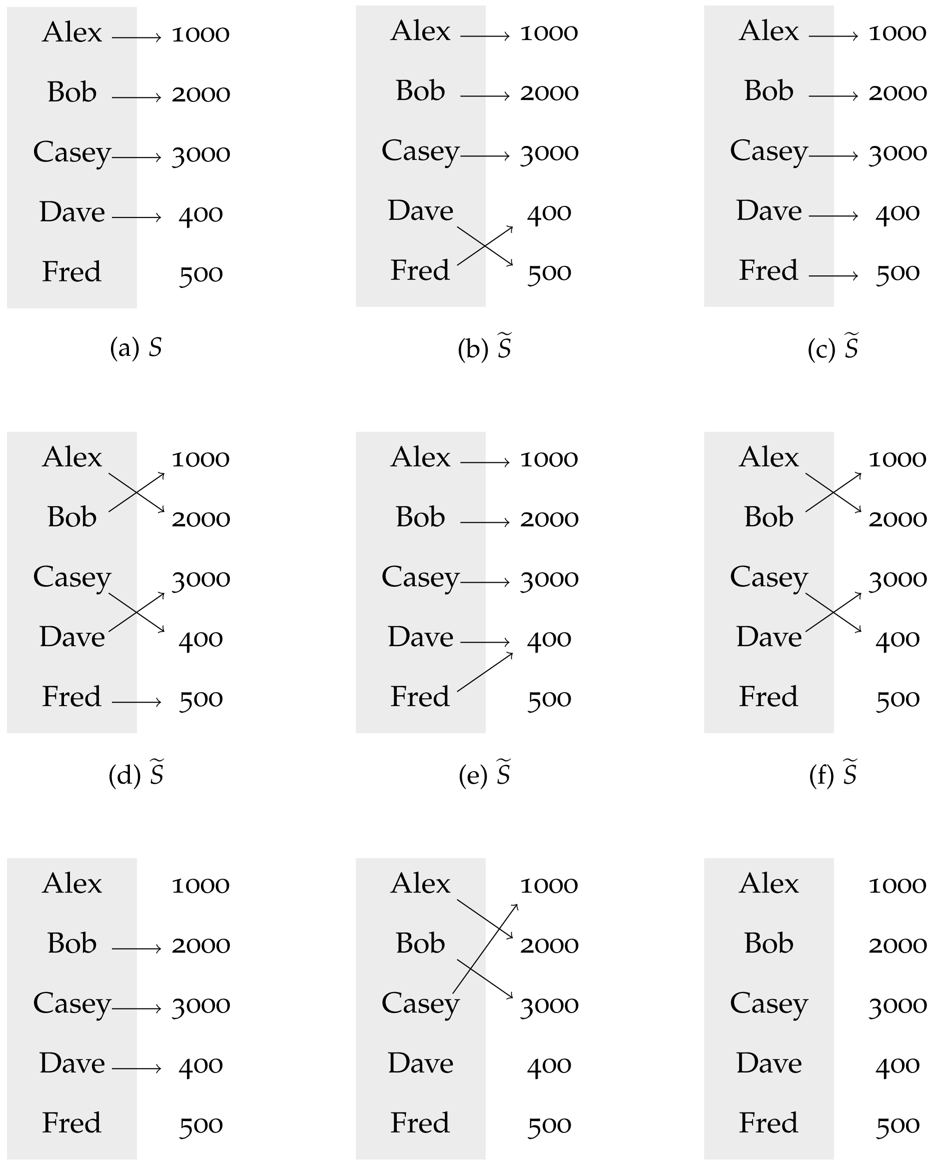
> do not reveal the set S

Even though the pattern demands that the set S must not be revealed, the specifics of how much information about S must be concealed has not been defined in the original literature. Table 5.4 lists some possible ways in which the inequality between two sets may be formalized using BCF in *Circus*.

Possible ways of specifying set inequality	Syntax in BCF in *Circus*
do not reveal the exact composition of the set S	$S \neq \widetilde{S}$
do not reveal any elements of the set S	$S \cap \widetilde{S} = \{\}$
do not reveal at least n elements from the set S	$(\# S + n) \geq \# \widetilde{S}$

Table 5.4: Possible ways of specifying an inequality between two sets S and $\widetilde{S}$

The subtleties listed in Table 5.4 is demonstrated using a set of tuples of the function S and $\widetilde{S}$ as shown in Figure 5.2. Each function maps a person identifier to his/her salary. Each mapping (x, y) is a tuple, such as (Alex, 1000) in Figure 5.2a, (Fred, 400) in Figure 5.2e and (Casey, 1000) in Figure 5.2h. Table 5.5 shows the differences between the function map in Figure 5.2a and each of the the function maps in Figure 5.2b to Figure 5.2i.



(a) S (b) $\widetilde{S}$ (c) $\widetilde{S}$

(d) $\widetilde{S}$ (e) $\widetilde{S}$ (f) $\widetilde{S}$

(g) $\widetilde{S}$ (h) $\widetilde{S}$ (i) $\widetilde{S}$

Figure 5.2: A function map for a function S and possible function maps for different variants of a its twin function $\widetilde{S}$

	$\mathrm{dom}(S)$	$\mathrm{ran}(S)$	$S \cap \widetilde{S} = \{\}$	$S \neq \widetilde{S}$	$(\# S + 1) \geq \# \widetilde{S}$
function map (b) as $\widetilde{S}$			×	✓	×
$\mathrm{dom}(\widetilde{S})$	$=$				
$\mathrm{ran}(\widetilde{S})$		$=$			
function map (c) as $\widetilde{S}$			×	✓	✓
$\mathrm{dom}(\widetilde{S})$	$\neq$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			
function map (d) as $\widetilde{S}$			✓	✓	×
$\mathrm{dom}(\widetilde{S})$	$=$				
$\mathrm{ran}(\widetilde{S})$		$=$			
function map (e) as $\widetilde{S}$			×	✓	×
$\mathrm{dom}(\widetilde{S})$	$=$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			
function map (f) as $\widetilde{S}$			✓	✓	✓
$\mathrm{dom}(\widetilde{S})$	$\neq$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			
function map (g) as $\widetilde{S}$			×	✓	✓
$\mathrm{dom}(\widetilde{S})$	$\neq$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			
function map (h) as $\widetilde{S}$			✓	✓	✓
$\mathrm{dom}(\widetilde{S})$	$\neq$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			
function map (i) as $\widetilde{S}$			✓	✓	✓
$\mathrm{dom}(\widetilde{S})$	$\neq$				
$\mathrm{ran}(\widetilde{S})$		$\neq$			

Table 5.5: A comparison of equality in function maps from Figure 5.2

NOTE:
- The n in $(\# S + n) \geq \# \widetilde{S}$ has been instantiated to 1, for the purposes of demonstration in Table 5.5.
- The ✓ denotes that the property defined in the column heading is satisfied while × denotes that the property is not satisfied.

5.4.1 Scenarios where different subtleties with inequality between two sets may satisfy a confidentiality requirement

The Table 5.6 shows how effective each possible way of specifying inequality between two sets is against confidentiality requirements, that have been identified in Section 5.3. The set S in Table 5.6 may be any expression that results in a set. The ✓ denotes that the property is satisfied by the type of implementation.

Set to be kept secret (S)	Specify a set inequality where we		
	Conceal the **exact** contents of the set	Conceal **all** the elements of the set	Conceal **at least** n elements from the set
set of salaries in a salary band with x number of employees [3]	may reveal M where $M \subset S$. M might contain $x - 1$ salaries. Using M and x we can compute the sum of the hidden salaries thereby revealing the only hidden salary	✓	✓ (if $n > 1$)
answers of a candidate c [4]	May reveal all answers except 1	✓	May reveal $(\# S - n)$ answers from S
set of medicines in a patients prescription history [5]	may reveal M where $M \subset S$. M might contain a specific medicine implying a specific medical condition of the patient	✓	may reveal M where $M \subset S$. M might contain a specific medicine implying a specific medical condition of the patient

Table 5.6: How confidentiality properties are addressed by subtleties in set inequality.

[3] Chivers (2006, p. 89) discusses a scenario where the relationship between an employee and his/her salary is confidential. Lunt (1989, p. 104) states that if the set of employees in a group is small enough then the association between a particular employee and his/her salary can be inferred.

[4] Foley and Jacob (1995, p. 143) state that the answers recorded by an examinee must not be revealed to any other examinee during the examination.

[5] Onabajo and Jahnke (2006a, p. 844) state that restricting the visibility of the prescription history is a patient's confidentiality requirement.

5.5 Identifying and formalizing generic patterns of confidentiality

This section presents a discussion on extracting generalized patterns from formal specifications of confidentiality requirement patterns that were identified in Section 5.3. The approach involves identifying commonalities that may exist in formalizing these patterns and deriving generalized patterns of confidentiality requirements based on these commonalities. These generalized patterns can also be categorised as property specification patterns since these patterns have been extracted from specifications of properties.

> "*A property specification pattern describes the essential structure of some aspect of a system's behaviour and provides expressions of this behaviour in a range of common formalisms*" (Dwyer et al., 1998, p. 9).

Konrad et al. (2003) provide a template for specifying security patterns. Further, he suggests a systematic process for simulating as well as model checking the resulting models. Figure 5.3 shows the steps that were followed in deriving these generalized patterns.

CP1 The confidentiality pattern **CP1** states:

do not reveal the relation between x and y in S

Here, the objective of **CP1** is to maintain the secrecy regarding the existence of the tuple or pair (x, y) in the set S. Binary relations and functions from the Z notation are used to model such a set of tuples (Spivey, 1989, p. 27).

> "*A relation is defined to be a set of pairs. A function is a particular form of relation, where each domain element has only one corresponding range element*" (ISO/IEC, 2002).

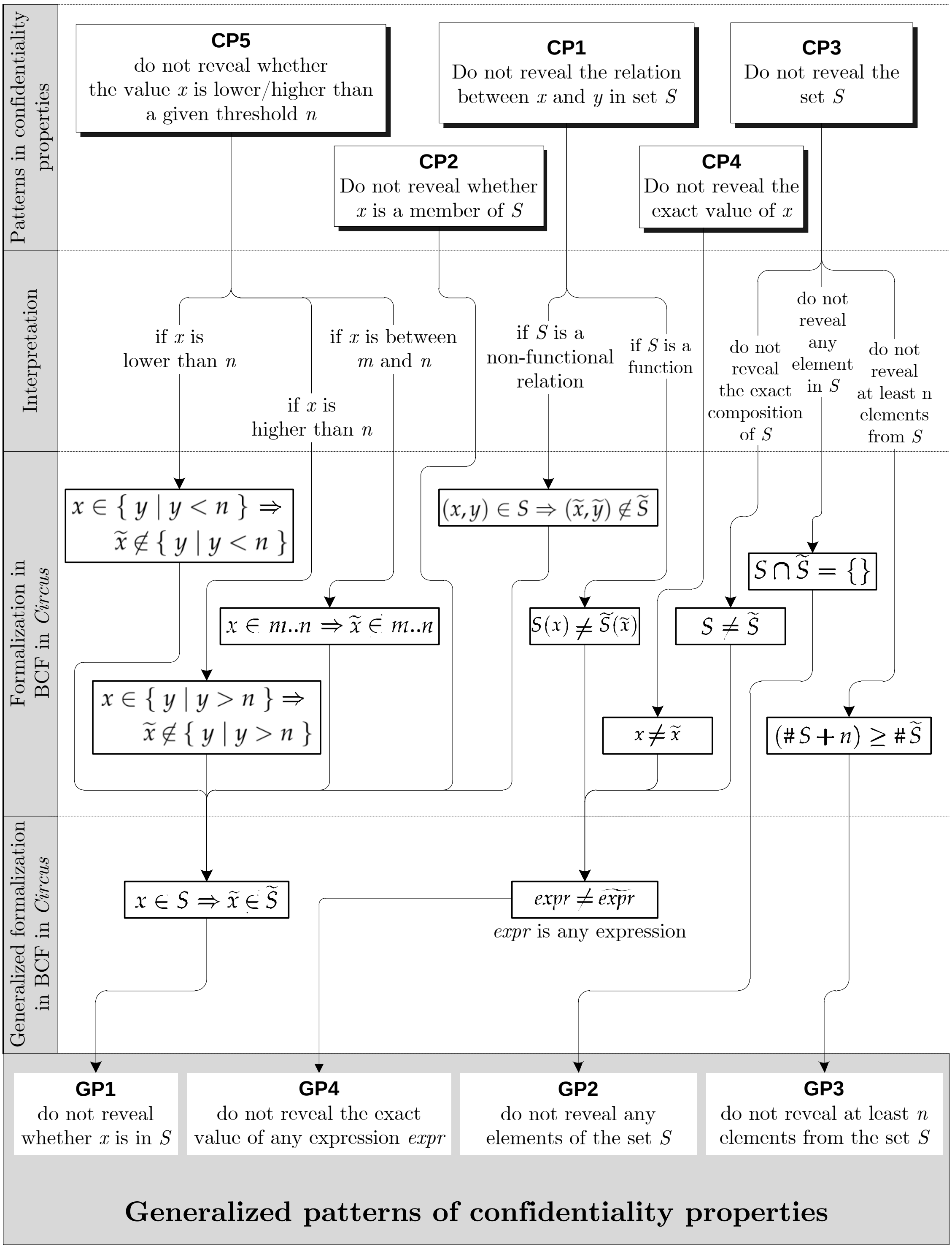


Figure 5.3: Deriving generalized patterns from patterns of confidentiality requirements

Recall from Section 2.5 that *Circus* combines the Z notation with other notations and techniques. The following are two formalisations of **CP1** depending on whether the set S is a relation or a function.

If S in CP1 is a non-functional relation

Where S is a non-functional relation, one possible formalisation of **CP1** using BCF in *Circus* can be:

$$(x, y) \in S \Rightarrow (\widetilde{x}, \widetilde{y}) \notin \widetilde{S} \tag{5.1}$$

The formalisation used in Equation (5.1) for specifying confidentiality in set S is specific to tuples. However, the formalisation is concerned with maintaining the secrecy of an element of in a given set. This is simillar to the requirement pattern captured in **CP2**.

If S in CP1 is a function

Where S is a function, one possible formalisation of **CP1** using BCF in *Circus* can be:

$$S(x) \neq \widetilde{S}(\widetilde{x}) \tag{5.2}$$

The formalisation in Equation (5.2) can be used in BCF in *Circus* to conceal the exact value of $S(x)$. This fulfils the confidentiality requirement pattern in **CP1** where **CP1** is concerned with maintaining the secrecy of the tuple $(x, S(x))$. Here, $S(x)$ represents the variable y is **CP1**. This is simillar to the requirement pattern captured in **CP4**.

CP2 The confidentiality pattern **CP2** states:

do not reveal whether x is a member of S

One possible formalisation of **CP2** using BCF in *Circus* can be:

$$x \in S \Rightarrow \widetilde{x} \notin \widetilde{S} \tag{5.3}$$

While Equation (5.3) is a possible formalisation of **CP2**, Equation (5.3) is also a more generalized formalisation of Equation (5.1) . The following generalized pattern can be derived from Equation (5.3).

■ **Generalized pattern GP1** : *do not reveal whether x is in S*

CP3 The confidentiality pattern **CP3** states:

do not reveal the set S

In Section 5.4, the need for introducing some subtly different interpretations of **CP3** were discussed. Further, formalisations for those interpretations were presented and how they address different confidentiality properties were discussed. Due to the lack of clear descriptions of confidentiality properties under **CP3**, it was important that those interpretations were available for accurately formalising the confidentiality properties. For this reason, the subtly different interpretations of **CP3** can be adopted as generalised patterns for maintaining the secrecy of a set. Here, the contents of Table 5.4 in Table 5.7 are being duplicated for easy reference. Further, a unique identifier for each possibility listed in Table 5.7 has been introduced.

id	Possible ways of specifying set inequality	BCF in *Circus*
S1	do not reveal the exact composition of the set S	$S \neq \widetilde{S}$
S2	do not reveal any elements of the set S	$S \cap \widetilde{S} = \{\}$
S3	do not reveal at least n elements from the set S	$(\# S + n) \geq \# \widetilde{S}$

Table 5.7: Possible ways of specifying an inequality between two sets S and $\widetilde{S}$

The formalisation of S1 in Table 5.7 is similar to the requirement pattern captured in **CP4** where **CP4** is a more generic formalisation of S1.

The following generalized pattern can be derived from the formalisation of S2 in Table 5.7.

■ **Generalized pattern GP2** : *do not reveal any elements of the set S*

The following generalized pattern can be derived from the formalisation of S3 in Table 5.7.

■ **Generalized pattern GP3** : *do not reveal at least n elements from the set S*

CP4 The confidentiality pattern **CP4** states:

do not reveal the exact value of x

Here, the objective of **CP4** is to maintain the secrecy of the exact value of x. One possible formalisation of **CP4** using BCF in *Circus* can be:

$$x \neq \widetilde{x} \tag{5.4}$$

Limited inference while maintaining secrecy of the exact value

Pattern **CP4** with definition "do not reveal the exact value of x" is a weak pattern because even after **CP4** is applied, sometimes critical information may be revealed, without revealing the exact value that is required to be kept secret. For example, consider the requirement where the exact value of a customer bank account is required to be a secret. If the balance *bal* of a customer called *bob* is $500 and if a user has access to the binary representation of the state variable *bal* except the last two bits, then the user can infer that *bal* is definitely between 500 and 503. In this scenario, even though **CP4** has been satisfied through bit obfuscation, the inference made by the user might not be acceptable. This is because, through inference, the user is able to learn *bal* to a high degree of accuracy. Table 5.8 represents the bit representation of numbers from 500 to 503.

values	256	128	64	32	16	8	4	2	1
500	1	1	1	1	1	0	1	0	0
501	1	1	1	1	1	0	1	0	1
502	1	1	1	1	1	0	1	1	0
503	1	1	1	1	1	0	1	1	1

Table 5.8: Bit representations of bank balances between 500 and 503

When using bit obfuscation for confidentiality, as discussed above, the minimum number of bits that needs to be obfuscated to maintain the secrecy of a value will depend on the confidentiality requirement, where the confidentiality requirement must define the degree to which the value should be kept confidential.

Essentially, both Equation (5.4) and Equation (5.2) are concerned with maintaining the secrecy of the exact value of an expression *expr*, where $expr \equiv x$ in Equation (5.4) and $expr \equiv f(x)$ in Equation (5.2). The expression $\widetilde{expr}$ is derived by renaming each state variable y in *expr* with its twin counterpart $\widetilde{y}$ as in $expr[y/\widetilde{y}]$. Equation (5.5) represents a more generalised formalisation of **CP4**.

$$expr \neq \widetilde{expr} \tag{5.5}$$

We may derive the following generalized pattern from Equation (5.5).

■ **Generalized pattern GP4** : *do not reveal the exact value of any expression expr*

CP5 The confidentiality pattern **CP5** states:

> do not reveal whether the value of x is lower/higher than a given threshold n

The objective of **CP5** is to maintain the secrecy of the upper bound and the lower bound of a value against some given thresholds. The pattern **CP5** has been extracted from the paper (De Landtsheer and Van Lamsweerde, 2005, p. 4). Infact, this pattern contains three generic patterns of confidentiality properties which they have formalised separately in (De Landtsheer and Van Lamsweerde, 2005, p. 4) using epistemic logic. Following are possible formalisations of those patterns using BCF in *Circus*.

lower bound do not reveal whether x is lower than the threshold m

$$x \in \{y \mid y < n\} \Rightarrow \widetilde{x} \notin \{y \mid y < n\} \tag{5.6}$$

upper bound do not reveal whether x is higher than the threshold m

$$x \in \{y \mid y > n\} \Rightarrow \widetilde{x} \notin \{y \mid y > n\} \quad (5.7)$$

between do not reveal whether x is between m and n

$$x \in m..n \Rightarrow \widetilde{x} \notin m..n \quad (5.8)$$

The formalisation used in Equation (5.8) specifies that the knowledge that the value of x falls within a certain range must be confidential. In general, the formalisation is concerned with maintaining the secrecy of an element in a given set, which in this case is the set of values in the range $m..n$. This is similar to the requirement pattern captured in **CP2**.

5.6 Generalized patterns of confidentiality requirements

A literature-related set of generalized patterns of confidentiality requirements related to data leakage has been derived through research carried out in this chapter. The set of generalized patterns derived are shown in Table 5.9. The table further shows how to specify each generalized pattern of confidentiality requirement using BCF in *Circus*.

Pattern id	Pattern description	How to specify a property with the pattern using BCF in *Circus*
GP1	do not reveal whether x is in S	$x \in S \Rightarrow \widetilde{x} \notin \widetilde{S}$
GP2	do not reveal any elements of the set S	$S \cap \widetilde{S} = \{\}$
GP3	do not reveal at least n elements from the set S	$(\# S + n) \geq \# \widetilde{S}$
GP4	do not reveal the exact value of any expression *expr*	$expr \neq \widetilde{expr}$

Table 5.9: A catalogue of generalized patterns of confidentiality requirements

5.7 Confidentiality requirement patterns in literature

Gurses et al. (2005) list a set of attributes that describe a confidentiality requirement. They include the *owner* of the confidentiality data, degree of *agreement* between the stakeholders of the data, the *counter-stakeholder* or the role from whom the owner wants to hide the data, the *information* to which the confidentiality requirement refers to, the owners *rationale* for the confidentiality requirement, the *temporal range* or how long the confidentiality requirement must be in place and the *context* or the cluster of system functionality where the requirement must be implemented.

De Landtsheer and Van Lamsweerde (2005) presents a catalogue of patterns on confidentiality along two dimensions. One is concerned with the degree of appropriate knowledge that must be kept confidential. The second is concerned with timing according to which the knowledge must be kept confidential. Similar to De Landtsheer and Van Lamsweerde (2005), BCF in *Circus* helps to formally specify the degree of confidentiality that must be maintained about a piece of data. BCF in *Circus* can address timing related confidentiality properties in terms of the order of states.

Both De Landtsheer and Van Lamsweerde (2005) and the generic patterns proposed in this thesis share the pattern "*do not reveal the exact value of a variable*". Further, De Landtsheer and Van Lamsweerde (2005) proposed the pattern **Confidential lower/upper bound** which states that "*An agent should not know that the value of some state variable is below/above some treshold*", which has been dissected into two generic patterns and included in the catalogue of generic patterns in Table 5.9. Also, De Landtsheer and Van Lamsweerde (2005) proposed the pattern **Fully confidential value** which states "An agent should not be able to infer any property about the value of some state variable". This pattern is just a conjunction of many other patterns proposed in his catalogue.

The timing related confidentiality patterns by De Landtsheer and Van Lamsweerde (2005, p. 45) include **Confidential now** that states that "*In the current state, an agent should not know about some state variable*"; **Confidential until expiration date** that states that "*An agent should not know about some state variable until some delay has expired*";

Confidential unless/until condition states that "*An agent should not know about some state variable unless or until some condition becomes true*"; **Confidential forever** that states that "*An agent should never know about some state variable*". Both confidentiality until a condition is met (see Section 6.2.4) and confidentiality forever are properties that can also be specified using BCF in *Circus*.

5.8 Patterns in software engineering

In the early 1990s, there was an interest in the software engineering community to identify situations in which design knowledge could be represented and shared between practitioners (Fowler, 1997, p. 5). Engineers explored the possibility of using the pattern language approach by Alexander et al. (1977) to represent knowledge that can possibly be shared. The OOPSLA workshops (Meyrowitz, 1986) provided an early platform for such discussions. Currently, the Pattern Languages of Programs (PLoP) conference series (The Hillside Group, 2017) is one of the annual platforms for such discussions.

Alexander et al. (1977) introduced the notion of pattern languages in the context of building architecture where the elements of the language were entities called patterns. He defined the term 'pattern' as follows.

> "*Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, In such a way that you can use this solution a million times over, without ever doing it the same way twice.*" (Alexander et al., 1977, p. x)

In the field of software engineering, pattern based approaches has been discussed with respect to various stages of a system development process. Some of the different kinds of patterns used in a system development process include *music design patterns* (Bouaziz et al., 2011), *design patterns*[6] (Andrews et al., 2008; Angkasaputra and Pfahl, 2004;

[6] "*Capturing expert-knowledge and providing proven solutions for recurring problems is the basic idea of software (design) patterns.*" (Schumacher, 2001, p. 4)

Baggetun et al., 2004; Bézivin et al., 2005; Fiadeiro and Andrade, 2001; Gamma et al., 1995; Gangemi et al., 2007), *learning flow patterns* (Bote-Lorenzo et al., 2004), *requirement patterns* (Maiden, 1998), *process patterns* (Ambler, 1998; Ambysoft and Ambler, 1998; Hagen and Gruhn, 2004; Ribó and Franch, 2002; Tran et al., 2006), *analysis patterns* (Fowler, 1997; Hahsler and Informationswirtschaft, 2001; Kodaganallur and Shim, 2006; Purao et al., 2003), *collaboration patterns* (Coplien, 2004), *re-factoring pattern* (Andrews et al., 2008), *architecture patterns* (Buschmann et al., 1996; Shaw and Garlan, 1996), *architecture reference patterns* (Buschmann et al., 1996), *improvement patterns* (Appleton, 1997) and *organizational patterns* (Campbell, 2004; Lukosch and Schümmer, 2006; Sommerville, 2016).

Patterns have also been utilized in formal methods technology. Freitas and Whiteside (2014) proposed proof tactics to facilitate less experienced proof engineers to attempt at difficult lemmas, reducing the proof cost and effort in the process.

5.9 Limitations of the study

There are a number of inherent limitations in the process adopted in compiling the catalogue of confidentiality properties. Firstly, during the literature search, it was found that often the search results included papers that discussed legal aspects of privacy and confidentiality while those papers had no discussions on confidentiality requirements. Combining this reality with our inclusion criteria where we select only the first 20 results from each "indexing service $\times$ keyword phrase" pair meant that papers discussing confidentiality requirements might have been pushed further down the stack past the first 20 results.

The interpretations proposed for some vague confidentiality requirements may be reasonable. However, those interpretations are still hand-crafted and hence need further evidence to strengthen the argument that the patterns derived from such interpreted confidentiality requirements are important. Rather than reading all 490 search results word for word, the effort was concentrated on locating any discussions of confidentiality properties both in the abstract as well as around each paragraph where the keyword ‘confidential’ was located.

The search functionality in Mendeley software was used to locate keywords in each paper. Such an approach was necessary because of the limited time frame available for this Ph.D. However, some useful discussions of confidentiality properties that did not contain the specific word ‘confidentiality’ might have been missed, as a result of following this process.

Finally, documents that cannot be indexed by Mendeley would not have been included in the search results that Mendeley produced. One or more potential discussions on confidentiality properties might have been overlooked because of this. It must be noted here that the decision to use Mendeley was a personal choice and has to do with its ease of user for the author.

5.10 Summary

The main objective of this chapter is to derive a set of generic patterns of confidentiality requirements from literature. Such a set is required to fill a vacuum in terms of a benchmark of confidentiality requirement patterns that can be used in testing tools that analyse systems for confidentiality.

In this chapter:

- a catalogue of confidentiality requirements from literature was compiled.
- a literature related set of patterns of confidentiality requirements were derived.
- generic patterns of confidentiality requirements were identified and formalized.
- existing literature specific to patterns of confidentiality requirements, as well as the emergence and use of patterns in software engineering in general was discussed.

6 Evaluation of mechanisation

6.1 Introducing

The objective of this chapter is to demonstrate that the CFAT tool developed under this research is practically applicable. This chapter presents an evaluation of the mechanisation of BCF in *Circus* described in Chapter 3. The evaluation of the mechanisation will involve analysing systems with different patterns of confidentiality requirements, that has been identified in Section 5.2.

In Chapter 5, a literature search was carried out to identify case studies that discusses systems with a confidentiality requirement. However, none of the papers identified in Chapter 5 contained a full system description or a full formal specification of a system, discussed in that paper. Further, none of the papers presented a confidentiality analysis using BCF. Papers by De Landtsheer and Van Lamsweerde (2005) and Howitt (2008) describe confidentiality analysis of systems based on other modelling techniques. In Section 2.2, a discussion of the differences between those techniques and the approach adopted by BCF in *Circus* (Banks, 2012) has been presented.

In the absence of a literature-supported full formal specifications of systems, hand-crafted possible system requirement specifications for systems had to be developed.

We will work through an example of each identified pattern where we will:

1. introduce a hand-crafted set of requirements for a system.
2. illustrate the functional structure of the system using a use-case diagram.
3. construct a *Circus* specification of the system manually.
4. specify the confidentiality requirements of the system using BCF in *Circus*.
5. construct a CFAT specification of the system based on the *Circus* specification and confidentiality requirement.
6. analyse the CFAT specification using the mechanisation tool to check the consistency of the requirements defined in the system.

There is no formal mapping between the use case and the formal model of the system captured in the *Circus* specification. The back propagation laws of BCF in *Circus* (Banks, 2012, p. 138) does not contain a back propagation law that can be used on parallel processes. And so, currently BCF in *Circus* can only be used to evaluate sequential access systems. Therefore, in all cases it is assumed that the systems modelled in this chapter are single user access.

The confidentiality requirements used in the analysis carried out in this chapter are deduced from the discussion of confidentiality in the published papers. This exercise has been carried out in Chapter 5 and the deduced confidentiality properties are listed in Table 5.3. An informal approach has been used to state the requirements of each system in natural language and then a *Circus* specification has been presented for that system.

In order to analyse each identified confidentiality requirement pattern *CP*, we will model a system *Y* described in one of the referenced papers *RP* in Table 5.3. Each confidentiality requirement *CR* stated for *Y* in Table 5.3 has been derived from the confidentiality properties discussed in *RP*. A *CP* represents a generalized definition for each *CR*. Table 5.2 groups all confidentiality requirements based on the *CP* which they

Encoding the concept of the *twin* or shadow state using the *Circus* notation

The concept of BCF is that at least one alternative similar observation exists for each observation of a state variable in the original system. BCF notation uses the decoration tilde ($\tilde{}$) as in $\widetilde{S}$ to specify a similar state space of a given state schema S. However, this notation is not supported by the CZT tool (Malik and Utting, 2005), which is used for type and syntax checking the *Circus* specification of the system.

A similar state space of a state schema S can be specified in the *Circus* notation using LaTeX by subscripting the schema name with a number such as by writing S_9. Each variable x in the new schema S_9 can then be referenced using the notation x_9. It must be highlighted that in all the formal statements presented in this chapter, x_9 has been used to represent each state variable x in the *twin* state space.

It must be noted here that the subscript 9 is an arbitrary choice that does not clash with anything else as long as the restrictions on the naming conventions are in place as discussed on Page 100. It must also be noted that using the subscript 9 is a coding trick to enable syntax and type checking by the CZT tool. It is important to declare this only as a coding trick because the semantics of this coding trick does not correctly capture the BCF concept '*at least one alternative similar observation exists for each observation of a state variable in the original system*'.

represent. Each case study analysis in this chapter involves using the mechanisation to verify the consistency of a BCF in *Circus* based formal model of Y against an associated CR.

The BCF in *Circus* based formal specification of a system contains syntactic decorations that are not supported by both CZT as well as the Isabelle theorem prover. Therefore, for the purposes of type and syntax checking the formal specification using CZT and for theorem proving using the Isabelle theorem prover, syntactic renaming of the *twin* state variables in the formal specification are required. Recall that Section 3.2.4 in

Page 100 discusses all the variables of the system specification that must be renamed by the user during the submission of the system specification to the mechanised tool as well as that will be renamed when files are generated by the mechanised tool. The explanation on Page 189 recalls how the *twin* or shadow state space is encoded in a *Circus* specification generated by the mechanised tool so that the specification can be type and syntax checked using CZT.

6.2 Mechanised analysis of confidentiality patterns

In Chapter 5, a set of patterns has been extracted from the confidentiality requirements described in a systematically compiled literature set. In this section, we will discuss the mechanised analysis of systems having confidentiality properties with one or more of those patterns.

The following steps will be carried out in each case study.

- Present the system requirement specification of the case study system.
- Develop and describe a possible formal specification of the functionality requirements of the case study system using the *Circus* notation.
- Discuss a possible formalisation of the confidentiality requirement(s) of the case study system using the extended *Circus* notation.
- Describe how the mechanisation in Chapter 3 can be used to analyse the formal specification.
- Present and discuss the results of the mechanised analysis of the formal specification that integrates the confidentiality requirement.

The above steps will be discussed in detail for the first pattern. For the subsequent patterns, the pattern and subsequently the results from analysing a system with a confidentiality property having that pattern will be present. Recall from Section 6.1 that BCF in *Circus* only supports sequential access systems and therefore in all the analysis carried out in this chapter, systems will be modelled with sequential access. Further, recall that all the derived confidentiality patterns are listed in Table 5.2 and all the identified confidentiality requirements are listed in Table 5.3.

6.2.1 Mechanised analysis of a system having a confidentiality property that reflects pattern CP1

The first case study to evaluate the mechanisation of BCF in *Circus* involves analysing a system with a confidentiality property that reflects the pattern **CP1**. The confidentiality requirement **CR18** has been chosen as an adhoc choice for this analysis. The confidentiality pattern **CP1** states:

> do not reveal the relation between x and y in S

For this analysis, a simple accounts system for a bank will be modelled. The system will be called the Bank information system. The confidentiality property modelled in this system has been borrowed from discussions by both Parveen et al. (2015) and Lapadula et al. (2008).

6.2.2 System requirement specification - Bank information system

A hand-crafted system requirement specification of a fictitious Bank information system is given below. The functions listed in the Bank information system are borrowed from commonly used use cases by Eckel (2005), Skon (2016) and Pearce (2017) for academic discussions in the context of a Bank information system.

Organisational structure

A *bank_balance* **is represented by a** *number***.**

A *customer* **is a** *person***.**

Mapping between the structures of a system specification and the *Circus* notation

The structures of a system requirement specification may be mapped onto structures of the *Circus* notation. Table 6.1 shows such a mapping. Every system requirement specification presented in this section has been structured accordingly for ease of readability. It must be noted that each developed *Circus* specification will be just one possible implementation of the original system.

System requirement specification	Structures of the *Circus* notation
Organisational structure (entities and attributes)	data types, data objects, global constants
Organisational rules and regulations	state invariants
Operations performed in the organisation	actions
Who can perform the functions	channelsets (representing user roles)
Which staff are included in each user role	state invariants that define elements of sets

Table 6.1: Mapping a system requirement specification to structures in a *Circus* specification

The company uniquely identifies the *person* **who is the** *manager* **of the company**.

The company uniquely identifies the *person* **who is the** *current_user* **of the system**.

The company maintains a list that contains every *customer* **of the company.**

The company maintains a list that contains every *cashier* **of the company.**

The company maintains a list that contains every *user* **of the company.**

The company maintains a *bank_balance* **for each existing** *customer***.**

Organisational rules

The same *person* **cannot be a** *customer* **and a** *cashier* and **and the** *manager*.

Every *user* **must be either a** *customer* **or a** *cashier* **or the** *manager*.

The *current_user* **must be included in the** *user* **list**.

User roles in the system

The *banking_staff* user role includes the *manager* and all users who are *cashiers*.
The *cashier* user role includes all users who are *cashiers*.
The *customer* user role contains all users who are *customers*.

Operations, user roles and permissions

Table 6.2 lists all the system operations, and the specific permissions on those operations by user role. Figure 6.1 presents a tripartite graph that shows the user-to-role and role-to-permission assignments in the Bank information system. User roles and how it is utilised in BCF in *Circus* for analysing data leakage in a system is discussed later in Figure 6.3.

	User roles		
Operation identifier Operations allowed on the Bank information system	Banking Staff	Cashier	Customer
Find_own_balance **Find** the *account_balance* of oneself.			✓
Find_customer_balance **Find** the *account_balance* of any *customer*.	✓		
Record_new_customer **Record** the *personal_details* of a new *customer*.		✓	
Deposit_to_customer **Calculate** and **Update** the *bank balance* of a particular *customer* which is derived using the customers existing *bank balance* and value deposited by the *customer*.		✓	
Withdraw_from_customer **Calculate** and **Update** the *bank balance* of a particular customer which is derived using the customers existing *bank balance* and value withdrawn by the *customer*.		✓	

Table 6.2: Roles and Permissions Matrix of the Bank information system

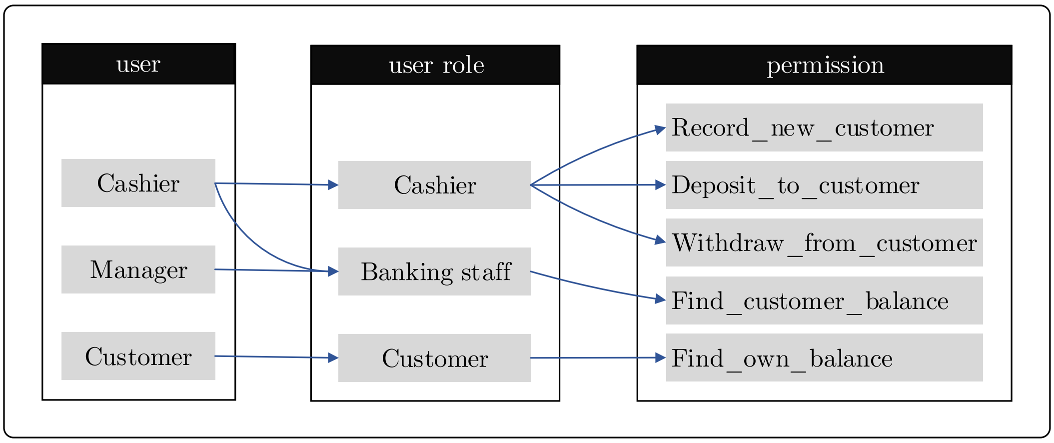


Figure 6.1: Tripartite graph of user-to-role and role-to-permission assignments in the Bank information system

Figure 6.2 presents a graphical summary of the system requirement specification of the Bank information system using a use case diagram.

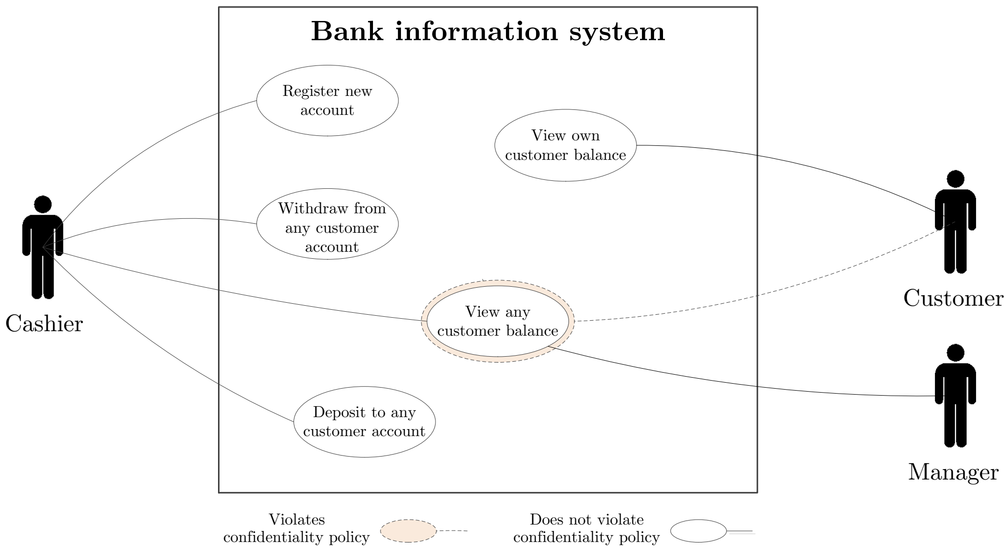


Figure 6.2: Use case diagram for the Bank information system

6.2.3 Formal specification - Bank information system

The actions in Table 6.3 addresses the operations of the Bank information system and reflects the system requirement specification of the Bank information system. The basic type in Table 6.5, state variables in Table 6.6 and state invariants in Table 6.7 reflect organisational structures that are described in the system requirement specification of the Bank information system in Section 6.2.2.

It is important to note that the action *Init* in Table 6.3 is not in the use case diagram in Figure 6.2. The action *Init* initializes the state variable that records the identifier of the customer whose information is being requested from the system. This is an internal initialization function.

Table 6.3: Bank information system - Description of the *Circus* actions

Action	Operation performed by the action
NewAccount	Allows a cashier to create a customer bank account in the system.
DepositMoney	Allows a cashier to deposit money to an existing bank account.
WithdrawMoney	Allows a cashier to withdraw money from an existing bank account.
GetMyBalance	Allows a customer to view his/her own account balance. The customer provides his/her person identifier which the operation uses to retrieve the account balance.
GetAnyCustBalance	Allows a cashier to view the account balance of any customer.

6.2.3.a User roles

As detailed on page 201, user roles are modelled in BCF in *Circus* using **channelset**s. Table 6.2 includes the user roles that are assumed as common in a typical Bank information system. These user roles in the specification of the Bank information system has been modelled using **channelset**s as shown in the *Circus* specification of the system in Figure 6.10 and these **channelset**s are listed in Table 6.4 with their descriptions.

Table 6.4: Bank information system - Description of the user roles

channelset as user role	Functions allowed for the user role
Customer	a user role where users have the right to view their own bank balances
Cashier	a user role where users have the right to create a new customer account with the information provided by the customer, carry out a deposit or a withdraw transaction on any customer account and also find the balance of any customer account.
BankingStaff	a user role where users have the right to view the balance of any customer account.

6.2.3.b Types

A basic type that contains the identifiers of all the possible people in the system is defined.

Table 6.5: Bank information system - Description of the basic types

Basic type	Description
PERSON	The set of all possible person identifiers.

6.2.3.c State variables

The following are organisational components which we believe are common in a banking environment. A state variable has been declared to represent each organisational component within the system specification. The description of these state variables are included in Table 6.6.

Table 6.6: Bank information system - Description of the state variables

State variable	Description
balance	A function that identifies the balance of a customer, if any.
managers	The set of identifiers of the managers.
cashiers	The set of identifiers of the cashiers.
customers	The set of identifiers of the customers.
loggedIn	The set of identifiers of the users who are logged into the system.

loginUser	The identifier of the person who is currently using the system.
reqCustomer	The identifier of the person about whom informaiton is being requested from the system.

6.2.3.d State invariants

We assume certain system constraints that must be respected throughout the life of the system. These constraints reflect the relevant organisational rules that we believe are typical in an accounts system in a bank. These constraints are defined as state invariants[1] in the system specification.

Table 6.7: Bank information system - Description of the state invariants

State invariants	Description
$loginUser \in loggedIn$	The current user must be from the set of users logged into the system.
$loggedIn \subseteq (customers \cup cashiers \cup managers)$	The current user of the system must either be from the group of customers, the group of cashiers or the manager.
$(customers \cap cashiers) = \{\}$	The same person cannot be a customer and a cashier at the same time.
$(customers \cap managers) = \{\}$	

[1] A state invariant of a system is a property that holds in every reachable state of the system (Kirby et al., 1999, p. 110).

The same person cannot be a customer and the manager at the same time.

$(cashiers \cap managers) = \{\}$

The same person cannot be a cashier and the manager at the same time.

$\mathrm{dom}\ (balance) \subseteq customers$

Every person who has a bank balance recorded in the system must be a customer.

Data leakage is analysed with respect to the user roles held by a user

A user role is a named instance where a set of permissions are assigned to a group of users to perform a set of tasks. In the *Circus* notation, a user may perform tasks on a system through communications allowed on a system, that are made possible through **channel**s. In this regard, a set of permissions are synonymous with a set of **channel**s or a **channelset** in the *Circus* notation. Therefore, a **channelset** is used to model a user role in a system. A user may belong to one or more user roles. For example, in Figure 6.3 user x belongs to the user role A whereas user y belongs to both user roles A and B.

The observations that a user can make by executing a function depend on the set of authorized permissions for that user. One way BCF in *Circus* can be used to analyse a system for data leakage is by comparing the set of prohibited observations for a particular user u against the set of observations the user u can make by executing the system.

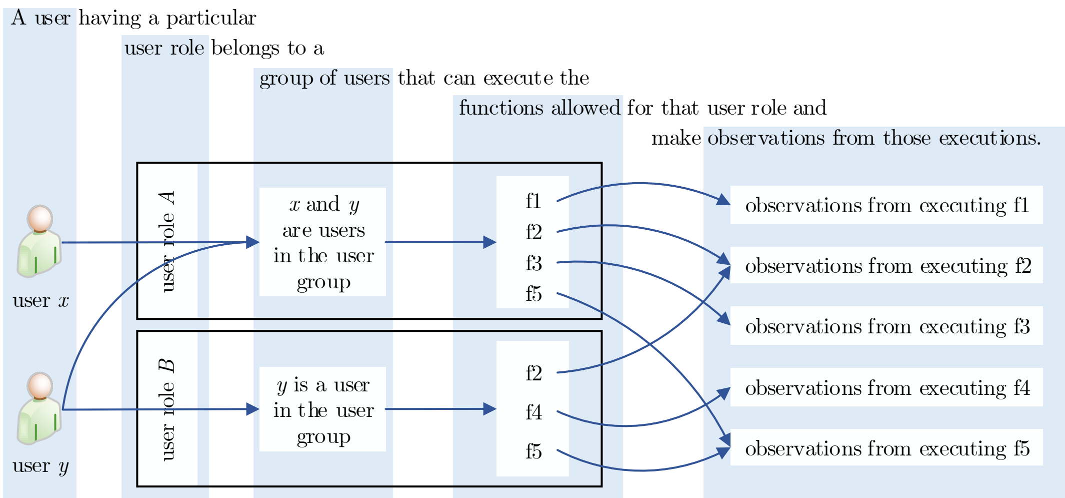


Figure 6.3: User roles and user observations

In the ongoing Bank information system example, the identity of the specific user who is currently logged into the system is represented by the variable *loginUser* and has the data type *PERSON*. The group of users that belong to the user role employees is represented by the variable *employees* and has the data type $\mathbb{F}$ *PERSON*.

6.2.3.e Formal specification of the Bank information system

The full formal specification of the Bank information system is presented in Figure 6.4.

(This page intentionally left blank)

$[\,PERSON\,]$

$$
\begin{array}{l}
\textit{State} \\
\hline
balance : PERSON \twoheadrightarrow\!\!\!\!\!\!\!+ \ \mathbb{N} \\
reqCustomer, loginUser : PERSON \\
loggedIn, customers, cashiers, managers : \mathbb{F}\, PERSON \\
\hline
\mathrm{dom}\,(balance) \subseteq customers \\
(customers \cap cashiers \cap managers) = \{\} \\
loggedIn \subseteq (customers \cup cashiers \cup managers) \\
loginUser \in loggedIn
\end{array}
$$

$$
\begin{array}{l}
\textit{HideBalCustomer} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad loginUser \neq reqCustomer \land \\
\quad loginUser \notin managers \land \\
\quad loginUser \notin cashiers \land \\
\quad reqCustomer \in \mathrm{dom}\,(balance) \Rightarrow \\
\qquad\quad (balance\ reqCustomer) \neq (balance_9\ reqCustomer_9)
\end{array}
$$

channel $newBalanceIn, mrbalOut, showBalanceOut, myBalanceOut : \mathbb{N}$
channel $withdrawAmountIn, depositAmountIn : \mathbb{N}$
channel $withdrawCustomerIn, depositCustomerIn, newCustomerIn : PERSON$
channel $rubIn, customerIn : PERSON$

channelset $BankingStaff == \{\!|\ customerIn, showBalanceOut\ |\!\}$
channelset $Cashier == \{\!|\ withdrawAmountIn, customerIn, showBalanceOut, depositAmountIn, depositCustomerIn, withdrawCustomerIn, newCustomerIn, newBalanceIn\ |\!\}$
channelset $Customer == \{\!|\ myBalanceOut\ |\!\}$

process $Bank\_information\_system \mathrel{\widehat=}$ **begin**

state $State$

$$
\begin{array}{lll}
Init & \mathrel{\widehat=} & reqCustomer := loginUser \\[1ex]
NewAccount & \mathrel{\widehat=} & \mathbf{var}\ newBalance : \mathbb{N}; \\
& & \quad newCustomer : PERSON \bullet \\
& & \quad newBalanceIn?newBalance \longrightarrow \\
& & \quad newCustomerIn?newCustomer \longrightarrow \\
& & \quad \big(\big(newCustomer? \notin \mathrm{dom}\,(balance) \land loginUser \in cashiers\big) \,\&\, \\
& & \qquad balance := balance \oplus \\
& & \qquad\qquad\qquad \{(newCustomer? \mapsto newBalance?)\}\big) \\[1ex]
DepositMoney & \mathrel{\widehat=} & \mathbf{var}\ depositAmount : \mathbb{N}; \\
& & \quad depositCustomer : \mathrm{dom}\,(balance) \bullet \\
& & \quad depositAmountIn?depositAmount \longrightarrow \\
& & \quad depositCustomerIn?depositCustomer \longrightarrow \\
& & \quad \big(\big(loginUser \in cashiers\big) \,\&\, \\
& & \qquad balance := balance \oplus \\
& & \qquad\quad \{(depositCustomer? \mapsto \\
& & \qquad\qquad (balance\ depositCustomer? - depositAmount?))\}\big)
\end{array}
$$

Figure 6.4: Specification of Bank information system - *code block 1 of 2*

$$
\begin{array}{lll}
\mathit{WithdrawMoney} & \widehat{=} & \mathbf{var}\ \mathit{withdrawAmount} : \mathbb{N}; \\
& & \quad \mathit{withdrawCustomer} : \mathrm{dom}\,(\mathit{balance}) \bullet \\
& & \quad \mathit{withdrawAmountIn}?\mathit{withdrawAmount} \longrightarrow \\
& & \quad \mathit{withdrawCustomerIn}?\mathit{withdrawCustomer} \longrightarrow \\
& & \quad (\big(\mathit{loginUser} \in \mathit{cashiers}\big) \& \\
& & \qquad \mathit{balance} := \mathit{balance} \setminus \\
& & \qquad\quad \{(\mathit{withdrawCustomer}? \mapsto \\
& & \qquad\qquad (\mathit{balance}\,\mathit{withdrawCustomer}? + \mathit{withdrawAmount}?))\})
\end{array}
$$

$$
\begin{array}{lll}
\mathit{GetMyBalance} & \widehat{=} & \mathit{reqCustomer} := \mathit{loginUser}; \\
& & \quad (\big(\mathit{loginUser} \in \mathit{customers} \wedge \\
& & \qquad \mathit{loginUser} \in \mathrm{dom}\,(\mathit{balance})\big) \& \\
& & \qquad \mathit{myBalanceOut}\,!(\mathit{balance}\,\mathit{loginUser}) \longrightarrow \mathbf{Skip})
\end{array}
$$

$$
\begin{array}{lll}
\mathit{GetAnyCustBalance} & \widehat{=} & \mathbf{var}\ \mathit{customer} : \mathit{PERSON} \bullet \\
& & \quad \mathit{customerIn}?\mathit{customer} \longrightarrow \\
& & \quad \mathit{reqCustomer} := \mathit{customer}?; \\
& & \quad (\big(\mathit{loginUser} \in \mathit{cashiers} \vee \mathit{loginUser} \in \mathit{managers}\big) \& \\
& & \qquad \mathit{showBalanceOut}\,!(\mathit{balance}\,\mathit{customer}?) \longrightarrow \mathbf{Skip})
\end{array}
$$

$$
\mathit{HideBalCustomer} \ \widehat{=}\ \mathit{HideBalCustomer}
$$

$$
\mathit{UserOptions} \ \widehat{=} \ \begin{pmatrix} & \mathit{NewAccount} \\ \Box & \mathit{DepositMoney} \\ \Box & \mathit{WithdrawMoney} \\ \Box & \mathit{GetAnyCustBalance} \\ \Box & \mathit{GetMyBalance} \end{pmatrix} ;\ \mathit{HideBalCustomer}
$$

$$
\bullet\ \langle \mathit{Init} \rangle\ ;\ \mu Y \bullet \big\langle (\mathit{UserOptions}\ ;\ Y) \big\rangle
$$

end

Figure 6.4 (cont.) : Specification of Bank information system - *code block 2 of 2*

6.2.4 Formalising the confidentiality requirement

In this section, a possible formalisation of the confidentiality requirement **CR18** is specified using the *Circus* notation. The general definition of **CP1** states:

> do not reveal the relation between x and y in S

The confidentiality requirement **CR18** of the Bank information system reads:

CR18 : permission to view the balance of a customer should be given only to an authorised user.

The confidentiality requirement **CR18** can be re-phrased as follows, to align with the definition of **CP1**.

if	the user is not authorised
then	do not reveal the association between a customer and his account balance

In this particular confidentiality requirement, the condition to hide the association between A and B is satisfied if the user is not authorised. Tschantz and Wing (2008) describes such a requirement as a *conditional confidentiality requirement* that contains a *conditional information flow* where information flow occurs only when some condition is met at runtime (Tschantz and Wing, 2008, p. 108).

Identify the condition for confidentiality. Papers published by Parveen et al. (2015, p. 2) and Lapadula et al. (2008, p. 713,714) that contain confidentiality requirements with **CP1** does not mention which set of users are authorised to view the data. Therefore, in the case of an accounts system at a bank, it is assumed that the current user of the system *loginUser* is authorised to view the balance of the bank account B which belongs to the customer *reqCustomer*, if one of the following conditions are satisfied.

- *loginUser* is the manager
- *loginUser* is a cashier
- *loginUser* and *reqCustomer* are the same

If **none of the above conditions are satisfied**, then the balance of the bank account *B* must never be revealed to the user *loginUser*. It must also be ensured that the account holder *reqCustomer* has a bank balance recorded in the bank balance register *balance* in the system. This combined condition can be written follows.

loginUser is not the manager
and *loginUser* is not a cashier
and *loginUser* and *reqCustomer* are different
and *reqCustomer* has an associated bank balance record in *balance*

The above condition may be formalised using the *Circus* notation as follows.

$$
\begin{aligned}
& loginUser \notin managers \\
\land\ & loginUser \notin cashiers \\
\land\ & loginUser \neq reqCustomer \\
\land\ & reqCustomer \in \operatorname{dom} balance
\end{aligned}
$$

Identify the confidential data. BCF states that whenever a user can observe the value of a variable x in the normal system state space he/she can assume that the shadow system must also have the same value for its twin variable $\widetilde{x}$.

In order to prevent the system from revealing the exact value of a particular variable, we must exclusively state a separation between the value of the variable in the original system and that in the shadow system. In this scenario we may write:

$$x \neq \widetilde{x}$$

In the case of the Bank information system, the value we must not reveal is:

$$balance\ reqCustomer$$

where *balance* is a function between a customer identifier and the bank balance of that customer if any and *reqCustomer* is the identifier of the customer whose bank balance is being requested. To state a minimum separation between the value $(balance\ reqCustomer)$ and its twin counterpart $(balance_9\ reqCustomer_9)$ we may write:

$$(balance\ reqCustomer) \neq (balance_9\ reqCustomer_9)$$

Build the confidentiality predicate. The *condition for confidentiality* and the *separation defined for the confidential data* are combined to come up with a formal definition for the confidentiality requirement **CR18** . The derived formal definition is shown below as a Z schema. As described in page 189, a subscript 9 is used to represent the state schema of the *twin* system as well as the variables from the *twin* system.

$$
\begin{array}{l}
\textit{HideBalCustomer} \\
\hline
\Xi State \\
\hline
\exists\, State\ _9 \bullet \\
\quad loginUser \neq reqCustomer \land \\
\quad loginUser \in customers \land \\
\quad reqCustomer \in \operatorname{dom}\ (balance) \Rightarrow \\
\qquad (balance\ reqCustomer) \neq (balance_9\ reqCustomer_9) \\
\hline
\end{array}
$$

The schema *HideBalCustomer* includes a confidentiality constraint that must be enforced on the state space of a particular state or states of the Bank information system where *HideBalCustomer* is observed.

A pre-requisite for using BCF in *Circus* to analyse systems for confidentiality is to understand how a formalized confidentiality requirement can be integrated into a

Circus specification.

6.2.5 Structure of the *Circus* specifications used in the mechanised analysis

A confidentiality integrated *Circus* specification is a *Circus* specification which includes one or more confidentiality annotations[2]. Figure 6.5 shows how a confidentiality integrated *Circus* specification has been structured for the purposes of the mechanised analysis carried out in this chapter. The structures *CA_schema_name*, *CA_Action* and *CA_predicate* are introduced into a *Circus* specification to integrate the confidentiality properties of a system within its specification. A detailed description of the *Circus* notation and how its structures can be used to model a system is given in Appendix A.1. Here, a summarised description of the main structures of a *Circus* specification are presented, which has been utilized in the case study specifications in this chapter. It must be noted that one can produce other possible specifications of the same system using the *Circus* notation.

The highlighted words **process**, **begin**, **state** and **end** in Figure 6.5 are *Circus* keywords. The description of the place-holders in Figure 6.5 are given below.

TypeDeclarations The place-holder for the names of the Basic types defined in the specification.

StateVariableDeclarations The place-holder for the declarations of state variables in the system.

StateInvariants The place-holder for the state invariants that are required in the system state.

StateName The place-holder for the name assigned to the schema that encodes the state of the system.

ChannelDefinitions The place-holder where channels[3] are defined in the spe-

[2] A brief introduction to confidentiality annotations (Banks, 2012, p. 105) is discussed in Section 2.6.2.

[3] The definition of channels and **channelset**s in the *Circus* notation are discussed in (Freitas, 2005, p. 13) .

TypeDeclarations

$$
\begin{array}{|l}
\hline
[StateName] \\
StateVariableDeclarations \\
\hline
StateInvariants \\
\hline
\end{array}
$$

$$
\begin{array}{|l}
\hline
CA\_schema\_name \\
\Xi StateName \\
\hline
CA\_predicate \\
\hline
\end{array}
$$

ChannelDefinitions

ChannelsetDefinitions

$$
\begin{array}{l}
\mathbf{process}\ ProcessName \mathrel{\widehat=} \mathbf{begin} \\
\quad \mathbf{state}\ StateName \\
\quad Action\_1 \mathrel{\widehat=} .... \\
\quad .... \\
\quad Action\_n \mathrel{\widehat=} .... \\
\quad CA\_Action \mathrel{\widehat=} CA\_schema\_name \\
\quad \bullet\ \langle MainAction \rangle \\
\mathbf{end}
\end{array}
$$

Figure 6.5: Structure of the *Circus* specifications used in the mechanised analysis

cification.

ChannelsetDefinitions — The place-holder where **channelsets**[3] are defined in the specification.

ProcessName — The place-holder for the name assigned to the *Circus* process that is defined in the specification.

Action_1 , ... , Action_n — Place-holders for the names of the *Circus* actions that are defined in the system.

CA_schema_name — The place-holder for the schema name that is defined to embed the confidentiality predicate.

CA_Action — The place-holder for the name of the *Circus* action that is defined to use the *CA_schema_name* schema as a *Circus* action.

CA_predicate — The place-holder for the formal predicate that represents a confidentiality property of the system being formalised.

MainAction — The label *MainAction* represents the place-holder for the nameless main action that defines the process behaviour. For the purposes of the mechanised analysis in this chapter we define the main action as a composite action that uses *Action_1* to *Action_n* and *CA_Action*.

6.2.6 Using the mechanised tool to analyse the system

The first step in using the mechanisation developed in this thesis, is to submit the BCF in *Circus* based formalization of the Bank information system (see Figure 6.10) to the CFAT tool in the CFAT format. Next, follow the steps in Figure 3.6 to analyse the submitted specification using the mechanisation. The possible results from the analysis and how they can be interpreted are described in Section 3.2.6.

6.2.7 Strengthening a weak specification

Recall from Section 4.3 that a specification is referred as a 'weak specification' if the specification is seemingly incorrect but the mechanised back propagation of the specification using BCF in *Circus* results in a predicate that can be simplified to **true**. The Bank information system specification in Figure 6.4 has a fundamental weakness in its role specification, where the three-way intersection is not strong enough to rule out the same user playing two roles at once. This subsection explores the specific weakness and its solution.

Assume that a fictitious organisation has the user roles A, B and C. Further, assume that the organisation has a particular piece of confidential data CI.

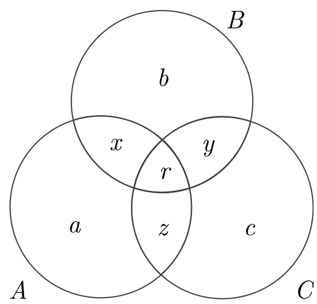


Figure 6.6: Intersection of user roles A, B and C

The seemingly correct formalisation of organisational rules. Assume the following organisational rules.

- **Rule** 1 - *CI* can be visible to users having the user role *B* and the user role *C*.
- **Rule** 2 - *CI* must not be revealed to users having the user role *A*.
- **Rule** 3 - Every user in the organisation must belong to either *A* or *B* or *C*.
- **Rule** 4 - A user cannot occupy more than one user role in the organisation.

Rule 1 was formalised as;

$$user \in (B \cup C) \Rightarrow \text{show } CI \tag{6.1}$$

and **Rule** 2 was formalised as;

$$user \in A \Rightarrow \text{conceal } CI \tag{6.2}$$

and **Rule** 3 was formalised as;

$$user \in (A \cup B \cup C) \tag{6.3}$$

and **Rule** 4 was formalised as;

$$A \cap B \cap C = \{\} \tag{6.4}$$

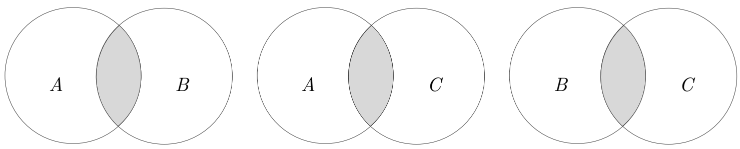
where *user* is the user who was requesting access to the confidential information *CI*, 'show *CI*' is a specification that allows the value of *CI* to be revealed and 'conceal *CI*' is a specification that states that the value of the state variable *CI* must not be revealed in the current state. The consistency of the requirements in the specification, that included the formalisations Equation (6.1), Equation (6.2), Equation (6.3) and Equation (6.4), could not be verified using the proposed mechanisation.

Strengthening the specification. In order to prove the consistency of the requirements in the formalised specification of the system, the formalisation of **Rule** 2 had to be strengthened by replacing Equation (6.2) with Equation (6.5) as follows.

$$user \notin (B \cup C) \Rightarrow \text{conceal } CI \tag{6.5}$$

Upon further investigation, it was found that the original formalisation of **Rule** 4 in Equation (6.4) only guaranteed that r in Figure 6.6 was empty. In this scenario, it may be possible that one or both of the subsets x and z might not be empty. In such a scenario, Equation (6.1) and Equation (6.2) will contradict each other. Strengthening the formalisation of **Rule** 2 worked because Equation (6.5) did not enforce **Rule** 2 on subsets x and z. However, this means that there might be the possibility of data leakage should there be a user who belonged to x or z and who was requesting for CI based on **Rule** 1. The mechanisation had detected this data leakage.

The solution. The correct formalisation of **Rule** 4 must define the sets x, y, z and r as empty to ensure that a user cannot occupy more than one user role. For this, all possible pairwise intersections for the user roles in the organisation must be defined as empty as shown in Figure 6.7.



$A \cap B = \{\}$ $\quad$ $A \cap C = \{\}$ $\quad$ $B \cap C = \{\}$

Figure 6.7: Pairwise disjoint statements for users roles A, B and C

If the pairwise disjoint statements in Figure 6.7 are used as invariants in the formal specification of the system, then the consistency of the requirements in the system against the confidentiality property in Equation (6.2) can be verified.

6.2.8 An example of strengthening a weak specification

Consider a fictitious hand-crafted bidding system where the value of the highest bid must never be revealed to a customer. Possible formal specifications of the system are presented in Figure 6.8 and Figure 6.9. Figure 6.8 presents a 'weak specification' of the system whereas the specification in Figure 6.9 presents a strengthened specification.

In both Figure 6.8 and Figure 6.9, the following representations are followed. The free type *PERSON* represents the identifiers of all the users who can use the system which includes *alice*, *bob*, *carol*, *dave* and *eve*. The *loginUser* is the identifier of the user who is currently using the system. The groups of users in the system include *loggedIn* which includes all the users currently using the system, *customers* that includes the identifiers of all the customers, *cashiers* that includes the identifiers of all the cashiers, *managers* that includes the identifiers of all the managers in the system. The system requires that the set of logged in users must always be from the combined set of *customers*, *cashiers* and *managers*. The system has two user roles where *Customer* includes all the users in *customers* and *Staff* includes all users in both *cashiers* and *managers*. The system has a function called *RecordHighestBid* which can be used to record the highest bid and *ShowHighestBid* which shows the highest bid recorded in the system.

Assume that the confidentiality requirement of the system states that the value of the highest bid *highestBidvalue* must never be revealed to the *customers* in the system. The confidentiality requirement may be formalised using the following schema.

HideHighestBidOriginal

$\Xi State$

$\exists\, State_9 \bullet$

$\quad loginUser \in customers \Rightarrow$

$\qquad highestBidvalue \neq highestBidvalue_9$

The specfcation that includes *HideHighestBidOriginal* is shown in Figure 6.8. When simplifying the predicate generated from back propagating the specification Figure 6.8, the Isabelle theorem prover highlights that there is contradiction in the predicate. This is because the triple intersection invariant

$$customers \cap cashiers \cap managers = \{\}$$

in the following *State* schema of the specification in Figure 6.8 does not define the three sets as disjoint sets, as discussed on Page 214.

State

$loginUser : PERSON$

$loggedIn, customers, cashiers, managers : \mathbb{F}\, PERSON$

$highestBidvalue : \mathbb{N}$

$loginUser \in loggedIn$

$loggedIn \subseteq (customers \cup cashiers \cup managers)$

$(customers \cap cashiers \cap managers) = \{\}$

In this scenario, the *loginUser* who is currently logged into the system may belong to both *customers* and either of *cashiers* or *managers*. The conflicting requirements of the functions allowed for a user role assigned to a *manager* or a *cashier* and the confidentiality requirements enforced on a user role assigned to a *customer* is detected during the simplification of the predicate. This conflict is detected as a potential data leakage.

Therefore, to make the requirements in the specification consistent, an upper limit is defined on the users to whom the confidential data in the confidentiality requirement can be revealed. The change is included in the modified confidentiality requirement *HideHighestBidModified* as follows.

HideHighestBidModified

$\Xi State$

$\exists\, State_9 \bullet$

$\quad loginUser \notin (cashiers \cup managers) \Rightarrow$

$\qquad highestBidvalue \neq highestBidvalue_9$

The confidentiality requirement in *HideHighestBidModified* states that *highestBidValue* must never be revealed to anyone except a user who belongs to the combined set of uses from *customers* and *managers*.

6.2.9 Strengthening the specification

In order to use *HideHighestBidOriginal*, the original formalisation of the confidentiality requirement that aligns with the description of the confidentiality requirement, we must modify the system state so that the sets *customers*, *cashiers* and *managers* are disjoint from each other. The system state is modified as follows to include pairwise intersections of the sets *cashiers*, *managers* and *customers*.

$$
\begin{array}{|l}
\hline
\textit{State} \\
\textit{loginUser} : \textit{PERSON} \\
\textit{loggedIn}, \textit{customers}, \textit{cashiers}, \textit{managers} : \mathbb{F}\, \textit{PERSON} \\
\textit{highestBidvalue} : \mathbb{N} \\
\hline
\textit{loginUser} \in \textit{loggedIn} \\
\textit{loggedIn} \subseteq (\textit{customers} \cup \textit{cashiers} \cup \textit{managers}) \\
(\textit{cashiers} \cap \textit{managers}) = \{\} \\
(\textit{customers} \cap \textit{managers}) = \{\} \\
(\textit{customers} \cap \textit{cashiers}) = \{\} \\
\hline
\end{array}
$$

The modified specification of the system is included in Figure 6.9. The consistency of the requirements in this strengthened specification can now be verified.

$PERSON ::= alice \mid bob \mid carol \mid dave \mid eve$

State

$$
\begin{array}{l}
loginUser : PERSON \\
loggedIn, customers, cashiers, managers : \mathbb{F}\, PERSON \\
highestBidvalue : \mathbb{N} \\
\hline
loginUser \in loggedIn \\
loggedIn \subseteq (customers \cup cashiers \cup managers) \\
(customers \cap cashiers \cap managers) = \{\}
\end{array}
$$

HideHighestBid

$$
\begin{array}{l}
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad loginUser \notin (cashiers \cup managers) \Rightarrow \\
\qquad highestBidvalue \neq highestBidvalue_9
\end{array}
$$

channel $recordBidIn, showLastBidOut : \mathbb{N}$

channelset $Customer == \{\!|\, showLastBidOut \,|\!\}$
channelset $Staff == \{\!|\, recordBidIn, showLastBidOut \,|\!\}$

process $SecretHighestBid \mathrel{\widehat=}$ **begin**

state $State$

$$
\begin{array}{lll}
RecordHighestBid & \widehat= & \mathbf{var}\ recordBid : \mathbb{N} \bullet \\
& & \quad recordBidIn?recordBid \longrightarrow \\
& & \quad \big(\big(loginUser \in cashiers \lor loginUser \in managers\big) \,\&\, \\
& & \qquad highestBidvalue := recordBid?\big) \\
\\
ShowHighestBid & \widehat= & \big(\big(loginUser \in cashiers \lor loginUser \in managers\big) \,\&\, \\
& & \qquad showLastBidOut\,!(highestBidvalue) \longrightarrow \mathbf{Skip}\big) \\
\\
HideHighestBid & \widehat= & HideHighestBid
\end{array}
$$

$$
\bullet\ \mu X \bullet \left(\left(\Box \begin{array}{l} \langle RecordHighestBid \rangle \\ \langle ShowHighestBid \rangle \end{array} \right) ; \ \langle HideHighestBid \rangle \ ; \ X \right)
$$

end

Figure 6.8: Specification of Secret Highest Bid - *code block 1 of 1*

(The weak specification)

$PERSON ::= alice \mid bob \mid carol \mid dave \mid eve$

State

$$
\begin{array}{l}
loginUser : PERSON \\
loggedIn, customers, cashiers, managers : \mathbb{F}\, PERSON \\
highestBidvalue : \mathbb{N} \\
\hline
loginUser \in loggedIn \\
loggedIn \subseteq (customers \cup cashiers \cup managers) \\
(cashiers \cap managers) = \{\} \\
(customers \cap managers) = \{\} \\
(customers \cap cashiers) = \{\}
\end{array}
$$

HideHighestBid

$$
\begin{array}{l}
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad loginUser \in customers \Rightarrow \\
\qquad\quad highestBidvalue \neq highestBidvalue_9
\end{array}
$$

channel $recordBidIn, showLastBidOut : \mathbb{N}$

channelset $Customer == \{\!|\ showLastBidOut\ |\!\}$
channelset $Staff == \{\!|\ recordBidIn, showLastBidOut\ |\!\}$

process $SecretHighestBid \mathrel{\widehat=}$ **begin**

state $State$

$$
\begin{array}{lcl}
RecordHighestBid & \widehat= & \mathbf{var}\ recordBid : \mathbb{N} \bullet \\
& & \quad recordBidIn?recordBid \longrightarrow \\
& & \quad \big(\big(loginUser \in cashiers \lor loginUser \in managers\big) \& \\
& & \qquad highestBidvalue := recordBid?\big) \\
\\
ShowHighestBid & \widehat= & \big(\big(loginUser \in cashiers \lor loginUser \in managers\big) \& \\
& & \qquad showLastBidOut\,!(highestBidvalue) \longrightarrow \mathbf{Skip}\big) \\
\\
HideHighestBid & \widehat= & HideHighestBid
\end{array}
$$

$$
\bullet\ \mu X \bullet \left(\left(\begin{array}{ll} & \langle RecordHighestBid \rangle \\ \Box & \langle ShowHighestBid \rangle \end{array} \right) ;\ \langle HideHighestBid \rangle ;\ X \right)
$$

end

Figure 6.9: Specification of Secret Highest Bid - *code block 1 of 1*

(**The strengthened specification**)

6.2.9.a Strengthened formal specification of the Bank information system

The strengthened formal specification of the Bank information system is presented in Figure 6.10.

(This page intentionally left blank)

$[\ PERSON\ ]$

$$
\begin{array}{l}
\textit{State} \\
\hline
balance : PERSON \ffun \mathbb{N} \\
reqCustomer, loginUser : PERSON \\
loggedIn, customers, cashiers, managers : \mathbb{F}\ PERSON \\
\hline
\mathrm{dom}\,(balance) \subseteq customers \\
(cashiers \cap managers) = \{\} \\
(customers \cap managers) = \{\} \\
(customers \cap cashiers) = \{\} \\
loggedIn \subseteq (customers \cup cashiers \cup managers) \\
loginUser \in loggedIn \\
\hline
\end{array}
$$

$$
\begin{array}{l}
\textit{HideBalCustomer} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad loginUser \neq reqCustomer \land \\
\quad loginUser \in customers \land \\
\quad reqCustomer \in \mathrm{dom}\,(balance) \Rightarrow \\
\qquad\quad (balance\ reqCustomer) \neq (balance_9\ reqCustomer_9) \\
\hline
\end{array}
$$

channel $newBalanceIn, mrbalOut, showBalanceOut, myBalanceOut : \mathbb{N}$
channel $withdrawAmountIn, depositAmountIn : \mathbb{N}$
channel $withdrawCustomerIn, depositCustomerIn, newCustomerIn : PERSON$
channel $rubIn, customerIn : PERSON$

channelset $BankingStaff == \{\!|\ customerIn, showBalanceOut\ |\!\}$
channelset $Cashier == \{\!|\ withdrawAmountIn, customerIn, showBalanceOut,$
$\quad depositAmountIn, depositCustomerIn, withdrawCustomerIn,$
$\quad newCustomerIn, newBalanceIn\ |\!\}$
channelset $Customer == \{\!|\ myBalanceOut\ |\!\}$

process $Bank\_information\_system \mathrel{\widehat=}$ **begin**

state $State$

$$
\begin{array}{lll}
Init & \mathrel{\widehat=} & reqCustomer := loginUser \\[1ex]
NewAccount & \mathrel{\widehat=} & \textbf{var}\ newBalance : \mathbb{N}; \\
& & \quad newCustomer : PERSON \bullet \\
& & \quad newBalanceIn?newBalance \longrightarrow \\
& & \quad newCustomerIn?newCustomer \longrightarrow \\
& & \quad \big(\big(newCustomer? \notin \mathrm{dom}\,(balance) \land loginUser \in cashiers\big) \,\&\, \\
& & \qquad balance := balance \oplus \\
& & \qquad\qquad\qquad \{(newCustomer? \mapsto newBalance?)\}\big) \\[1ex]
DepositMoney & \mathrel{\widehat=} & \textbf{var}\ depositAmount : \mathbb{N}; \\
& & \quad depositCustomer : \mathrm{dom}\,(balance) \bullet \\
& & \quad depositAmountIn?depositAmount \longrightarrow \\
& & \quad depositCustomerIn?depositCustomer \longrightarrow \\
& & \quad \big(\big(loginUser \in cashiers\big) \,\&\, \\
& & \qquad balance := balance \oplus \\
& & \qquad\quad \{(depositCustomer? \mapsto \\
& & \qquad\qquad (balance\ depositCustomer? - depositAmount?))\}\big)
\end{array}
$$

Figure 6.10: Specification of Bank information system - *code block 1 of 2*

$$
\begin{array}{lll}
\mathit{WithdrawMoney} & \widehat{=} & \mathbf{var}\ \mathit{withdrawAmount} : \mathbb{N}; \\
& & \quad \mathit{withdrawCustomer} : \mathrm{dom}\,(\mathit{balance}) \bullet \\
& & \quad \mathit{withdrawAmountIn}?\mathit{withdrawAmount} \longrightarrow \\
& & \quad \mathit{withdrawCustomerIn}?\mathit{withdrawCustomer} \longrightarrow \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{cashiers}\big) \mathbin{\&} \\
& & \qquad \mathit{balance} := \mathit{balance} \setminus \\
& & \qquad\quad \{(\mathit{withdrawCustomer}? \mapsto \\
& & \qquad\qquad (\mathit{balance}\,\mathit{withdrawCustomer}? + \mathit{withdrawAmount}?))\}) \\[1em]
\mathit{GetMyBalance} & \widehat{=} & \mathit{reqCustomer} := \mathit{loginUser}; \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{customers} \land \\
& & \qquad \mathit{loginUser} \in \mathrm{dom}\,(\mathit{balance})\big) \mathbin{\&} \\
& & \qquad \mathit{myBalanceOut}\,!(\mathit{balance}\,\mathit{loginUser}) \longrightarrow \mathbf{Skip}) \\[1em]
\mathit{GetAnyCustBalance} & \widehat{=} & \mathbf{var}\ \mathit{customer} : \mathit{PERSON} \bullet \\
& & \quad \mathit{customerIn}?\mathit{customer} \longrightarrow \\
& & \quad \mathit{reqCustomer} := \mathit{customer}?; \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{cashiers} \lor \mathit{loginUser} \in \mathit{managers}\big) \mathbin{\&} \\
& & \qquad \mathit{showBalanceOut}\,!(\mathit{balance}\,\mathit{customer}?) \longrightarrow \mathbf{Skip}) \\[1em]
\mathit{HideBalCustomer} & \widehat{=} & \mathit{HideBalCustomer}
\end{array}
$$

$$
\mathit{UserOptions} \mathrel{\widehat{=}} \begin{pmatrix} & \mathit{NewAccount} \\ \Box & \mathit{DepositMoney} \\ \Box & \mathit{WithdrawMoney} \\ \Box & \mathit{GetAnyCustBalance} \\ \Box & \mathit{GetMyBalance} \end{pmatrix} ;\ \mathit{HideBalCustomer}
$$

$$
\bullet \ \langle \mathit{Init} \rangle \,;\ \mu Y \bullet \big\langle (\mathit{UserOptions} \,;\ Y) \big\rangle
$$

end

Figure 6.10 (cont.) : Specification of Bank information system - *code block 2 of 2*

6.2.10 Results of the analysis

Table 6.8 presents the results of the mechanised analysis of the Bank information system. The total time taken for the mechanised analysis is the combined total of the time it takes to back propagate the specification using the CFAT tool and the time it takes to simplify the generated predicate using the Isabelle theorem prover.

The process of back propagation calculates the user's inference about the process state at each step of the process execution (Banks, 2012, p. 186). The results of the back propagation are dependent on the set of channels that is accessible to a user (see page 201). Since each user role in this system has access to a different set of channels, the results of the mechanised analysis of the system is presented in relation to users in each user role.

User role against which the system has being analysed	Cashier	Customer	Manager
Time taken for back propagation	474 ms	1055 ms	641 ms
Time taken for predicate simplification	2043 ms	2194 ms	2120 ms
Total time taken for evaluation	2517 ms	3249 ms	2761 ms
Result of the mechanised evaluation	Simplified	Simplified	Simplified

Table 6.8: Results of the mechanised analysis of the Bank information system

The results show that the tool saves time by executing the back propagation in a matter of milliseconds. However, as demonstrated with a smaller specification in Section 4.2 , a manual application of the back propagation process will be very much slower while also being error prone.

Table 6.8 shows that the analysis of the system with respect to the three user roles in the Bank information system results in the outcome "Simplified". Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification can be simplified, then according to BCF in *Circus*, there are no contradictions in the specification of the system being analysed.

6.2.11 Negative testing

Positive testing is used to verify the functionality of a product whereas negative testing is used to verify that a product does not do something (Oehlert, 2005, p. 58). In the context of this thesis, positive testing is used to verify that there are no contradictions between the functionality and confidentiality requirements in a system. Negative testing uses cases that are expected to fail (Olan, 2003, p. 320).

> *"Negative testing is performed to ensure that the system is able to handle inconsistent information. Negative acceptance tests (often expressed in the form of negative scenarios) are increasingly recognized as a powerful way of thinking about requirements, possible conflicts, and identifying threats."* (Melnik et al., 2006, p. 41)

In the context of testing systems for data leakage related confidentiality requirements, using BCF in *Circus*, a potential negative test will be to evaluate what will happen in a scenario where one accidentally introduces a side channel that violates access control requirements in a system. To simulate this scenario, an explicit side channel has been introduced to the hand-crafted system specification of the Bank information system. The basic approach is to:

introduce	a channel based access to a piece of data *d* for a user role *ur*
while	there is already an existing confidentiality requirement that exclusively restricts the user role *ur* from having access to *d*.

Such a test is expected to fail since there is a contradiction in the defined access parameters.

To introduce a side channel, a function with unconstrained access is introduced to the system specification of the Bank information system. This new *Circus* action, called *GetBalance*, allows any user using the system to view the account balance of any customer. The formal specification of the action *GetBalance* is as follows.

$$
\begin{array}{lll}
GetBalance & \widehat{=} & \mathbf{var}\ rub : \mathrm{dom}\ (balance) \bullet \\
 & & \quad rubin?rub \longrightarrow \\
 & & \quad reqCustomer := rub?; \\
 & & \quad mrbalOut\ !(balance\ rub?) \longrightarrow \mathbf{Skip}
\end{array}
$$

The confidentiality requirement *HideBalCustomer* restricts certain users from knowing the balance of any customer while the *Circus* action *GetBalance* allows any user to know the balance of any customer. Table 6.9 illustrates the results of a mechanised analysis of a formal specification that includes *GetBalance*.

Table 6.9 shows that the analysis of the Bank information system specification (that includes the side channel), with respect to the user role "Customer", results in the outcome "Time-out". Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification does not reach a conclusion during simplification but rather times-out, then nothing can be concluded about the presence or absence of contradictions in the specification. As stated earlier in Section 3.2.6, the result can be interpreted as provably true or provably false.

User role against which the system has being evaluated	Cashier	Customer	Manager
Time taken for back propagation	374 ms	344 ms	350 ms
Time taken for predicate simplification	771 ms	-	930 ms
Total time taken for evaluation	1145 ms	344 ms	1280 ms
Result of the simplification by the theorem prover	Simplified	Time-out	Simplified

Table 6.9: Result of the mechanised evaluation of the Bank information system with a side channel

6.2.12 Analysing other confidentiality patterns

Next , the confidentiality patterns **CP2**, **CP3**, **CP4** and **CP5** will be analysed in order.

6.2.12.a Analysing the confidentiality pattern CP2

The following is an analysis of a system with a confidentiality property that reflects the confidentiality pattern **CP2**. The confidentiality requirement **CR14** has been chosen as an adhoc choice for this analysis.

The mechanised analysis of **CR14** will be discussed using a hand-crafted system requirement specification of a fictitious Phone book system of a Secret government agency (Cerny and Alur, 2009b, p. 175). The fictitious Phone book system of a Secret government agency has been used as a case study for confidentiality analysis by others such as Lunt (1989) and Jajodia and Meadows (1995).

The full formal specification for the Phone book system is included in Appendix A.5.1. Here, we present the requirement specification of the system and the results of analysing the presented specification of the system. It must be noted that the formal specification included in Appendix A.5.1 is just one possible implementation of the system using the *Circus* notation.

6.2.12.a.1 Requirement specification of a system having CP2

The following requirement specification of the Phone book system has been divided into the organisational structure, the organisational rules, the user roles in the system, the operations and the user roles and permissions matrix of the system. Figure 6.11 presents a summarised use case diagram of the Phone book system.

Organisational structure

- **Every** *engineer, secretary, official* **and the** *manager* **is an** *employee* **of the agency**.
- **The agency uniquely identifies the** *employee* **who is the** *manager* **of the agency**.
- **The agency maintains a list that contains every** *engineer* **of the agency.**
- **The agency maintains a list that contains every** *secretary* **of the agency.**
- **The agency maintains a list that contains every** *official* **of the agency.**
- **The agency maintains a list that contains every** *official with a confidential phone number* **in the agency.**
- **The agency maintains a** *phone number* **for a subset of existing** *officials* **in the agency.**

Organisational rules

- **The same** *employee* **cannot be a** *secretary* **and an** *engineer*.
- **The same** *employee* **cannot be a** *secretary* **and the** *manager*.
- **The same** *employee* **cannot be an** *engineer* **and the** *manager*.

- **The agency phone book can only be used by either a** *secretary* **or an** *engineer* **or the** *manager*.
- **The set of** *officials* **with a confidential** *phone number* **must be from the set of** *officials* **whose phone numbers have been recorded in the phone book**.

User roles in the system

The following are user roles of the system. These user roles reflect the actors that are included in the use case diagram in Figure 6.11 The tasks that can be performed by a user belonging to each user role is described in Table 6.4.

- The *Manager* user role includes the manager of the agency.
- The *Secretary* user role includes all users who are *secretaries* in the agency.
- The *Engineer* user role contains all users who are *engineers* in the agency.

Operations, user roles and permissions

Table 6.10 lists all the system operations, and the specific permissions on those operations by user role.

	User roles		
Functions that can be performed in the Phone book system	Secretary	Engineer	Manager
Record the *phone_number* of a particular *official* in the phone book.	✓		
Find the *phone number* of an official who is not in the list of officials with a confidential phone number.	✓	✓	
Find the *phone number* of any official, recorded in the phone book.			✓
Record the name of an *official* in the list of *official*s whose *phone number*s are to be kept confidential.			✓

Table 6.10: Roles and Permissions Matrix of the Phone book system

6.2.12.a.2 Formalising the confidentiality requirement CR14

In this section, a possible formalisation of the confidentiality requirement **CR14** is presented using the *Circus* notation. The general definition of **CP2** states:

> do not reveal whether x is a member of S

The confidentiality requirement **CR14** of the Phone book system discussed in Cerny and Alur (2009b, p. 175) reads:

> **CR14** : The property to be kept secret for the example is whether a particular string, say '555-55' is in the phone book.

Recall that the confidentiality requirement **CR14** has been rephrased as follows, to align with the definition of **CP2**.

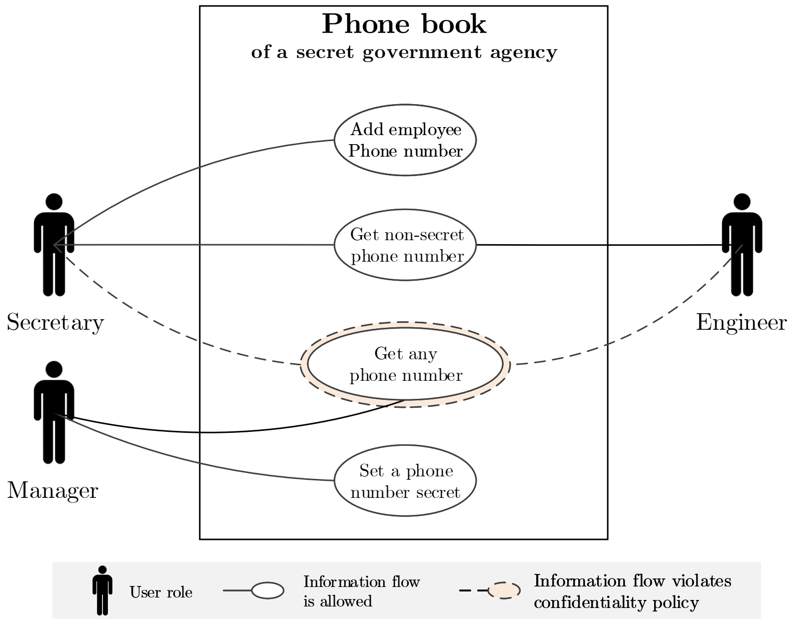


Figure 6.11: Use case diagram for the Bank information system

if the user is not authorized **then** for every given x, do not reveal whether x is a member of the set S (where S contains the phone numbers in the phone book)

This is another confidentiality requirement with a *conditional information flow* (Tschantz and Wing, 2008, p. 108) where the condition to hide the information about the membership of x in S is satisfied if the user is not authorised.

Identify the condition for confidentiality. Cerny and Alur (2009b) do not detail the specific users from whom the information is required to be hidden. Therefore, in the case of the Phone book system, it is assumed that the current user of the system *loginUser* is not authorised to view the phone number of a secret official if the user is not the *manager* and the name of the requested official *reqOfficial* is in the list of secret officials. These conditions can be combined and written as follows.

loginUser is not the manager
and *reqOfficial* is in the list of secret officials

The above condition may be formalised using the *Circus* notation as follows.

$$\begin{aligned} & loginUser \notin managers \\ \wedge\ & reqOfficial \in secretList \end{aligned}$$

Identify the confidential data. In order to hide the membership of a particular variable x in the set S in the normal state space, it is required to have the cover story that the *twin* variable x_9 is not a member of the *twin* set S in the *shadow* state space. BCF states that whenever a user can observe the value of a variable x in the normal system state space he/she can assume that the shadow system must also have the same value for its twin variable x_9.

In order to prevent the system from revealing the exact value of a particular variable, we must exclusively state a separation between the value of the variable in the original system and that in the shadow system. In this scenario we may write:

$$x \in S \Rightarrow x_9 \notin S_9$$

In the case of the Phone book system, where phone number of a secret official *reqOfficial* is requested, information about the membership of the official in the phone book register *PhoneNumbers* must not revealed. This may be formalised as follows:

$$\begin{aligned} & reqOfficial \in \mathrm{dom}\ phoneNumbers \\ & \quad \Rightarrow reqOfficial_9 \notin \mathrm{dom}\ phoneNumbers_9 \end{aligned}$$

where *PhoneNumbers* is a function between an identifier for an *official* and a phone number, if any.

Build the confidentiality predicate. Now, we combine the condition for confidentiality and the separation defined for the confidential data to come up with a formal definition for the confidentiality requirement **CR14** . The derived formal definition is shown below as a Z schema.

HideSecretNumber

$$
\begin{array}{l}
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad reqOfficial \in secretList \land \\
\quad reqOfficial \neq loginUser \land \\
\quad loginUser \neq manager \Rightarrow \\
\qquad\qquad reqOfficial \in \operatorname{dom}(phoneNumbers) \Rightarrow \\
\qquad\qquad\qquad reqOfficial_9 \notin \operatorname{dom}(phoneNumbers_9)
\end{array}
$$

The schema *HideSecretNumber* includes a confidentiality constraint that must be enforced on the state space of a particular state or states of the Phone book system where *HideSecretNumber* is observed.

6.2.12.a.3 Results of analysing the Phone book system

Table 6.11 shows that the analysis of the system with respect to the three user roles in the Phone book system results in the outcome “Simplified”. Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification can be simplified, then according to BCF in *Circus*, there are no contradictions in the specification of the system being analysed.

User role against which the system has being analysed	Secretary	Engineer	Manager
Time taken for back propagation	338 ms	223 ms	445 ms
Time taken for predicate simplification	1904 ms	2919 ms	1802 ms
Total time taken for evaluation	2242 ms	3142 ms	2247 ms
Result of the simplification by the theorem prover	Simplified	Simplified	Simplified

Table 6.11: Results of the mechanised analysis of the Phone book system

6.2.12.b Analysing the confidentiality pattern CP3

The following is an analysis of a system with a confidentiality property that reflects the confidentiality pattern **CP3**. The confidentiality requirement **CR21** has been chosen as an adhoc choice for this analysis.

The mechanised analysis of **CR21** will be discussed using the Secure electronic examination system by Foley and Jacob (1995). For this, a hand-crafted system requirement specification of a fictitious Secure electronic examination system has been developed. Some functions listed in this specification have been borrowed from the description of the Secure electronic examination system by Foley and Jacob (1995).

The full formal specification for the Secure electronic examination system is included in Appendix A.5.2. Here, we present the requirement specification of the system and the results of analysing the presented specification of the system. It must be noted that the formal specification included in Appendix A.5.2 is just one possible implementation of the system using the *Circus* notation.

6.2.12.b.1 Requirement specification of a system having CP3

The following requirement specification of the Secure electronic examination system has been divided into the organisational structure, the organisational rules, the user roles in the system, the operations and the user roles and permissions matrix of the system. Figure 6.12 presents a summarised use case diagram of the Secure electronic examination system.

Organisational structure

- **A *chair* is a *user*.**
- **A *setter* is a *user*.**
- **A *checker* is a *user*.**
- **A *grader* is a *user*.**
- **The company maintains a *chair* for each existing *subject*.**
- **The company maintains a *setter* for each existing *paper*.**
- **The company maintains a *checker* for each existing *paper*.**
- **The company maintains a *grader* for each existing *paper*.**
- **The company maintains a *result* for each existing *candidate*.**
- **The company maintains a *paper status* for each existing *paper*.**
- **The company maintains a *subject* of each existing *paper*.**
- **The company maintains a list that contains every *student* of the company.**
- **The company maintains a list that contains every *lecturer* of the company.**
- **The company maintains a list that contains every *loggedInUser* of the company.**

- **The company uniquely identifies the** *user* **who is the** *current_user* **of the company**.
- **The company uniquely identifies the** *can* **who is the** *current_user* **of the company**.
- **The company records the relationship between a** *candidate* **and a** *paper***.**
- **The company records the relationship between a** *candidate* **and a** *answer***.**
- **The company records the relationship between a** *paper* **and a** *question***.**
- **The company records the relationship between a** *paper* **and a** *answer***.**

Organisational rules

- All subject chairs, setters, checkers and graders must be lecturers.
- A lecturer cannot have more than one role. Hence, the lecturer can either be a subject chair, setter, checker or grader.
- The set of users allowed access to the system is a subset of the set of lecturers and students.
- A person cannot be both a lecturer and a student in the system.
- Every paper with a paper status must belong to an announced examination.
- Every paper for which a setter has been assigned must have a paper status.
- Every paper for which a checker has been assigned must have a paper status.
- Every paper for which a grader has been assigned must have a paper status.
- Every paper on which a question is recorded must have a paper status.
- Every paper on which an answer is recorded must have a paper status.
- Every paper registered for, must have a paper status.

- Every student registered for a paper must be a registered candidate.
- Every student registered as a candidate must be a student recorded in the system.
- Every result must belong to a registered paper.
- Every answer recorded must be for a registered paper.
- Lecturers who record questions in the system must be setters.
- Every question recorded in the system must be for a registered paper.
- Every answer recorded in the system must be for a registered paper.

User roles in the system

The following are user roles of the system. These user roles reflect the actors that are included in the use case diagram in Figure 6.12. The tasks that can be performed by a user belonging to each user role is described in Table 6.12.

- The *Chair* user role contains all users who are *subject chairs* in the institution.
- The *Setter* user role includes all users who are *setters* of examination papers in the institution.
- The *Checker* user role includes all users who check examination papers in the institution.
- The *Marker* user role includes all users who grade the examination papers in the institution.
- The *Student* user role contains all users who are *studying* in the institution.

Operations, user roles and permissions

Table 6.12 lists all the system operations, and the specific permissions on those operations by user role.

	User roles				
Functions that can be performed on the Phone book system	Chair	Setter	Checker	Marker	Student
Announce an examination for a particular subject.	✓				
Appoint a lecturer for the position of a *setter* from the relevant subject group to set the paper.	✓				
Appoint a lecturer for the position of a *checker* from the relevant subject group to check the paper[a].	✓				
Appoints a lecturer called a *grader* from the relevant subject group to grade the candidates who grade the paper.	✓				
Set a paper if the user is authorised to do so.		✓			
Release a paper if the user is authorised to do so.		✓			
Close an examination if the user is authorised to do so.		✓			
Check a paper if the user is authorised to do so.			✓		
Grade a paper if the user is authorised to do so.				✓	
Publish grades of candidates who set for a particular paper if the user is authorised to do so.				✓	
Register oneself as a candidate to sit for a particular paper.					✓
Record an answer for particular paper if the user is registered as a candidate for that particular paper.					✓
Find results of oneself for a particular paper.					✓
Cancel ones own registration for a particular paper.					✓

Table 6.12: Roles and Permissions Matrix of the Secure electronic examination system

[a] In the paper Secure Electronic Examinations by Foley and Jacob (1995) many setters and checkers could be appointed. However to keep our model simple, we consider a single setter and a single checker for a paper.

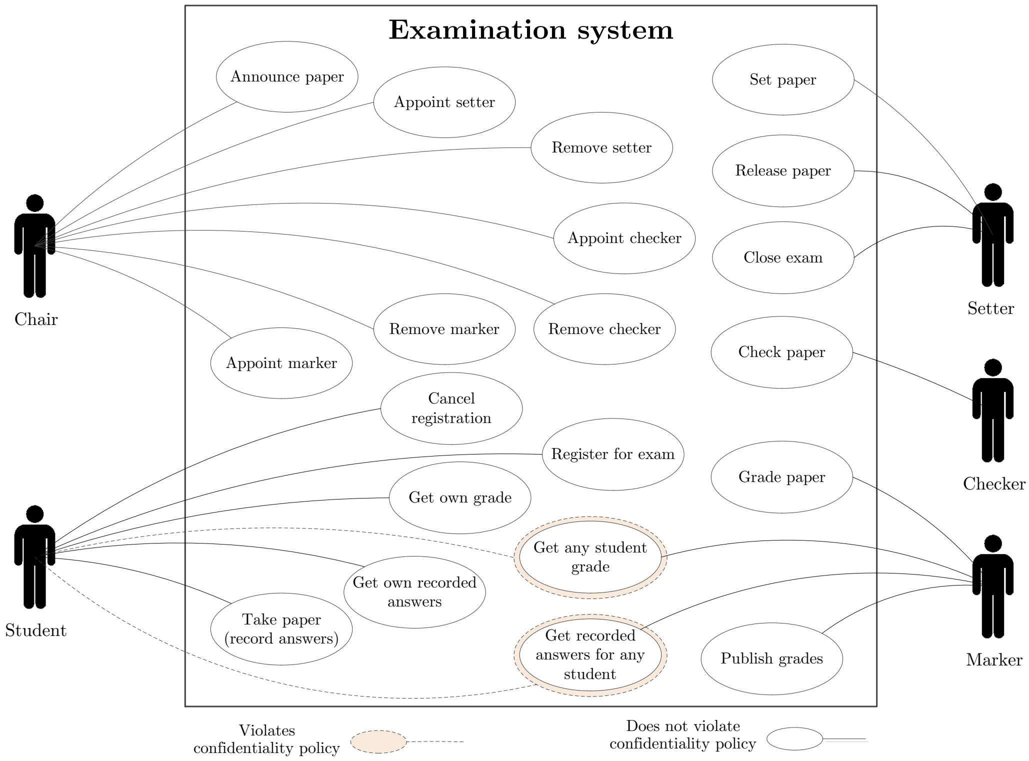


Figure 6.12: Use case diagram for the Secure electronic examination system

6.2.12.b.2 Formalising the confidentiality requirement CR21

The general definition of confidentiality pattern **CP3** reads:

> do not reveal the set S

The confidentiality requirement **CR21** identified from the Secure electronic examination system states:

CR21 :	No examinee should learn any details of the contents of any other examinees answer paper between the start of the examination and the end of the examination.

Recall from page 162 that the confidentiality requirement **CR21** has been rephrased as follows, to align with the definition of **CP3**.

> **if** the user u currently using the system is not requesting information
> that belongs to him/her
> **and** exam e has started but not ended
> **then** do not reveal the set S
> (where S represents the answers recorded by a user other than u
> in the exam e)

Similar to the earlier discussion in Section 6.2.4, **CR21** is also a *conditional confidentiality requirement* (Tschantz and Wing, 2008). The formalisation of the condition for confidentiality and the confidential data are discussed separately.

Identify the condition for confidentiality. In this particular confidentiality requirement, the condition to hide the set containing the answers recorded by other examinees from the current user of the systems is satisfied if the examination for the paper of the requested userhas started and has but not ended yet.

In our hand-crafted formal specification for the Secure electronic examination system (see Appendix A.5.2), the possible states of a paper is represented by the free type *PAPERSTATUS*. The description of all these states can be found in Appendix A.5.2. The status of the paper between the start of an examination for that paper and its end is represented by the value *released*.

We may write the conditions required to satisfy the confidentiality requirement using the *Circus* notation as follows:

condition stated in the confidentiality requirement	one possible specification in *Circus*
examination of the paper for which the current user is a candidate has started and not ended	$pStatus\ (regPaper\ theCandidate) = released$
the user currently using the system is not requesting information that belongs to him/her	$((regStudent)^{\sim})\ loginUser \neq theCandidate$

Table 6.13: Formal specification of conditions required to satisfy the confidentiality requirement **CR21**

The confidentiality of the data must be enforced if all the conditions in Table 6.13 are satisfied. We may write this combined condition as follows.

$$\begin{aligned} & ((regStudent)^{\sim})\ loginUser \neq theCandidate \\ \wedge\ & pStatus\ (regPaper\ theCandidate) = released \end{aligned}$$

Identify the confidential data. Here, we are to hide every single answer recorded by the examinee *theCandidate* from the current user. The set of answers recorded by the examinee *theCandidate* is represented by the set *answersB*:

$$answersB \equiv \{theCandidate\} \lhd ansStudent$$

where *ansStudent* is a relation between candidate identifiers and answers they have recorded. In the shadow system, the set of answers recorded by the examinee *theCandidate* is represented by the set $answersB_9$:

$$answersB_9 \equiv \{theCandidate_9\} \lhd ansStudent_9$$

where $ansStudent_9$ is the twin counterpart of *ansStudent*. To prevent the system from revealing any value in the set *answersB* we state that the sets *answersB* and $answersB_9$ are disjoint.

$$(\{b\} \lhd ansStudent) \cap (\{b_9\} \lhd ansStudent_9) = \{\}$$

Build the confidentiality predicate. We now combine the condition and the action to come up with a formal definition for the confidentiality requirement **CR21** . The derived formal definition is shown below.

$$
\begin{array}{l}
\textit{HideOthersAnswers} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad ((regStudent)^{\sim})\ loginUser \neq theCandidate \land \\
\quad pStatus\ (regPaper\ theCandidate) = released \Rightarrow \\
\qquad\qquad (\mathrm{ran}(\{theCandidate\} \lhd ansStudent)\ \cap \\
\qquad\qquad\ \ \mathrm{ran}(\{theCandidate_9\} \lhd ansStudent_9)) = \{\} \\
\hline
\end{array}
$$

The schema *HideOthersAnswers* includes a confidentiality constraint that must be enforced on the state space of a particular state or states of the Secure electronic examination system where *HideOthersAnswers* is observed.

6.2.12.b.3 Results of analysing the Secure electronic examination system

Table 6.14 shows that the analysis of the system with respect to the user roles in the Secure electronic examination system results in the outcome "Simplified". Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification can be simplified, then according to BCF in *Circus*, there are no contradictions in the specification of the system being analysed.

User role against which the system has been evaluated	Setter	Marker	Chair	Checker	Student
Time taken for back propagation	12854 ms	15282 ms	4860 ms	7378 ms	9887 ms
Time taken for predicate simplification	7772 ms	8808 ms	7371 ms	6201 ms	7558 ms
Total time taken for evaluation	20626 ms	24090 ms	12231 ms	13579 ms	17445 ms
Result of the simplification by the theorem prover	Simplified	Simplified	Simplified	Simplified	Simplified

Table 6.14: Results of the mechanised evaluation of the Secure electronic examination system

6.2.12.c Analysing the confidentiality pattern CP4

The following is an analysis of a system with a confidentiality property that reflects the confidentiality requirement pattern **CP4**. The confidentiality requirement **CR16** has been chosen as an adhoc choice for this analysis.

The mechanised analysis of **CR16** will be discussed using a hand-crafted system requirement specification of a fictitious **CR16** . The fictitious ePurse system has been used as a case study for confidentiality analysis by De Landtsheer and Van Lamsweerde (2005, p. 44).

The full formal specification for the ePurse system is included in Appendix A.5.1. Here, we present the requirement specification of the system and the results of analysing the presented specification of the system. It must be noted that the formal specification included in Appendix A.5.3 is just one possible implementation of the system using the *Circus* notation.

6.2.12.c.1 Requirement specification of a system having CP4

The following requirement specification of the ePurse system has been divided into the organisational structure, the organisational rules, the user roles in the system, the operations and the user roles and permissions matrix of the system. Figure 6.13 presents a summarised use case diagram of the ePurse system.

Organisational structure

- **The ePurse system maintains an** *ePurse* **for every** *buyer* **identifier from a subset of** *buyers* **in the system**.
- **The ePurse system maintains a** *balance* **identifier for every** *ePurse* **from a subset of** *ePurses* **in the system**.
- **The ePurse system maintains an** *ePurse* **identifier for every** *transaction* **from a subset of** *transactions* **in the system**.
- **The ePurse system maintains a** *terminal* **identifier for every** *transaction* **from a subset of** *transactions* **in the system**.
- **The ePurse system maintains a** *balance* **identifier for every** *transaction* **from a subset of** *transactions* **in the system**.
- **The ePurse system maintains an** *ePurse* **for every** *buyer* **from a subset of** *buyers* **in the system**.
- **The ePurse system maintains a** *validation status* **for every** *transaction* **from a subset of** *transactions* **in the system**.
- **The ePurse system uniquely identifies the** *agent* **that is currently requesting to execute a function in the system**.

- **The ePurse system uniquely identifies the** *ePurse*, **the balance of which is requested from the system**.

Organisational rules

- The *ePurse*, **of which a balance is requested from the system**, must have a balance recorded in the system.
- The *ePurse*, **of which a balance is requested from the system**, must have an associated owner recorded in the system.
- Every transaction that has an associated agent must also have a transaction amount recorded in the system.
- Every transaction that has an associated ePurse must also have a transaction amount recorded in the system.
- Every transaction that has an associated validation status must also have a transaction amount recorded in the system.
- Every ePurse that has a transaction associated with it must also have a balance recorded in the system.
- Every ePurse that has a balance associated with it must belong to an agent in the system.

User roles in the system

The following are user roles of the system. These user roles reflect the actors that are included in the use case diagram in Figure 6.13 The tasks that can be performed by a user belonging to each user role is described in Table 6.15.

- The *Buyer* user role includes the buyers in the ePurse system.
- The *Seller* user role includes the sellers in the ePurse system.
- The *Terminal* user role includes the terminals in the ePurse system

Operations, user roles and permissions

Table 6.15 lists all the system operations, and the specific permissions on those operations by user role.

	User roles		
Operations that can be performed on the ePurse system	Seller	Buyer	Terminal
Record a *transaction* in the system.	✓		
Approve a *transaction* on the ePurse of a buyer.		✓	
Process the payment for a *translation*.			✓
Get the *balance* in the ePurse of a given buyer.			✓

Table 6.15: Roles and Permissions Matrix of the ePurse system

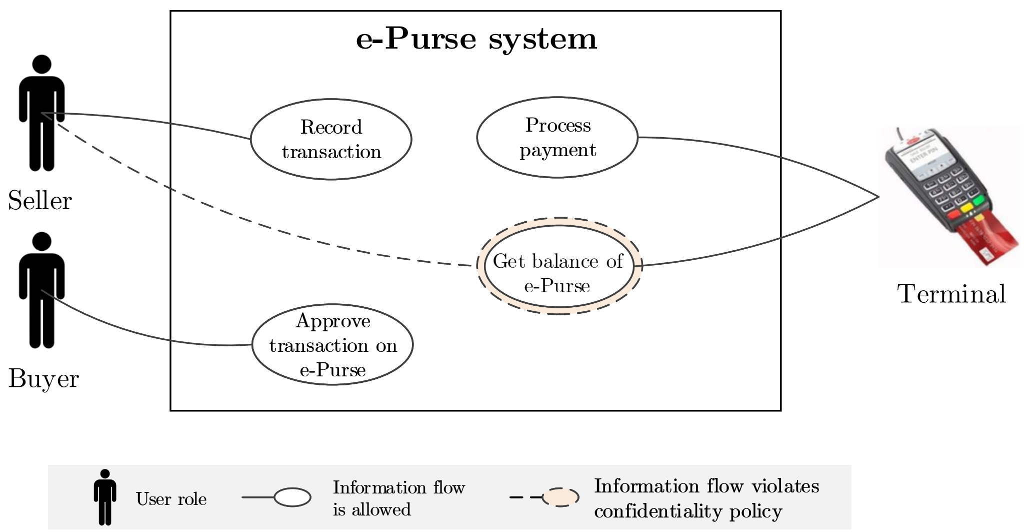


Figure 6.13: Use case diagram for the e-Purse system

6.2.12.c.2 Formalising the confidentiality requirement CR16

In this section, a possible formalisation of the confidentiality requirement **CR16** is specified using the *Circus* notation. The general definition of **CP4** states:

> do not reveal the exact value of x

The confidentiality requirement **CR16** of the ePurse system by De Landtsheer and Van Lamsweerde (2005, p. 44) reads:

CR16 :	agents who are not the card holder should not know the exact value of some state variable.

Recall that the confidentiality requirement **CR16** has been rephrased as follows, to align with the definition of **CP4**.

if	the agent is not the card holder
then	<u>do not reveal the value</u> of x

Once again, like the previous confidentiality requirements, this confidentiality requirement requires confidentiality of information under certain conditions.

Identify the condition for confidentiality. De Landtsheer and Van Lamsweerde (2005, p. 44) state that the current agent *currAgent* using the system is not authorised to view the exact value of a state variable if does not. If that state variable is the balance of a particular ePurse *reqPurse*, then the requirement states that *currAgent* must not know the exact balance of *reqPurse* if *currAgent* does not own *reqPurse*. This confidentiality condition can be written as follows.

currAgent is not the *owner* of the *ePurse*

The above condition may be formalised using the *Circus* notation as follows.

$$(currAgent \mapsto reqPurse) \notin owns$$

where *own* is a function that identifies the ePurse of a given agent, if any.

Identify the confidential data. In order to prevent the system from revealing the exact value of a particular variable, we must exclusively state a separation between the value of the variable in the original system and that in the shadow system. In the case of the ePurse system, such a separation is formalised as follow.

$$(balance\ reqPurse) \neq (balance_9\ reqPurse_9)$$

Build the confidentiality predicate. Now, the condition for confidentiality and the separation defined for the confidential data must be combined to come up with a formal definition for the confidentiality requirement **CR16** . The derived formal definition is shown below as a Z schema.

$$
\begin{array}{|l}
\hline
\textit{HideExactBalance} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad (currAgent \mapsto reqPurse) \notin owns \land \\
\quad currAgent \neq terminal \land \\
\quad reqPurse \in \mathrm{dom}\,(balance) \Rightarrow \\
\qquad (balance\ reqPurse) \neq (balance_9\ reqPurse_9) \\
\hline
\end{array}
$$

The schema *HideExactBalance* includes a confidentiality constraint that must be enforced on the state space of a particular state or states of the ePurse system where *HideExactBalance* is observed.

6.2.12.c.3 Results of analysing the ePurse system having CR16

Table 6.16 shows that the analysis of the system with respect to the three user roles in the ePurse system results in the outcome "Simplified". Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification can be simplified, then according to BCF in *Circus*, there are no contradictions in the specification of the system being analysed.

User role against which the system has being analysed	Seller	Buyer	Terminal
Time taken for back propagation	481 ms	394 ms	653 ms
Time taken for predicate simplification	1590 ms	1329 ms	1460 ms
Total time taken for evaluation	2071 ms	1723 ms	2113 ms
Result of the simplification by the theorem prover	Simplified	Simplified	Simplified

Table 6.16: Results of the mechanised analysis of the ePurse system

6.2.12.c.4 Negative test with an automatic counter example

In some scenarios the theorem prover may identify a counter example after running possible combinations to simplify the submitted predicate. Consider the *Circus* specification of the ePurse system in Figure A.8. Extend the specification in Figure A.8 by introducing the schema *HideIfNotTerminal* that represents a confidentiality annotation and the *Circus* action *ShowAnyBal*. The schema *HideIfNotTerminal* formalises a confidentiality requirement where the system must never reveal the balance of any ePurse if the current user agent is not a *terminal*. The *Circus* action *ShowAnyBal* formalises a function where the balance of any requested ePurse can be viewed. The descriptions of the variables in both *HideIfNotTerminal* and *ShowAnyBal* are included in Appendix A.5.3.

$$
\begin{array}{|l}
\hline
\textit{HideIfNotTerminal} \\
\Xi \textit{State} \\
\hline
\exists\, \textit{State}\,_9 \bullet \\
\quad \textit{currAgent} \neq \textit{terminal} \Rightarrow \\
\qquad (\textit{balance reqPurse}) \neq (\textit{balance}_9\ \textit{reqPurse}_9) \\
\hline
\end{array}
$$

$$
\begin{array}{lll}
\textit{ShowAnyBal} & \widehat{=} & \textbf{var}\ \textit{anyPurse} : \mathrm{dom}\,(\textit{balance}) \cap \mathrm{ran}\,\textit{owns} \bullet \\
 & & \quad \textit{anyPurseIn}?\textit{anyPurse} \longrightarrow \\
 & & \quad \textit{reqPurse} := \textit{anyPurse}?; \\
 & & \quad \textit{showAnyPurseOut}\,!(\textit{balance anyPurse}?) \longrightarrow \textbf{Skip}
\end{array}
$$

The main action of the specification of the ePurse system in Figure A.8 is modified to include *HideIfNotTerminal* and *ShowAnyBal* as follows.

$$
\bullet\ \mu X \bullet \left(\textit{SelectAgent}\,; \left(\begin{array}{ll}
 & \langle \textit{ApproveTrnsctn} \rangle \\
\Box & \langle \textit{ShowBalSec} \rangle \\
\Box & (\langle \textit{ShowAnyBal} \rangle\ ;\ \langle \textit{HideIfNotTerminal} \rangle) \\
\Box & \langle \textit{DoPayment} \rangle \\
\Box & \langle \textit{RecordTrnsctn} \rangle
\end{array} \right) ;\ X \right)
$$

Analysing the resulting specification using the mechanisation of BCF in *Circus* proposed in this research resulted in the Isabelle theorem prover suggesting a counter example. The Isabelle theorem prover command "**apply** smt" suggested that the variable *currAgent* might assume the value *seller* or *buyer*. In this case, the antecedent in the implication in *HideIfNotTerminal* will be satisfied resulting in a contradiction between the output action in *ShowAnyBal* and the consequent in the implication in *HideIfNotTerminal*.

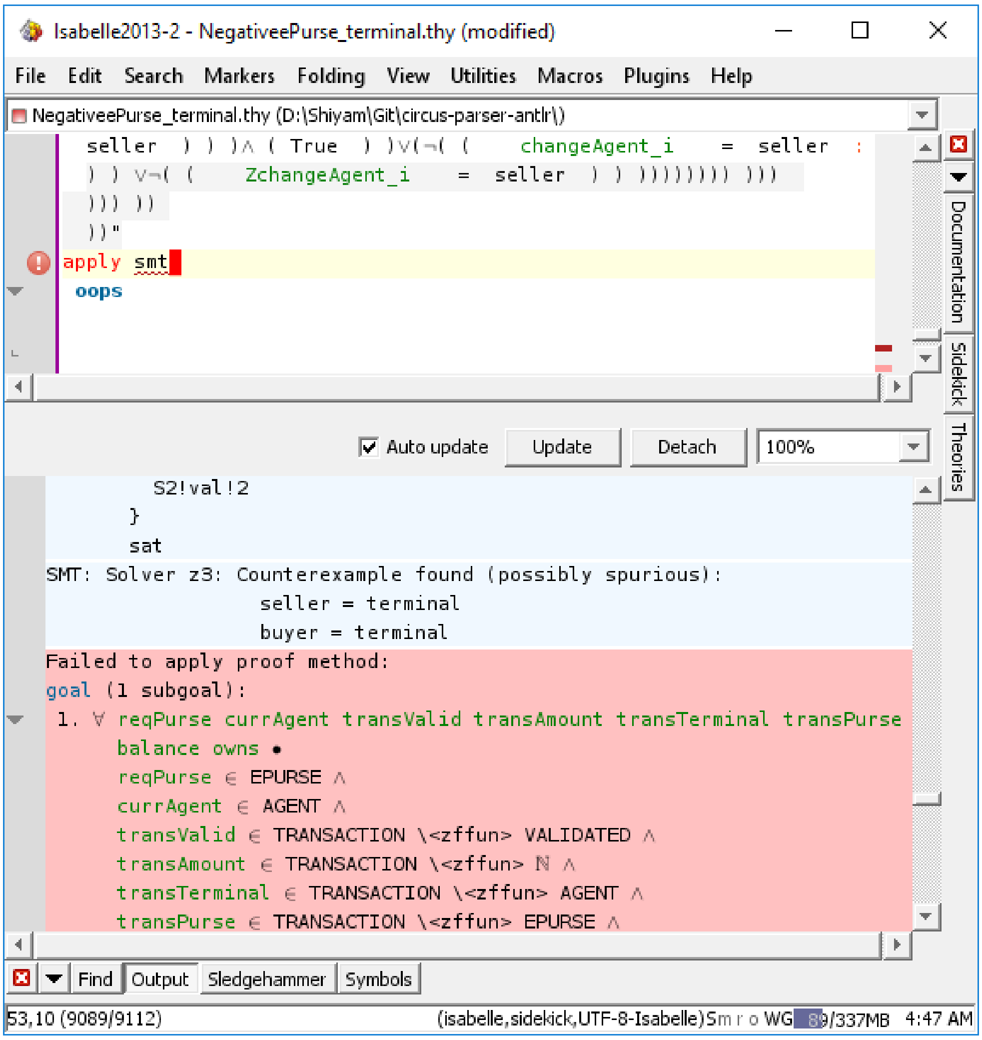


Figure 6.14: Counter example generated due to an insecure operation

6.2.12.d Analysing the confidentiality pattern CP5

The ePurse system discussed earlier contains the confidentiality property **CR17** that reflects the confidentiality requirement pattern **CP5**. Therefore, the same model of that ePurse system will be reused here for analysing a system with a confidentiality property that reflects **CP5**. As mentioned earlier, the full formal specification for the ePurse system is included in Appendix A.5.3 and it must be noted that this formal specification is just one possible implementation of the system using the *Circus* notation.

6.2.12.d.1 Formalising the confidentiality requirement CR17

In this section, a possible formalisation of the confidentiality requirement **CR17** is specified using the *Circus* notation. The general definition of **CP5** states:

> do not reveal the exact value of x

The confidentiality requirement **CR17** of the ePurse system by De Landtsheer and Van Lamsweerde (2005, p. 44) reads:

CR17 :	agents who are not the card holder should not know whether a state variable is above/below a given threshold.

Recall that the confidentiality requirement **CR17** has been rephrased as follows, to align with the definition of **CP5**.

if	the agent is not the card holder
then	do not reveal whether the value y is above/below a certain threshold n

Once again, like the previous confidentiality requirements, this confidentiality requirement requires confidentiality of information under certain conditions. The confidentiality requirement **CR17** has the same condition.

The formal definition of the condition for confidentiality has been presented earlier in the analysis for **CP4**. The confidentiality requirement **CR17** has the same condition for confidentiality. In addition, the balance of a requested customer being below a certain threshold *bmin* is a condition to be enforced this confidentiality requirement.

$$balance\ reqPurse \in \{r : \mathbb{N} \mid r < bmin\}$$

To hide the set of possible values of *balance reqPurse* we define the set of possible values of *balance reqPurse* and $balance_9\ reqPurse_9$ to be disjoint.

$$\begin{aligned}&balance\ reqPurse \in \{r : \mathbb{N} \mid r < bmin\}\\&\quad \Rightarrow balance_9\ reqPurse_9 \notin \{r : \mathbb{N} \mid r < bmin\}\end{aligned}$$

The derived formal definition of **CR17** is shown below as a Z schema.

HideMinBalance

$$\begin{array}{l}\Xi State\\ \hline \exists\, State_9 \bullet\\ \quad (currAgent \mapsto reqPurse) \notin owns \wedge\\ \quad currAgent \neq terminal \wedge\\ \quad reqPurse \in \mathrm{dom}\,(balance) \wedge\\ \quad balance\ reqPurse \in \{r : \mathbb{N} \mid r < bmin\} \Rightarrow\\ \quad\quad balance_9\ reqPurse_9 \notin \{r : \mathbb{N} \mid r < bmin\}\end{array}$$

The schema *HideMinBalance* includes a confidentiality constraint that must be enforced on the state space of a particular state or states of the ePurse system where *HideMinBalance* is observed. The main action of the ePurse system has been modified as follows for this analysis.

$$\bullet\ \mu X \bullet \left(\langle \mathit{SelectAgent} \rangle\ ;\ \left(\begin{array}{ll} & \langle \mathit{ApproveTrnsctn} \rangle \\ \Box & (\langle \mathit{ShowBalSec} \rangle\ ;\ \langle \mathit{HideMinBalance} \rangle) \\ \Box & \langle \mathit{DoPayment} \rangle \\ \Box & \langle \mathit{RecordTrnsctn} \rangle \end{array} \right)\ ;\ X \right)$$

The ePurse system in the specification in Figure A.8, having the modified main action as above, is analysed using the mechanisation. The results of this analysis is discussed next.

6.2.12.d.2 Results of analysing the ePurse system having CR17

Table 6.17 shows that the analysis of the system with respect to the three user roles in the ePurse system results in the outcome “Simplified”. Recall from Section 3.2.6 that if the predicate generated from back propagating a system specification can be simplified, then according to BCF in *Circus*, there are no contradictions in the specification of the system being analysed.

User role against which the system has being analysed	Seller	Buyer	Terminal
Time taken for back propagation	481 ms	394 ms	653 ms
Time taken for predicate simplification	1590 ms	1329 ms	1460 ms
Total time taken for evaluation	2071 ms	1723 ms	2113 ms
Result of the simplification by the theorem prover	Simplified	Simplified	Simplified

Table 6.17: Results of the mechanised analysis of the ePurse system

6.2.13 A comparison of results of the mechanised analysis

In order to compare the results of the mechanised analysis shown in Table 6.8, Table 6.11, Table 6.14, Table 6.16 and Table 6.17 we must first have a way to identify the relative size of each *Circus* specification that was analysed. The author does not know of any prior work on comparing the relative size of two formal specifications in the *Circus* notation. Further, the reader must also be informed that the implemented back propagation process in the CFAT tool uses regular expressions and pattern matching for renaming variables in the generated predicate. Alternatively, with the right programming skills, one could have implemented the same mechanisation using a functional programming language. In this scenario, regular expressions and pattern matching might not be required.

BCF laws (see Table 2.4) used in the analysis in this chapter are:

- **bw** *external choice*
- **bw** *sequence*
- **bw** *assignment*
- **bw** *guard*
- **bw** *input prefix*
- **bw** *output prefix*

The **bw** *sequence* and **bw** *external choice* laws are for the composite operators, sequential composition and external choice respectively. Apart from that, BCF back propagation laws for the atomic actions in the *Circus* notation manipulate the incoming predicate during the back propagation process. For example, **bw** *guard*, **bw** *input prefix* and **bw** *output prefix* laws add additional text to the predicate being calculated. However, the **bw** *assignment* law applies pattern matching through regular expressions to manipulate the predicate being calculated. It is expected that as the predicate grows in size, more computing time is required for pattern matching. Therefore, a correlation can be expected between the number of "assignment" actions in a given specification and the average time taken for back propagating the same specification. Such a correlation is reflected in Table 6.18 . However, this is less true for **bw** *guard*, **bw** *input prefix* and **bw** *output prefix* laws where:

Application of the input and output laws depends on the channelset L upon which the specification S is lifted. If there are output actions in S that uses a channel in L additional text will be introduced to the back propagated predicate, increasing its size. Likewise, base on whether an input action uses a channel in the channelset L for communication, the resulting text introduced to the back propagated predicate will be different. Therefore it will be difficult to derive a meaningful correlation between the number of input actions in a *Circus* specification and the time it takes for back propagating that specification.

The back propagation of the guarded action also introduce new text to the back propagated predicate. However, this text depends on the size of the *guard* in a guarded action. Therefore, existence of a guard will have little impact on the time taken for back propagation.

It must be strongly noted that this is too little a dataset to make a strong conclusion regarding the correlation. A much larger dataset from a range of systems must be analysed if we are to make a more accurate conclusion regarding the relation between the specification size and time taken for its mechanised analysis.

Context	Bank information system	Phone book system	Secure electronic examination system	ePurse system	ePurse system
Confidentiality requirement	**CR18**	**CR14**	**CR21**	**CR16**	**CR17**
Confidentiality pattern	**CP1**	**CP2**	**CP3**	**CP4**	**CP5**
Number of *Circus* actions					
Guarded action	5	4	19	4	4
Input action	8	5	15	10	10
Output action	2	2	3	1	1
Assign action	6	5	34	7	7
The average back propagation time	434 ms	252 ms	2792 ms	1477 ms	1587 ms
The average simplification time	1271 ms	1656 ms	2095 ms	1095 ms	1219 ms

Table 6.18: A comparison of the average analysis times for different systems

6.3 Summary

The main contribution of this chapter is the analysis carried out to evaluate the mechanisation of BCF in *Circus*, developed under this research. This fulfills the objective of this chapter by demonstrating that the mechanisation of BCF in *Circus* is practically applicable.

In this chapter:

- the mechanisation of BCF in *Circus* has been used to analyse systems with confidentiality requirements that reflect five different types of confidentiality requirement pattern identified in this research.
- the issue with a weak specification and how the weak specification maybe strengthened has be demonstrated.
- the concept of negative testing has been discussed and the results of carrying out a negative test has been discussed.
- the results obtained from executing different sizes and complexities of case studies has been critiqued.
- a possible correlation between the number of "assignment" actions in a given specification and the average time taken for back propagating the same specification has been identified. It must be noted that this maybe due to the programming style used for mechanising BCF where pattern matching has been used text replacement in a predicate.

7 Evaluation

This chapter presents an overall evaluation of the research presented in this thesis.

7.1 Introduction

Recall from Chapter 1 that the hypothesis of this research states that:

> *a practically applicable approach exists that supports the process of analysing system models using Banks's Confidentiality Framework (BCF) (Banks, 2012) to verify if those models respect the integrated confidentiality requirements pertaining to data leakage through legitimate channels.*

The author argues that the hypothesis has been fully satisfied through the proposed mechanisation in this thesis. The argument for the practical applicability of the proposed mechanisation approach has been justified by showing the time taken for analysing specifications of different systems with varying sets of functions. A possible approach for calculating the efficiency of the mechanisation has been discussed through a comparison between the time taken for a manual run of a BCF in *Circus* based analysis of a system and a mechanised run of the same analysis.

The author is quick to acknowledge that the current mechanisation does not support the analysis of recursion and parallel processes in systems. This is due to the current limitations in BCF in *Circus*, as discussed in the next section. For this reason, the mechanisation supports only sequential access systems.

7.2 Factors that could have influenced the quality of the analysis

The following factors could have strengthened the overall value of the outcome of the analysis carried out in this thesis.

Availability of real *Circus* specifications of Systems. If the case studies conducted in this research were based on real *Circus* specifications of systems or on real confidentiality requirements relating to data leakage then the justification of the advantages brought by the proposed mechanisation could have been stronger. Having to invent and hand-craft these specifications has been one of the limitations of this research as detailed in Section 7.4.

Availability of descriptions of real-life systems. The research conducted in this thesis required a catalogue of system descriptions of real-life systems, that could be used as a benchmark for testing the mechanisation of BCF in *Circus*. However, the author was not able to find a literature backed catalogue of formal specifications or even system descriptions of real-life systems having a confidentiality requirement. Therefore, such a catalogue has been compiled through a literature search, as part of this research. Many limitations have shaped the catalogue that was compiled eventually. However, if such a comprehensive catalogue was available, results from analysing systems in that catalogue would have contributed towards evaluating the value that the mechanisation can bring to the system engineering discipline. The author believes that the catalogue provided in Chapter 5 can be a starting point for such requirements for a benchmark.

Support for recursion in BCF in *Circus*. Banks (2012, p. 148) discussed a method for deriving an invariant obligation that is required to back propagate a loop body in a recursion. However, he stated that the method cannot be used in all scenarios and therefore sometimes one must resort to intuition to identify the invariant obligation.

> *"We leave the problem of devising more sophisticated techniques for identifying invariant obligations for future work."*
> (Banks, 2012, p. 148)

In some scenarios, the user may identify an invariant obligation. However, Banks does not provide a mechanisable law for these scenarios. Hence, the current version of the CFAT tool is not designed to provide support for back propagating recursion constructs. Section 3.4.3 discusses a scenario where a data leakage may occur through recursion.

Support for parallel processes in BCF in *Circus*. BCF in *Circus* does not have a mechanizable back propagation law for parallel processes that can be used for automating the back propagation of parallel constructs. This is a limitation of BCF in *Circus* as discussed in Section 2.8. Concurrent access to systems is an important aspect of information systems. A comprehensive analysis of confidentiality in a concurrent access system must involve analysing the parallel process blocks in the system specification.

7.3 Benefits derived from the mechanisation

The proposed mechanisation was intended to provide a number of benefits that would enhance the value of BCF in *Circus*. The intended benefits have been discussed in Section 3.1. The following is a discussion on the extent to which these intended benefits have been realized.

Practicality. The evaluation of the proposed mechanisation has shown that the proposed mechanisation is practically applicable. This has been demonstrated by presenting the time taken for analysing a number of hand crafted systems that are based on scenarios supported by literature. Based on the However, the performance of the mechanisation can be improved on many fronts. For example, currently the LaTeX model of the system and the HOL based back propagated predicate needs to be manually submitted to the CZT and the Isabelle theorem prover respectively. This process could be automated to achieve a seamless process for analysing systems using the proposed mechanisation of BCF in *Circus*.

Suitability. Apart from practicality, another intended purpose of the mechanisation of BCF in *Circus* is to show whether systems with different types of confidentiality requirements can be analysed. Two types of confidentiality properties that are supported by BCF in *Circus* has been identified. The suitability of the mechanisation to detect both types of confidentiality requirements supported by BCF in *Circus* has been demonstrated through the use of negative testing (see Section 6.2.11). It must be noted that the testing for suitability carried out in this thesis is not strong as the proposed mechanisation does not support recursion and parallel constructs, due to limitations with BCF in *Circus*. Therefore, in an ideal world, these tests will fall short of reflecting real world scenarios of the consistency of requirements in a system specification. Developing mechanizable laws for recursion and parallel constructs of the *Circus* notation is a further work required.

Efficiency. The comparison between the mechanised versus the manual analysis of a trivial system in Section 3.5.1 has shown that the proposed mechanisation of BCF in *Circus* in this thesis is multifold efficient than the manual approach. While the relative efficiency has been shown for a trivial example, there is no way to conclude whether the derived ratio of the Temporal Efficiency (see Section 3.5.1) will be constant as the size and complexity of the specifications change. The author believes that the discussion on relative efficiency between the manual versus the mechanized analysis approach in Section 3.5 has demonstrated that an efficient approach for analysing systems using BCF in *Circus* has been achieved through the mechanisation.

7.4 Contributions and Limitations

In this section, a discussion of the contributions and some of the limitations of those contributions are presented.

Catalogue of case studies with a confidentiality requirement. The catalogue of case studies with a confidentiality requirement is an original contribution made in this thesis as far as the author is aware of. As an initial catalogue, this provides a good collection of case studies that has been derived through a systematic process. Further, this collection can be used by other researchers to analyse other dimensions in relation to a confidentiality requirement literature. For example, context where security is most sought after. Researchers working on vertical areas of research such as eliciting confidentiality requirements and various formalisms of confidentiality requirement specifications can use scenarios from the case studies in this catalogue to align their research with this existing literature discussing different scenarios with a confidentiality requirement. This is because there is a vacuum of such real-world case studies.

> "*there is a vacuum of real-world case studies and experience reports on how confidentiality requirements are dealt with in practice*"
> (Gurses et al., 2005, p. 102).

The major limitation of the proposed catalogue in this thesis is its derivation process. Because the scenarios were identified by focussing on pages in a paper where a certain keyword was found, prospective descriptions of confidentiality related requirements in other pages of the paper might have been missed, if such a discussion did not contain the keyword 'confidential'. Because of the limited set of relevant papers that were identified, it was necessary to consider discussions where confidentiality was mentioned in a very general way without giving much details about the context except a reference for the system environment, such as 'a banking system', 'an electronic voting system', etc.

Generalized patterns of confidentiality requirements. Generalized patterns of confidentiality requirements is an original contribution as far as the author is aware of. These patterns will greatly help the confidentiality engineering community as the pattern catalogue can be used as a baseline benchmark to address confidentiality properties in the literature. However, while using the catalogue as a benchmark, the user must also be aware that the catalogue could be improved on many grounds. The pattern catalogue can also be useful for comparing different formalisms that can be used to analyse systems with a confidentiality requirement.

Assumptions were made when standardizing some confidentiality requirements described in some papers. Those assumptions were necessary because some of the requirements were not clearly stated in terms of:

- the exact data that needed concealing.
- the user roles that were supposed to be unauthorised, with regards to a particular piece of data in a given context.

Some patterns might be weak because the confidentiality requirements from which those patterns were derived were partially hand-crafted. The author acknowledges this weakness as a limitation. This limitation can only be overcome when systems and their confidentiality requirements, considered as source material for such a catalogue, are specified in a clear and unambiguous manner.

Further, because of the above mentioned limitation, the author anticipates further patterns, should there be a more in-depth literature search exercise for confidentiality properties in systems.

Confidentiality Framework Application Tool. The CFAT tool is an original contribution of this research. A mechanised back propagation apparatus does not exists to the author's knowledge. Banks acknowledges this as an impediment to BCFs deployment (Banks, 2012, p. 187). With the CFAT tool, this has been addressed. The CFAT tool has been developed as part of this research. The biggest advantage of the CFAT tool is that it makes the task of back propagation practically applicable.

The ability to generate a LaTeX based *Circus* specification of a system being analysed is an important feature of the CFAT tool. Engineers can type check and syntax check the generated *Circus* specification to provide a degree of certainty about the validity of specification.

The major limitation hindering the use of the CFAT tool is that the user must be equipped with expertise in using the CFAT notation. One further improvement required is the ability to automatically submit the generated LaTeX based *Circus* specification and the Isabelle theorem file to CZT and Isabelle theorem prover respectively.

Further to the limitations in the contributions that has been made with this thesis, there were other limitations that confined the landscape available for this research. Following are such limitations.

Programming style not scalable. The use of an imperative programming approach to code the back propagation logic used in the proposed mechanisation tool is not scalable. This is one of the shortcomings of the tool proposed in this thesis. A more appropriate approach would have been to use functional programming. However, a functional programming approach was not pursued because the author does not have the relevant background.

Having to hand-craft specifications. Since formal system specifications were not available for the systems modelled in the case studies in this thesis, specifications of those systems had to be hand-crafted. The resulting specifications might not have reflected the real life scenarios in those contexts.

Unable to analyse systems with parallel processes. If BCF in *Circus* supported parallel processes then the mechanisation of BCF in *Circus* could have been extended and used to analyse multi-user parallel processing environments. Such an analysis would have reflected a much closer view about the consistency of the requirements in the system, as many systems designed for use by members of an organisation allow parallel access.

Unable to analyse the recursion construct. BCF in *Circus* does no have a back propagation law for recursion. Because of this, the recursion construct had to be bypassed during the back propagation stage of every analysis carried out in this research. Banks (2012, p. 148) discussed how one may approach to back propagate the recursion construct in *Circus*. However, this discussion is in its early stages and needs further research to produce a mechanizable back propagation law for recursion. As such, this endeavour is not within the scope of this thesis.

The global state promotion dilemma. The technique adopted by BCF for reasoning about confidentiality in systems is to make specifiers define the level of separation between the real and the *twin* system and use the result of the back propagation application on the system specification to prove this separation. A separation for a state variable can be defined if that variable exists in the global state space of the system. This becomes an issue if the engineer wants to protect the value of a particular function application such as $f(x)$ where f is a function in the global state space whereas x is a runtime variable whose value is provided by the user during the execution of the program. Therefore, in order to define the required separation, the value of x must be assigned to a global state variable y and subsequently the formalisation of the confidentiality requirement must use f and y rather than f and x.

7.5 Mechanization vs. manual back propagation

Banks (2012) did not present any analysis on the feasibility of the manual application of BCF. Rather, he did state that:

> "*The lack of any dedicated tool support for our platform is arguably the main impediment to its deployment.*" (Banks, 2012, p. 187)

The benefit of the mechanisation can be visible when the results of a manual back propagation of a system and the mechanised back propagation of the same system are compared side by side. The manual back propagation shown in Section 4.2 is for a system formalized with a *Circus* specification that contains one *input* action, one *assignment* action, one *guarded* action and one *output* action. Manual analysis of that system using BCF in *Circus* takes roughly one hour while the mechanized analysis of the same system takes 120 milliseconds as stated on Section 4.2.

A more promising set of results of a mechanised analysis that includes the time taken for back propagating non-trivial system models is shown in Table 6.18 . For example, the mechanized back propagation of the secure examination system with 71 atomic actions takes an average of 2792 milliseconds or 2.79 seconds.

7.6 A critical analysis of the adopted mechanisation approach

Circus is not ideal as a formalism to adapt for instantiating BCF. The most important issue is that there is no official BNF for the *Circus* notation. Some researchers do include variations of what they say is the BNF of *Circus* such as in the papers by Woodcock and Cavalcanti (2001b, P. 292), Woodcock and Cavalcanti (2002, P. 185), Sampaio et al. (2003, P. 149), Freitas (2005, P. 13), Cavalcanti and Woodcock (2002, P. 149), Oliveira et al. (2006, P. 3) and Oliveira et al. (2009, P. 5). However, unlike the ISO standardisation of the Z notation (ISO/IEC, 2002) there is no single standardisation of the *Circus* notation nor there is a working group that identifies themselves as the caretaker of this formalism.

Another issue with the *Circus* notation is that there are no reliable and stable tool support that can cater for type checking and model checking *Circus* specifications. The only type checking tool available for type checking a *Circus* specification is CZT. However, it does not contain useful error messages, syntax highlighting or navigation capabilities for *Circus* specific constructs in the specification. Ye and Woodcock (2017) has proposed an approach for model checking *Circus* specifications by linking *Circus* to CSP||B[1]. Their approach involves transforming the state part of a *Circus* specification to a B machine while converting the behavioural part to CSP and finally using ProB (Leuschel and Butler, 2003) to model check the resulting CSP||B specification. The problem here is that the limitations in CSP||B confine the type of *Circus* specifications that are supported in this approach. Ye and Woodcock (2017, p. 94) discusses these limitations. Tools such as *CRefine* (Oliveira et al., 2008) and *JCircus* (Barrocas and Oliveira, 2012) have been developed in the past to cater for a specific need of a research conducted in the past. However, to the author's knowledge there is no evidence that either these tools or any other *Circus* tools are actively being developed and maintained in such a away that other researchers can build upon its code-base. Further, research on the *Circus* notation has yet to be taken up by the broader research community rather than being confined to a small cohort of collaborating academics from a limited set universities, as is the case at present.

Isabelle theorem prover is not ideal for simplifying the predicate generated from back propagating a formal specification based on *Circus*. One reason is that mechanical theorem proving used in Isabelle theorem prover requires guidance by an expert. On the contrary, finite-state verification techniques[2] such as model checking can fully be automated.

[1] "CSP||B is a combination of CSP and B aiming to introduce behavioural specification into state-based B machines. The B method characterises abstract state, operations with respect to their enabling conditions and their effect on the abstract state, while CSP specifies overall system behaviour. But different from *Circus*, the CSP specification and B machine in CSP||B are always orthogonal.They are individually complete specifications and can be checked separately" (Ye and Woodcock, 2017, p. 76).

[2] "Finite-state verification refers to a set of techniques for proving properties of finite-state models of computer systems" (Dwyer et al., 1998, p. 7).

> *"In contrast to mechanical theorem proving, which often requires guidance by an expert, most finite-state verification techniques can be fully automated, thus relieving the user of the need to understand the inner workings of the verification process"* (Dwyer et al., 1998, p. 7).

When compared to theorem proving, the advantages of model checking include full automation and the ability to generate counter examples that help in debugging (Ye and Woodcock, 2017, p. 73). However, a proof based approach excels in certain aspects such as being able to handle very complex systems because it does not have to directly check every state and also because its logics are typically more expressive (Amjad, 2004, p. 16). The ideal scenario would be to use a platform that has an efficient combination of model checking and theorem proving. Such combinations have been proposed in the past researchers such as Arkoudas et al. (2004), Amjad (2004), Aagaard et al. (1999), Bjørner et al. (1997), Dingel and Filkorn (1995), Shankar (1996), McMillan (1999) and Rajan et al. (1995).

Generating and submitting the back propagated predicate in a format that is supported by such a combined platform will be a valuable further improvement for the mechanisation approach proposed in this thesis.

The CZT platform was considered for building custom extensions on top of it, to support the mechanisation of the calculations required by BCF in *Circus* and subsequently for code genration. However, the architecture and inner workings of the CZT editor was very complex that demand a steep learning curve before the CZT editor could be extended. Kimber (2007) considered the CZT editor as an input interface which he planned to extend for code generation to produce *PerfectDeveloper* (Crocker, 2003) code from Object-Z specifications. However, after reviewing the CZT editor, Kimber (2007) concluded that the DTDs and schemas of CZT projects were quite impenetrable.

HiVe Mathematical Tool-kit is not ideal for the purpose of the mechanisation proposed in this thesis. This is because the theory package does not provide a set of tactics which can be used in dispatching automatic proofs for theories.

7.7 Critical factors that would have altered the direction of this research

The following are some critical factors that would have altered the direction of this research, if they were available at the beginning of this research.

Knowledge of Isabelle/Isar and Standard ML. If the author had been well versed with Isabelle/Isar[3] and standard ML (Wenzel, 2013, p. i) then the author could have embedded *Circus* and the *block* structure (Banks, 2012, p. 102) of BCF in *Circus* inside the Isabelle theorem prover, like HOL-Z (Brucker et al., 2003), Z and HOL (Bowen and Gordon, 1994), CML (Woodcock and Miyazawa, 2012) or Isabelle/*Circus* (Feliachi et al., 2012). Further, using ML, the author could have mechanised the back propagation logic and subsequently simplify the predicate within the Isabelle theorem prover.

Detailed developer guide for CZT. If there was a clear documentation regarding the architecture of CZT and how one may extended it, the author could have extended CZT to generate the theorem file from the standard LaTeX format supported by the CZT tool. In this scenario, the user could have specified the system using the *Circus* notation rather than having to get expertise in using the CFAT notation which is required in the current mechanisation proposed in this thesis. The author attempted to extend CZT during the course of this research. However, similar to Kimber (2007), the author found it impenetrable within the time frame of this research.

> *"Indeed, the DTDs and schemas downloaded from existing projects such as CZT were quite impenetrable."* (Kimber, 2007, p. 59)

[3] Isabelle/Isar provides an interpreted language support for interactive theorem proving in the Isabelle theorem prover whereas the host language of the Isabelle theorem prover is standard ML (Wenzel, 2013, p. i).

7.8 Further work

The contributions made in this thesis has enabled many interesting directions of further research that could be explored in future.

Comparative analysis of BCF in *Circus*. The proposed mechanisation in this thesis and other similar mechanisations proposed in the literature, for analysing systems with a confidentiality requirement, can be compared side by side on the basis of analysis time and competence required. Such as exercise may reveal the comparative strengths and weaknesses of the compared approaches. BCF in *Circus* supports certain sub classes of confidentiality properties as stated in Section 5.3. Therefore, it is important to confine this comparative analysis to systems with properties that are supported by all compared approaches.

Extension of the mechanisation of BCF in *Circus* to support additional constructs. If further research on BCF in *Circus* results in the introduction of support for data leakage analysis of parallel processes, then such extensions can easily be adapted in the mechanisation proposed in this thesis. Further, results of such an analysis will more closely reflect the information flows in a real life execution of a system with parallel processes rather than an exercise that cannot analyse a system with parallel processes.

Embedding in Higher Order Logic (HOL). An on-going work (Zeyda et al., 2017) at the University of York is concerned with embedding *Circus* in Isabelle/UTP. This work further involves translating *Circus* notations into corresponding operators within this embedding. The confidentiality framework can be mechanized as an Isabelle/HOL theory by extending this embedding, so that *Circus* models with a confidentiality requirement can be directly written in the Isabelle theorem prover similar to HOL-Z and Isabelle/*Circus*. Tactics can be developed to facilitate the simplification of these system models.

Prototyping for black-box testing. *Circus* formal models may be translated to executable OCAML programs for rapid prototyping. These prototypes may be used by security experts to conduct data secrecy tests.

BCF and Event-B. BCF can be adopted for the Event-B notation provided that there is a UTP semantics for the notation. The back propagation laws of BCF can then be mechanized by extending the RODIN tool. The RODIN tool already has support for modelling and refinement of Event-B specifications. This effort may result in a more integrated tool that supports confidentiality verification.

Improving the efficiency and effectiveness of the mechanisation. The proposed mechanisation can be improved on many grounds so that engineers can save time when using the mechanisation. Some potential areas of the mechanisation that can be improved to achieve a better efficient and effective performance from the tool include:

- Building support in the CFAT tool for a Controlled Natural Language (CNL) as detailed in page 275-276. CNL can lower the barrier of entry for the CFAT tool by allowing users to specify systems using a natural language rather than having to use a structured notation.
- Automating the submission of the back propagated predicate to the Isabelle theorem prover. This can be possible through the use of command line tools of the Isabelle theorem prover.
- Automating the validation of the generated LaTeX specification using CZT. This can be possible through the use of command line tools of CZT.
- Develop tactics in the Isabelle theorem prover for improving the automation of the simplification. Most probably, this will be an extension to the HiVe mathematical toolkit.

Techniques to improve the identification of data leakage risks. The process followed in this thesis, for analysing systems with a confidentiality requirement, can be strengthened by improving the confidentiality requirement elicitation stage of the process. The current approach involves formalizing the given confidentiality requirement and including it as part of the formal specification of the system. However, if the system requirements could be analysed using techniques for identifying security requirements from business goals, it can only help to improve the set of security requirements of the system. The following are some useful techniques in this domain that future researchers can utilize.

Abuse cases Abuse cases utilizes use case models to model complete interactions between a systems and one or more actors (McDermott and Fox, 1999). In comparison to normal use cases, the result of the interaction in an abuse case is harmful to one of the actors or stakeholders of the system.

> "*In a requirements phase, abuse case models can be used to increase both user and customer understanding of the security features of a proposed product*."
> (McDermott and Fox, 1999, p. 63)

Misuse cases Sindre and Opdahl (2005) introduced *misuse cases*, which are inverted use cases that describe functions that the system should not allow. Use cases and *misuse cases* are included in the same diagram of the system model, rather than being on different diagrams like use cases and *Abuse cases*. *Misuse-case* diagrams link regular use cases to both threats and potential countermeasures which aids in prioritization of requirements since the real cost of implementing a use case includes the protection needed to mitigate all serious threats to it (Sindre and Opdahl, 2005, p. 41).

Deviational techniques A security analysis using deviational techniques such as HAZOP (Kletz, 1999) on use cases may identify security requirements which otherwise might have slip through unnoticed. Srivatanakul (2005) demonstrated that deviational techniques can be used on use cases in UML to identify security requirements.

Anti-goals Another technique for identifying security requirements is through the use of anti-models. An anti-model includes anti-goals, which are attackers own goals that are intentional obstacles to security goals, set up by the attackers to threaten security goals (Elahi et al., 2010, p. 21). Lamsweerde (2004) extended KAOS, a goal-oriented security requirements engineering methodology to capture anti-goals and other obstacles that capture exceptional behaviour.

Tool-supported automation of translations. From the initial business goals to the formal specification of confidentiality integrated systems, there are many stages where there are requirements for syntactic translations of requirements between stages. Figure 7.1 shows some of these stages with a T. Further work on automating the translation at each stage is recommended to introduce a systematic process for each translation. One such technique for enabling such translations is to use a Controlled Natural Language (CNL) for describing systems. A small introduction to CNL is given on page 275 - 276.

Controlled Natural Language (CNL)

Two important issues that one must address when writing a system requirement specification for an information system are that:

- the organisational structure and rules that are to be incorporated into the information system must be described in a language that can be understood by all stakeholders.
- the specification should be unambiguous so that traceability can be established between the system requirement specification and its eventual implementation.

Unambiguity is also required in a system requirement specification in order to avoid inconsistencies between stakeholders as well as in order to formally reason about system models. One way to ensure unambiguity in a system requirement specification is to use a Controlled Natural Language (CNL) (Schwitter, 2010).

A CNL is a subset of a natural language where the grammar and vocabulary are restricted in a systematic way to reduce the ambiguity and complexity found in a full natural language (Schwitter, 2010, p. 1113). Some CNLs include *INCOSE* (Condamines and Warnier, 2014, p. 36), *Attempto Controlled English (ACE)* (Fuchs et al., 2008) and *Computer-Processable Language (CPL)* (Clark et al., 2005).

RuleCNL by Feuto Njonko et al. (2014) is a domain independent CNL that systematically embeds domain facts and terms in grammatically correct sentences. In an organisational setting these domain fact and terms can be synonymous with organisational rules and structure.

Controlled Natural Language (CNL) (*continued*)

> *"An ontology models a part of the world. Such a model can be used by humans and computers in order to establish a common 'understanding' of relevant concepts and the relations between them."*
> (Schumacher, 2001, p. 32)

A future area of work can be to work on a CNL that adopts the concept of embedding organisational rules and structures similar to RuleCNL. This CNL can be designed to provide a set of necessary patterns that can be used to describe a simple system in such a way that the system description can be systematically translated into a *Circus* specification. Table 7.1 shows the mapping between some components of a system requirement specification and a *Circus* specification. A set of rules can be proposed that can be used to describe the organisational structure, rules and regulations using natural language. Subsequently, a mapping for translating compliant sentences to the *Circus* notation can be provided.

System requirement specification	Structures of the *Circus* notation
Organisational structure	data types, data objects, global constants
Organisational rules and regulations	state invariants
Operations performed in the organisation	actions
Who can perform the functions	channelsets (representing user roles)
Which staff are included in each user role	state invariants that define elements of sets

Table 7.1: Mapping a system requirement specification to structures in a *Circus* specification

Controlled Natural Language (CNL) (*continued*)

A comprehensive set of sentence patterns are not required for using a CNL, but rather a minimal set of patterns that can be used to derive unambiguous and grammatically correct sentences to describe the structure, rules and regulations of an organisation is enough as a start. Nonetheless, the grammar can be extended later to support a richer set of patterns of sentences in order to describe other identified components of a system requirement specification as listed in Table 7.1.

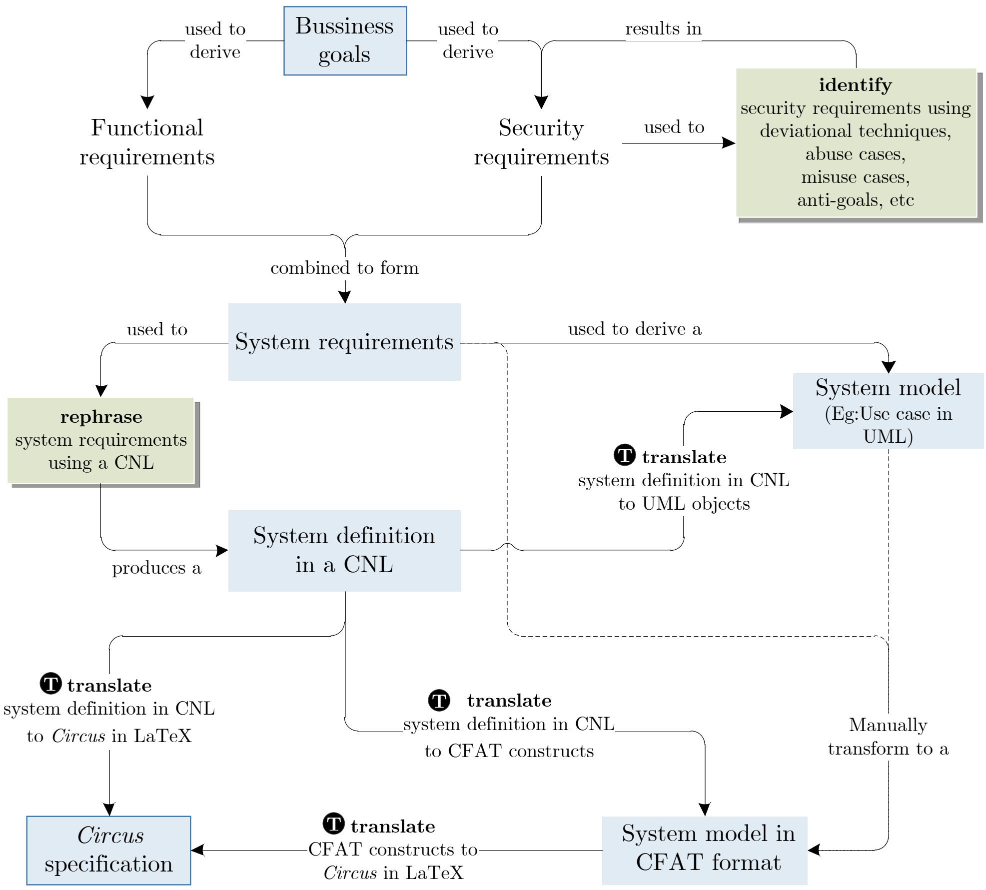


Figure 7.1: Some possible stages and paths that can be taken when moving from business goals to *Circus* specifications

A Appendix

A.1 Modelling a system using the *Circus* notation

One way to model a system using the *Circus* notation, is to model the individual components of the system and then combine them into a single system definition called a *Circus* specification. The specifications of individual components are called *Circus* paragraphs[1]. A *Circus* specification may contain zero, one or many *Circus* paragraphs. This section describes how the *Circus* notation has been used to formally model the range of systems discussed in this thesis.

The application of the *Circus* constructs, discussed in this section, are illustrated using the specification of an Online expenditure tracker system (see Figure A.1). The components of this specification are explained one-by-one, as we progress through the following sub-sections. In summary, this system allows an on-line customer to purchase items. Money spent on every purchase is tallied with his/her previous purchases. The system also allows a customer to check his/her total expenditure.

A.1.1 Defining the data types and state variables

A.1.1.a Data types

In this thesis, systems are modelled as abstract formal specifications. Significant examples of system scenarios are taken from the literature. The data structures of these systems are modelled as abstract sets of elements or relations and functions.

[1] A *Circus* paragraph is a syntactic structure of the *Circus* specification language (Sampaio et al., 2003).

Basic types In the *Circus* notation, an abstract data type can be defined by providing the name of the type enclosed in a pair of square brackets. Such type definitions are called *basic types* (Spivey, 1989, p. 47). Similarly, multiple types can be defined by providing a comma separated sequence of type names.

e.g. $[CUSTOMER, ITEM]$

In the example, the *basic types* $CUSTOMER$ and $ITEM$ are defined using the statement $[CUSTOMER, ITEM]$. The *basic type* $CUSTOMER$ represents the set of all the customer identifiers and the *basic type* $ITEM$ represents the set of all the item identifiers used in the system.

Free types A type with a finite number of elements can be defined in *Circus* using the *free type* construct. A free type can be used to define a set of distinct constants (Spivey, 1989, p. 82).

e.g. $Status ::= InUse \mid NotInUse$

The statement $Status ::= InUse \mid NotInUse$ defines the *free type* (Spivey, 1989) $Status$ to be a set containing exactly two distinct elements that represent two values. The *free type* definitions in this thesis use simple free types. More complex *free types* can be defined as show in (Spivey, 1989, p. 82).

A.1.1.b State variables and invariants

State variables are variables that are declared in the global scope of the system. For example, the data structures *spent*, *price* and *currentCustomer* need to be accessible throughout the scope of the process *Online_expenditure_tracker* (see Figure A.1) and so they are defined as state variables. The description of the state variables in the specification are included in the Table A.1.

Table A.1: Online expenditure tracker - Description of the state variables

State variable	Description
spent	A function that identifies the amount spent by a customer, if any.
price	A function that identifies the price of an item, if any.
currentCustomer	The user who is currently logged into the system.

The system enforces constraints encoded as state invariants on the values that can be assumed by the state variables. These constraints encode the policies of the parent organisation. The description of these state invariants are included in Table A.2.

Table A.2: Online expenditure tracker - Description of the state invariants

State invariants	Description
$currentCustomer \in (\mathrm{dom}\ (spent))$	The current user who is logged into the system must have a spent value recorded in the system.

$[\, CUSTOMER, ITEM \,]$

State

$$\begin{array}{|l}
spent : CUSTOMER \pfun \mathbb{N} \\
currentCustomer : CUSTOMER \\
price : ITEM \pfun \mathbb{N} \\
\hline
currentCustomer \in (\mathrm{dom}\,(spent))
\end{array}$$

channel $mySpentAmountOut : \mathbb{N}$
channel $buyItemIn : ITEM$

channelset $Customer == \{\!| buyItemIn, mySpentAmountOut |\!\}$

process $Online\_expenditure\_tracker \mathrel{\widehat=}$ **begin**

state *State*

$$\begin{array}{lcl}
RecordMyReciept & \mathrel{\widehat=} & \mathbf{var}\ buyItem : ITEM \bullet \\
& & \quad buyItemIn?buyItem \longrightarrow \\
& & \qquad ((buyItem? \in \mathrm{dom}\,(price)) \,\&\, \\
& & \qquad\quad spent := spent \oplus \{(currentCustomer \mapsto \\
& & \qquad\qquad (spent\ currentCustomer + price\ buyItem?))\}) \\
\\
GetMySpent & \mathrel{\widehat=} & mySpentAmountOut\,!(spent\ currentCustomer) \longrightarrow \mathbf{Skip}
\end{array}$$

$$\bullet\ \mu X \bullet \left(\left(\begin{array}{l} \quad RecordMyReciept \\ \Box\ GetMySpent \end{array} \right) ;\ X \right)$$

end

Figure A.1: Specification of Online expenditure tracker - *code block 1 of 1*

A.1.2 Establishing the communication channels

The system must have communication channels so that the customer can interact with the system, by way of inputs and outputs.

Channels A channel can be declared by using the syntax **channel** $x^+ : T$, where **channel** is a keyword, x^+ denotes a single or a comma separated sequence of channel names and T denotes the type of data that can be communicated through the channels. If a *Circus* channel is declared with this syntax, it can be used by the system for communicating with the environment by way of inputs and outputs. For example, the statement;

$$\textbf{channel}\ \ itin : ITEM$$

in the running example defines a channel called *itin* with the data type *ITEM* to input item identifiers. It is important to note here that channels are strongly typed in *Circus*, and hence a channel will restrict the data it communicates based on its data type[2].

In a system environment, confidentiality requirements may be enforced on all users or various requirements may be enforced on various sub-groups of users. BCF (see Section 2.3) provides constructs to enforce confidentiality requirements on a defined sets of channels. In this regard, a confidentiality requirement may be enforced on a user by enforcing the confidentiality requirement on the set of channels through which the user communicates with the system.

Channel sets A set of channels with a given name is called a channelset. A channelset is defined using the notation **channelset** $::= \{\!| \ x^+ \ |\!\}$, where **channelset** is a keyword and x^+ denotes a single or a comma separated sequence of channel names. For example, the statement;

$$\textbf{channelset}\ \ Customer == \{\!|\ buyItemIn, mySpentAmountOut\ |\!\}$$

[2] A channel can also be defined without a data type. Such channels are called synchronisation points and they do not communicate any value (Freitas, 2005).

in the running example defines a channelset called *Customer* that represents the set of channels allowed to a customer of the system.

A.1.3 Defining the system operations

The term 'action', in the *Circus* terminology refers to any operation of a system and hence, from now on this term will be used to refer to system operations accordingly. Here, we define the syntax of the common actions used in the *Circus* specifications discussed in this thesis.

Primitive actions. The action **Skip** terminates immediately and does not make any changes to the system state (Oliveira et al., 2009, p. 7).

Declaring a variable. A variable can be declared using the statement $\mathbf{var}\ v^+ : T$ where v^+ denotes a single or a comma separated sequence of variable names and T denotes the datatype of v that represents the values that v can assume.

The statement $\mathbf{var}\ n : \mathbb{N};\ c : CUSTOMER$ declares the variable n that can store data of type $\mathbb{N}$ and the variable c that can store data of type $CUSTOMER$.

Input and output events. A prefixed action is defined to achieve input or output communications whereby the communication event defined in the prefix takes place before the action starts. A prefixed action is defined using the format $Comm \longrightarrow A$ as found in the BNF in Figure A.2 where $Comm$ is a communication event and A is a *Circus* action.

Inputting a value
A prefixed action for input is written $c?x \longrightarrow A$, whereby the system accepts a value to the variable x through the channel c and then behaves like A and x is in the scope of A (Oliveira, 2005).

Outputting a value
A prefixed action for output is written $c!y \longrightarrow A$ whereby the system outputs the value of the expression y through the channel c and then behaves like A.

Assigning a value to a variable. A value can be assigned to a variable using the action statement $a := E$ where a is a variable defined in the scope of the assignment action and E is an expression that evaluates to a value of the same type as the state variable a.

A.1.4 Defining the overall behaviour of the system

In the *Circus* notation, a system may be defined with one or more processes. Each process may contain one or more actions and a main action. However, all the systems analysed in this thesis are based on systems composed of multiple actions within a single process. This is because our work uses BCF in *Circus* (Banks, 2012) where the verification laws developed so far have been restricted to single processes.

A *Circus* specification supports multiple actions through action composition using the CSP operators in the *Circus* BNF in Figure A.2. The following constructs are utilized in this thesis for process composition.

Recursion. The recursion construct $\mu X \bullet A\,;\; X$ recursively executes the action A where X is a recursion label defined using the construct μX. We may define multiple recursions in a single main action.

Sequential composition. The construct $A\,;\; B$ defines a sequential composition of two actions whereby '$;$' is the sequential composition operator and the execution of the action A is immediately followed by the execution of the action B.

In the example the statement $(RecordMyReciept \mathbin{\Box} GetMySpent)\,;\; X$ defines a sequential composition where the composite action $(RecordMyReciept \mathbin{\Box} GetMySpent)$ is immediately followed by X, a recursive invocation of the process starting at the label X.

$$
\begin{array}{lll}
\mathsf{Program} & ::= & \mathsf{CircusPar}^{*} \\
\mathsf{CircusPar} & ::= & \mathsf{ZParagraph} \mid \mathsf{ChanDecl} \mid \mathsf{CSetDecl} \mid \mathsf{ProcDecl} \\
\mathsf{ChanDecl} & ::= & \mathbf{channel}\ \mathsf{CDecl} \\
\mathsf{SeqCDecl} & ::= & \mathsf{CDecl} \mid \mathsf{SeqCDecl}\ ;\ \mathsf{CDecl} \\
\mathsf{CDecl} & ::= & \mathsf{N}^{+} \mid \mathsf{N}^{+} : \mathsf{ZExpr} \\
\mathsf{CSDecl} & ::= & \mathbf{channelset}\ \mathsf{N} == \mathsf{CSExpr} \\
\mathsf{CSExpr} & ::= & \{\!|\ |\!\} \mid \{\!|\ \mathsf{N}^{+}\ |\!\} \mid \mathsf{N} \mid \mathsf{CSExpr} \setminus \mathsf{CSExpr} \\
 & \mid & \mathsf{CSExpr} \cup \mathsf{CSExpr} \mid \mathsf{CSExpr} \cap \mathsf{CSExpr} \\
\mathsf{PDecl} & ::= & \mathbf{process}\ \mathsf{N} \mathrel{\widehat=} \mathsf{ProcDef} \\
\mathsf{PDef} & ::= & \mathbf{begin}\ \mathsf{PPar}^{*}\ \mathbf{state}\ \mathsf{Schema\text{-}Expr}\ \mathsf{PPar}^{*} \bullet \mathsf{Act}\ \mathbf{end} \\
\mathsf{PPar} & ::= & \mathsf{Zparagraph} \mid \mathsf{N} \mathrel{\widehat=} \mathsf{Act} \mid \mathsf{NameSetDecl} \\
\mathsf{Act} & ::= & \mathsf{Schema\text{-}Expr} \mid \mathsf{CSPAct} \\
\mathsf{CSPAct} & ::= & \mathsf{Skip} \mid \mathsf{Stop} \mid \mathsf{Chaos} \mid \mathsf{Comm} \rightarrow \mathsf{Act} \mid \mathsf{Cmd} \mid \mathsf{ZPred}\ \&\ \mathsf{Act} \\
 & \mid & \mathsf{N} \mid \mu \mathsf{N} \bullet \mathsf{Act} \mid \mathsf{Act}\ ;\ \mathsf{Act} \mid \mathsf{Act} \sqcap \mathsf{Act} \mid \mathsf{Act} \Box \mathsf{Act} \\
 & \mid & \mathsf{Act} \parallel\![\ \mathsf{NSExpr} \mid \mathsf{CSExpr} \mid \mathsf{NSExpr}\ ]\!\parallel \mathsf{Act} \mid \mathsf{Act} \setminus \mathsf{CSExpr} \\
 & \mid & \mathrel{|||} \mathsf{ZDecl} \bullet \mathsf{Act} \\
\mathsf{Cmd} & ::= & \mathbf{var}\ \mathsf{x} : \mathsf{ZExpr} \bullet \mathsf{Act} \mid \mathsf{N}^{+} := \mathsf{ZExpr} \\
\mathsf{Comm} & ::= & \mathsf{N}\ \mathsf{CParam}^{*} \\
\mathsf{CParam} & ::= & ?\mathsf{N} \mid ?\mathsf{N} : \mathsf{ZPred} \mid !\ \mathsf{ZExpr} \mid .\mathsf{ZExpr} \\
\mathsf{NSDecl} & ::= & \mathbf{nameset}\ \mathsf{N} == \mathsf{NSExpr} \\
\mathsf{NSExpr} & ::= & \{\} \mid \{\ \mathsf{N}^{+}\ \} \mid \mathsf{N} \mid \mathsf{NSExpr} \setminus \mathsf{NSExpr} \\
 & \mid & \mathsf{NSExpr} \cup \mathsf{NSExpr} \mid \mathsf{NSExpr} \cap \mathsf{NSExpr}
\end{array}
$$

Figure A.2: *Circus* BNF as published in Freitas (2005) doctoral thesis

NOTE : Pages 31 to 35 of the ISO standard for the Z notation (ISO/IEC, 2002) contains the complete BNF of the Z notation.

External choice. The logged in user is allowed to either increment his expenditure total by recording a new receipt in the system or view his/her total expenditure recorded in the system.

$$RecordMyReciept \Box GetMySpent$$

These are multiple execution paths which the user can choose from. The external choice operator $\Box$ can be used to define a composite action with multiple execution paths where the selected path depends on the external input.

Main action. The overall behaviour of a *Circus* process is defined by defining a nameless action within the process scope. The overall behaviour of the system in the running example is defined using the following *Circus* action.

$$\bullet\ \mu X \bullet \left(\left(\begin{array}{ll} & \mathit{RecordMyReciept} \\ \Box & \mathit{GetMySpent} \end{array} \right) ;\ X \right)$$

An implementation of the system specification in Figure A.1 will behave as follows. In the beginning state of the system, it is assumed that the state variables *price* and *spent* have already been populated with the necessary data. While in this state, the *Circus* action *RecordMyReciept* or *GetMySpent* can be chosen by the environment. At the end of the run, the recursive label X locates the program counter to the state at the beginning of the program where the label X is defined.

A.1.5 Recursion

The recursion construct in the *Circus* notation is of the form $\mu X \bullet F(X)$. To left justify the lifted body $\langle F(X) \rangle$ with respect to the confidentiality annotation θ, we have to identify an invariant obligation θ_i where $\theta \sqsubseteq \theta_i$ (Banks, 2012, p. 148). Consider the original confidentiality annotation θ as θ_0. The following calculation is used to identify a θ_n such that $\theta_n = \theta_{n+1}$.

$$\theta_{i+1} \quad = \quad \theta_i \wedge \mathbf{bw}(\langle F(X) \rangle, \theta_i)$$

Banks's argues that this method is not guaranteed to identify a finite n such that $\theta_n = \theta_{n+1}$ (Banks, 2012, p. 148) in the general case. He further states that, in this case one may resort to intuition by analysing patterns of obligations to derive an invariant obligation.

The calculation of the invariant obligation needs further research to derive any useful laws that can be used for back propagation calculations and as such this endeavour is not within the scope of this thesis. For this reason, we do not calculate invariant obligations when back propagating the systems in the case studies in this thesis. I note that omitting the calculation of the invariant obligation is a limitation of the case study analysis done in this thesis.

A.2 A comparison of the tools that provide any form of support for specifying systems in the *Circus* notation

Tool support for the *Circus* notation is limited. To the author's knowledge, the only tools that provide any form of support for specifying systems in the *Circus* notation are Symphony IDE supporting COMPASS Modelling Language (CML), CZT and *CRefine*. The following describes the extent to which each tool supports specifying systems in the *Circus* notation and the effort required to modify the tool to support an extension to the *Circus* notation.

Symphony IDE supporting COMPASS Modelling Language (CML). Symphony IDE supports the domain specific language CML that is designed for modelling and analysing systems of systems (Woodcock and Miyazawa, 2012). CML is based on VDM (Gulati and Singh, 2012), CSP (Hoare, 1980) and *Circus* (Oliveira et al., 2006). Symphony IDE (Coleman et al., 2014) is a tool that utilizes CML models to generate Isabelle theorem files to reason about certain properties of those models. Hence, CML, Symphony IDE and the Isabelle theorem prover provide a clear path from formal models based on *Circus* to Isabelle theorem prover, where we can reason about various properties of those models. However, the generated theorem files are based on the Isabelle/UTP framework (Woodcock et al., 2015). The foundation of the Isabelle/UTP framework is based on a custom definition for the UTP variable and a value model that complements the typing requirements for those variables. In order to extend the Isabelle/UTP to support the extended *twin* semantics of BCF we need to code a new definition for every

UTP notation and function of the theory of designs in the Isabelle/UTP. Therefore, CML is not a viable alternative for the purpose of extending it to support BCF.

Symphony IDE generates Isabelle theorem files based on CML system models to reason about certain properties of these models. The theorem files are based on a theory package that needs extensive extension from the ground up if twin semantics was to be supported.

Community Z Tools (CZT). CZT (Malik and Utting, 2005) supports the parsing of *Circus* specifications. However, the architecture and inner workings of the CZT editor is very complex that demand a steep learning curve before the CZT editor could be extended to support reasoning about confidentiality requirements in a given *Circus* specification. Kimber (2007) considered the CZT editor as an input interface which he planned to extend for code generation to produce *PerfectDeveloper* (Crocker, 2003) code from Object-Z specifications. However, after reviewing the CZT editor, Kimber (2007) concluded that the DTDs and schemas of CZT projects were quite impenetrable.

CRefine. *CRefine* (Oliveira et al., 2008) is a tool that supports the use of *Circus* refinement calculus (Sampaio et al., 2003). It has an inbuilt proof obligation manager, that automatically dispatch proofs for some of its refinement steps (Oliveira et al., 2008). However, since *CRefine* extends CZT (Gurgel et al., 2008), it suffers from the same architectural complexities.

A.3 Decisions regarding the development of a custom tool for BCF application

For design decisions regarding the development of a BCF application and code generation tool, it is best to learn how the past researchers have approached it. *CRefine*, *Symphony IDE* and *Perfect Developer* (Crocker, 2003) are some of the tools that have been developed in the past for the formal specification and verification of systems. *Perfect Developer* (Crocker, 2003) is a tool that allows a user to define and later refine a formal specification to object oriented code. In addition, it generates "proof obligations" from pre-conditions, invariants, etc to verify the correctness of the system model being defined (Kimber, 2007). These three tools allow the formal specification systems and dispatch proofs about certain properties of those systems. *CRefine* and *Symphony IDE* both support *Circus* or a close variant of it. Our requirements for a formal tool for reasoning about confidentiality, also share these characteristics.

Even-though *CRefine* accepts a LaTeX document, it has support for a unicode (on-screen pretty printing) display format because the author's of the *CRefine* tool believe that its target audience is mostly not familiar with LaTeX and also that "*pretty printing is a success among researchers, since it unconditionally makes the presentation of the development more user friendly*" (Oliveira et al., 2008). *Perfect developer* adopts a non-LaTeX notation similar to any object oriented language, to make it more "*accessible for software developers with limited mathematical knowledge*". CML is also a non-LaTeX notation.

A.4 Translating CFAT notation to HOL

The following subsections describe how the some CFAT structures that represent Z data structures are translated into equivalent HOL data structures in the Isabelle theorem prover. The following presents a discussion of how the the data structures of CFAT notation is translated to similar HOL data structures.

Variable definition. Z is a strongly typed language and hence a variable declaration in Z implies that the universal set that contains all elements for that type (Kolyang et al., 1996) restricts the possible values of that variable. This implication is the type invariant for that type. For, e.g., The Z statement *user* : *EMPLOYEE*;

- defines a state variable "*user*" with an arbitrary type *EMPLOYEE* (**type definition**), but it also
- implies that "*user*" belongs to an arbitrary set *EMPLOYEE* of the same type (**type invariant**).

However, in HOL notation, the type definition and the type invariant must be stated separately. To standardize the translation from Z to HOL and also for ease of readability, the convention we have adopted is that we write;

- the lowercase of the given Z type name *EMPLOYEE*, as the equivalent arbitrary type name in HOL (type *EMPLOYEE* in Z written as type employee in HOL)
- the given type *EMPLOYEE* (also the assumed arbitrary set) in Z as name of the universal set representing the given type in HOL (arbitrary set *EMPLOYEE* is Z written as arbitrary set EMPLOYEE in HOL)

For example, Equation (A.1) defines a variable in the Z notation where the variable name is *user* and its type is *EMPLOYEE*.

$$user \ : \ EMPLOYEE \tag{A.1}$$

The variable definition in Equation (A.1) can be written in equivalent HOL term as in Equation (A.2).

$$\forall\, (\texttt{user::employee})\,.\, \texttt{user} \in \texttt{EMPLOYEE} \tag{A.2}$$

where *employee* is an arbitrary type, *user* is universally quantified and *EMPLOYEE* is a set of the same type *employee*.

Each basic type defined in the Z notation is considered to be synonymous with a universal set of labels that represent that type. Hence, we translate every basic type defined in the Z notation as the Isabelle theorem prover type *string*, that represent a set of strings. In the Isabelle theorem prover, we defined this type synonym with the statement;

```
type_synonym employee = string
```

Subsequently, we define the arbitrary sets of basic types as sets of strings as shown below.

```
definition EMPLOYEE  ::  "string set "
    where "EMPLOYEE  ==  v. ∃ (s::string) .  v = s"
```

Relations and functions. A relation is a set of cartesian products of some given types. Throughout this thesis, we restrict ourself to binary relations which are relations between two given types. In Z notation, a relation is enforced between two types via the use of the infix operator $\leftrightarrow$. Given two types *DOCTOR* and *PATIENT* , Equation (A.3) defines a relation between the two.

$$GP : DOCTOR \leftrightarrow PATIENT \tag{A.3}$$

Equation (A.3) can be read as: *the relation GP relates doctors to patients* . The HOL notation equivalent for the Equation (A.3) is shown as Equation (A.4).

$$\forall\, (\texttt{GP::doctor <=> patient})\,.\, \texttt{GP} \in (\texttt{DOCTOR <-> PATIENT}) \tag{A.4}$$

Here, *doctor* and *patient* are two type variables representing types of the elements in the two universal sets *DOCTOR* and *PATIENT* defined by the two given types and <=> is the type constructor for the "relation type" in the Mathematical tool-kit. The invariant $GP \in (DOCTOR$ <-> $PATIENT$) defines the valid elements that belong to the set of the cartesian products of the relation *GP*. The set of elements *DOCTOR* and *PATIENT* of the arbitrary types *doctor* and *patient* are defined as follows.

```
definition DOCTOR  ::  "string set "                    (A.5)
    where "DOCTOR  ==  v.∃ (s::string) .  v = s"        (A.6)
```

Set definition for basic type DOCTOR

```
definition PATIENT  ::  "string set "                   (A.7)
    where "PATIENT  ==  v.∃ (s::string) .  v = s"       (A.8)
```

Set definition for basic type PATIENT

Functions are special types of relations. The toolkit by Bowen and Gordon (1994) defines functions that restrict the subset of relations that are healthy with respect to various function definitions. Appendix A.4 presents operators in the toolkit that are defined for functions over relations and components of those relations.

Function type	Z infix notation	HiVe notation
Binary relation	$\leftrightarrow$	`<->`
Partial function	$\nrightarrow$	`-|->`
Total function	$\rightarrow$	`->`
Function application		`%^`
Cartesian product	$\times$	`><`
Maplet	$\mapsto$	`|->`

Table A.3: Operators in HiVe for the Z mathematical constructs

Following are the function definitions for partial and total functions.

$$X \nrightarrow Y == \{f\ .\ f : (S \leftrightarrow R) \wedge (\forall\ x\ y1\ y2.\ (x, y1) : f \wedge (x, y2) : f \Rightarrow (y1 = y2))\}$$
$$X \rightarrow Y == \{s.s : S \nrightarrow R \wedge dom\ s = S\}$$

In a system where only some doctors are assigned patients, a partial relation exists between the doctors and the patients. In such a case, the relation *GP* can be defined as;

$$GP : DOCTOR \nrightarrow PATIENT$$

whereas the HOL equivalent definition is,

$\forall$ (`GP::doctor <=> patient`) . `GP` $\in$ (`DOCTOR -|-> PATIENT`)

A.5 Description and formal specification of systems

A.5.1 Case study - Phone book system

A hand-crafted documentation with a formal specification of the Phone book system of a secret government agency is presented. A *Circus* action is defined for each use case in the use case diagram of the Phone book system shown in Figure A.3. The operations performed by these actions are described in Table A.5. It is important to note that the action *Init* in Table A.5 is not in Figure A.3. This is because *Init* initializes system variables and is not executed through external action. The following table of contents may be useful for easy navigation within this case study.

A.5.1.a Operations

The operations of the system are formalized as *Circus* actions and described in Table A.5.

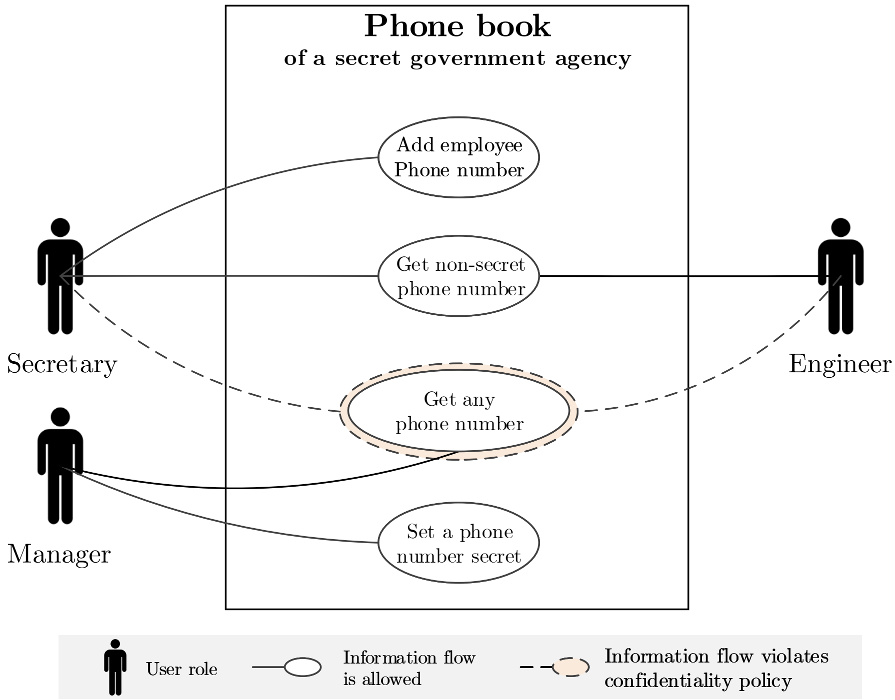


Figure A.3: Use case diagram for the Phone book system

Table A.5: Phone book system - Description of the *Circus* actions

Action	Operation performed by the action
AddPhoneNumber	Adds a phone number to the phone book.
SetSecretPhoneNumber	Adds an official into the list of high ranking officials whose phone numbers should never be revealed.
GetPhoneNumberNoSecret	Outputs the phone number of a given official, as long he is not included in the list of high ranking officials.
GetPhoneNumberAny	Outputs the phone number of a given offical.

A.5.1.b Data types of system entities

The entities of the system are employees and their phone numbers. These are represented using basic types. These basic types are described in Table A.6.

Table A.6: Phone book system - Description of the basic types

Basic type	Description
EMPLOYEE	set of all possible identifiers for employees
TELEPHONE	set of all possible telephone numbers

A.5.1.c State variables

The state of the system is recorded by the schema *State*. The state variables that record and maintain various information about the system state are described in Table A.7.

Table A.7: Phone book system - Description of the state variables

State variable	Description
phoneNumbers	A relation that identifes the telephone number allocated to each unique employee.
secretList	The set of unique identifiers that represents the set of employees whose phone numbers are considered secret.
loggedIn	The set of identifiers of the users who are logged into the system.

loginUser	The identifier that represents the user who is currently logged into the system.
reqOfficial	The identifier of the official whose phone number is being requested from the system.
officials	The set of identifiers that represents all the officials whose phone numbers have been recorded in the system.
secretaries	The set of unique identifiers that represents the secretaries of the organisation.
engineers	The set of identifiers that represents all the engineers whose phone numbers have been recorded in the system.
manager	The identifier that represents the manager of the organisation.

A.5.1.d State invariants

Further, the system is designed to respect the following constraints.

Table A.8: Phone book system - Description of the state invariants

State invariants	Description
$\mathrm{dom}\ (phoneNumbers) \subseteq officials$	The set of people whose phone numbers are recorded in the system must be from the set of officials recorded in the system.
$secretList \subseteq \mathrm{dom}\ (phoneNumbers)$	

The set of officials whose numbers are considered confidential must be from the set of officials whose phone numbers have been recorded in the system.

$reqOfficial \in \mathrm{dom}\ (phoneNumbers)$

The official whose phone number is being requested from the system must have his/her phone number recorded in the system.

$loginUser \in loggedIn$

The current user must be from the set of users logged into the system.

$loggedIn \subseteq officials$

The set of users who are logged into the system must be from the set of officials in the agency.

$officials \subseteq (secretaries \cup engineers \cup \{manager\})$

The set of officials of the agency mustbe from the group of secretaries, the group of engineers or the manager.

$(engineers \cap \{manager\}) = \{\}$

The same person cannot be an engineer and the manager at the same time.

$(\{manager\} \cap secretaries) = \{\}$

The same person cannot be the manager and a secretary at the same time.

$(engineers \cap secretaries) = \{\}$

The same person cannot be an engineer and a secretary at the same time.

$[\ TELEPHONE, EMPLOYEE\ ]$

$$
\begin{array}{l}
\textbf{State} \\
\hline
phoneNumbers : EMPLOYEE \pfun TELEPHONE \\
manager, reqOfficial, loginUser : EMPLOYEE \\
engineers, secretaries, officials, loggedIn, secretList : \mathbb{F}\ EMPLOYEE \\
\hline
(engineers \cap secretaries) = \{\} \\
(\{manager\} \cap secretaries) = \{\} \\
(engineers \cap \{manager\}) = \{\} \\
officials \subseteq (secretaries \cup engineers \cup \{manager\}) \\
loggedIn \subseteq officials \\
loginUser \in loggedIn \\
reqOfficial \in \mathrm{dom}\,(phoneNumbers) \\
secretList \subseteq \mathrm{dom}\,(phoneNumbers) \\
\mathrm{dom}\,(phoneNumbers) \subseteq officials \\
\hline
\end{array}
$$

$$
\begin{array}{l}
\textbf{HideSecretNumber} \\
\hline
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad reqOfficial \in secretList \land \\
\quad reqOfficial \neq loginUser \land \\
\quad loginUser \neq manager \Rightarrow \\
\qquad\qquad reqOfficial \in \mathrm{dom}\,(phoneNumbers) \Rightarrow \\
\qquad\qquad\qquad reqOfficial_9 \notin \mathrm{dom}\,(phoneNumbers_9) \\
\hline
\end{array}
$$

channel $addPhoneNumberIn, anyPhoneOut, noSecPhoneOut : TELEPHONE$
channel $noSecOfficialIn, setSecretOfficialIn, addPhoneOfficialIn : EMPLOYEE$
channel $anyOfficialIn : EMPLOYEE$

channelset $Engineers == \{\!|\ noSecPhoneOut, noSecOfficialIn\ |\!\}$
channelset $Manager == \{\!|\ setSecretOfficialIn, anyPhoneOut, anyOfficialIn\ |\!\}$
channelset $Secretaries == \{\!|\ addPhoneOfficialIn, noSecPhoneOut, noSecOfficialIn, addPhoneNumberIn\ |\!\}$

process $Phone\_book\_system \mathrel{\widehat=}$ **begin**

state $State$

$$Init \mathrel{\widehat=} reqOfficial := loginUser$$

$$
\begin{array}{ll}
AddPhoneNumber \mathrel{\widehat=} & \mathbf{var}\ addPhoneNumber : TELEPHONE; \\
& \quad addPhoneOfficial : officials \bullet \\
& \quad addPhoneNumberIn?addPhoneNumber \longrightarrow \\
& \quad addPhoneOfficialIn?addPhoneOfficial \longrightarrow \\
& \quad \big(\big(loginUser \in secretaries\big) \mathbin{\&} \\
& \qquad\quad phoneNumbers := phoneNumbers \oplus \\
& \qquad\qquad\quad \{(addPhoneOfficial? \mapsto addPhoneNumber?)\}\big)
\end{array}
$$

$$
\begin{array}{ll}
SetSecretPhoneNumber \mathrel{\widehat=} & \mathbf{var}\ setSecretOfficial : \mathrm{dom}\,(phoneNumbers) \bullet \\
& \quad setSecretOfficialIn?setSecretOfficial \longrightarrow \\
& \quad \big(\big(loginUser = manager\big) \mathbin{\&} \\
& \qquad\quad secretList := secretList \cup \{setSecretOfficial?\}\big)
\end{array}
$$

Figure A.4: Specification of Phone book system - *code block 1 of 2*

$$
\begin{array}{lcl}
\mathit{GetPhoneNumberNoSecret} & \widehat{=} & \mathbf{var}\ \mathit{noSecOfficial} : \mathrm{dom}\,(\mathit{phoneNumbers}) \bullet \\
& & \quad \mathit{noSecOfficialIn}?\mathit{noSecOfficial} \longrightarrow \\
& & \quad \mathit{reqOfficial} := \mathit{noSecOfficial}?\,; \\
& & \quad ((\mathit{noSecOfficial}? \notin \mathit{secretList} \lor \\
& & \quad \ \mathit{loginUser} = \mathit{manager})\,\& \\
& & \quad \quad \mathit{noSecPhoneOut}\,!(\mathit{phoneNumbers}\ \mathit{noSecOfficial}?) \longrightarrow \mathbf{Skip})
\end{array}
$$

$$
\begin{array}{lcl}
\mathit{GetPhoneNumberAny} & \widehat{=} & \mathbf{var}\ \mathit{anyOfficial} : \mathrm{dom}\,(\mathit{phoneNumbers}) \bullet \\
& & \quad \mathit{anyOfficialIn}?\mathit{anyOfficial} \longrightarrow \\
& & \quad \mathit{reqOfficial} := \mathit{anyOfficial}?\,; \\
& & \quad ((\mathit{loginUser} = \mathit{manager})\,\& \\
& & \quad \quad \mathit{anyPhoneOut}\,!(\mathit{phoneNumbers}\ \mathit{anyOfficial}?) \longrightarrow \mathbf{Skip})
\end{array}
$$

$$
\mathit{HideSecretNumber} \ \widehat{=}\ \mathit{HideSecretNumber}
$$

$$
\mathit{Options} \ \widehat{=} \ \left(\begin{array}{ll}
 & \mathit{AddPhoneNumber} \\
\Box & \mathit{SetSecretPhoneNumber} \\
\Box & \mathit{GetPhoneNumberNoSecret} \\
\Box & \mathit{GetPhoneNumberAny}
\end{array}\right) ;\ \mathit{HideSecretNumber}
$$

$$
\bullet\ \langle \mathit{Init} \rangle\ ;\ \mu Y \bullet \langle \mathit{Options}\ ;\ Y \rangle
$$

end

Figure A.4 (cont.) : Specification of Phone book system - *code block 2 of 2*

A.5.2 Case study - Secure electronic examination system

A hand-crafted documentation with a formal specification of the Secure electronic examination system is presented. A *Circus* action is defined for each use case in the use case diagram of the Secure electronic examination system shown in Figure A.5. The operations performed by these actions are described in Table A.14. It is important to note that the action *Init* in Table A.14 is not in Figure A.5. This is because *Init* initializes system variables and is not executed through external action. The following table of contents may be useful for easy navigation within this case study.

A.5.2.a Data types of system entities

The entities of the system including the actors Chair, Student, Setter, Checker and Grader as well as the components Paper, Question, Answer and Candidate are represented using basic types. These basic types are described in Table A.10.

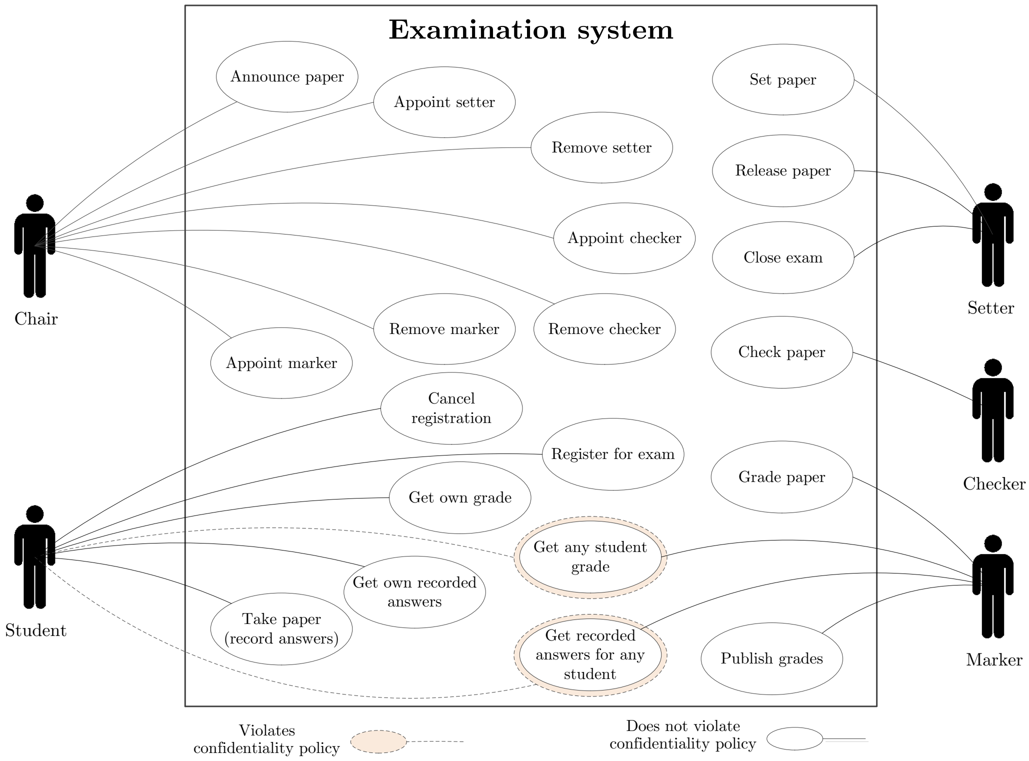


Figure A.5: Use case diagram for a Secure electronic examination system

Table A.10: Secure electronic examination system - Description of the basic types

Basic type	Description
EXAMINER	The set of all possible identifiers for examiners
USER	The set of all users who are allowed access to the system
SUBJECT	The set of all identifiers for subjects
PAPER	The set of all identifiers for all subject examination papers announced and managed in the system
QUESTION	The set of all identifiers for questions in all the subject examination papers.
ANSWER	The set of all identifiers for answers recorded by students against the subject examination papers
CANDIDATE	The set of all identifiers representing candidates who are students who have registered in the system to sit on examinations.

The login status of users and the status of the examination papers are attributes that define values for certain properties of some entities in the system. These attributes are declared as free types in the system and are described in Table A.11.

Table A.11: Secure electronic examination system - Description of the free types

Free type	Item	Meaning
PAPERSTATUS	*announced*	The paper has been announced.

setting	The paper is currently being set.
checked	The paper has been checked.
released	The paper has been released for candidates to take the paper.
paperclosed	The examination has ended and answers will not be accepted from candidates for that paper.
grading	The paper is currently being graded.
gradepublished	The results have been published.

A.5.2.b State variables

The state of the system is recorded by the schema *State*. The state variables that record and maintain various information about the system state are described in Table A.12.

Table A.12: Secure electronic examination system - Description of the state variables

State variable	Description
chair	A function that identifies the lecturer appointed as the chair for a subject, if any.
exams	A relation between subjects and examination papers initiated for those subjects.
setter	A function that identifies the lectuer appointed as the setter for a paper, if any.

checker	A function that identifies the lectuer appointed as the cheker for a paper, if any.
grader	A function that identifies the lectuer appointed as the marker for a paper, if any.
pStatus	A function that identifies the status of a paper, if any.
regStudent	A function that identifies the student for a given candidate, if any.
regPaper	A function that identifies the paper registered by a candidate, if any.
questions	A relation between papers and questions that belong to those papers.
ansPaper	A relation between papers and answers recorded on those papers.
ansStudent	A relation between candidate and answers they have recorded.
result	A function that represents the grade obatained by a candidate, if any.
students	The set of identifiers of the students.
lecturers	The set of identifiers of the lecturers.
users	The set of identifiers of the users who are allowed acces to the system.
loginUser	The user who is currently logged into the system.
theCandidate	The candidate whose grade or answer is being requested from the system.

A.5.2.c State invariants

Further, the system is designed to respect the following constraints.

Table A.13: Secure electronic examination system - Description of the state invariants

State invariants	Description
$((\mathrm{ran}\, chair) \cup (\mathrm{ran}\, setter) \cup (\mathrm{ran}\, checker) \cup (\mathrm{ran}\, grader)) \subseteq lecturers$	The set of lecturers who are appointed as chairs of subjects a subset of the set of chairs recorded in the system.
$((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, setter)) = \{\}$	A lecturer cannot be a subject chair and a setter at the same time.
$((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, checker)) = \{\}$	A person cannot be both a chair and a checker in the system.
$((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, grader)) = \{\}$	A person cannot be both a chair and a grader in the system.
$((\mathrm{ran}\, setter) \cap (\mathrm{ran}\, checker)) = \{\}$	A person cannot be both a setter and a checker in the system.
$((\mathrm{ran}\, setter) \cap (\mathrm{ran}\, grader)) = \{\}$	A person cannot be both a setter and a grader in the system.
$((\mathrm{ran}\, checker) \cap (\mathrm{ran}\, grader)) = \{\}$	

A person cannot be both a checker and a grader in the system.

$users \subseteq (lecturers \cup students)$

The set of users allowed access to the system is a subset of the set of lectuers and students.

$(lecturers \cap students) = \{\}$

A person cannot be a lecturer and a student at the same time.

$loginUser \in users$

The user currently using the system must be from the set of users allowed access to the system.

$\mathrm{dom}\ (pStatus) \subseteq \mathrm{dom}\ (exams)$

A paper for which a paper status has been recorded must belong to a particular subject.

$\mathrm{dom}\ (setter) \subseteq \mathrm{dom}\ (pStatus)$

A paper for which a setter has been assigned must have a paper status.

$\mathrm{dom}\ (checker) \subseteq \mathrm{dom}\ (pStatus)$

A paper for which a checker has been assigned must have a paper status.

$\mathrm{dom}\ (grader) \subseteq \mathrm{dom}\ (pStatus)$

A paper for which a grader has been assigned must have a paper status.

$\mathrm{dom}\ (questions) \subseteq \mathrm{dom}\ (pStatus)$

Every paper on which a question is recorded must have a paper status.

$\mathrm{dom}\ (ansPaper) \subseteq \mathrm{dom}\ (pStatus)$

Every paper on which an answer is recorded must have a paper status.

$\mathrm{ran}\, regPaper \subseteq \mathrm{dom}\ (pStatus)$

Every paper registered for, must have a paper status.

$\mathrm{dom}\ (regPaper) \subseteq \mathrm{dom}\ (regStudent)$

Every student registered for a paper must be a registered candidate.

$\mathrm{ran}\, regStudent \subseteq students$

A student registered as a candidate must be a student recorded in the system.

$\mathrm{dom}\ (result) \subseteq \mathrm{dom}\ (regPaper)$

Every result recorded in the system must be for a registered paper.

$\mathrm{dom}\ (ansStudent) \subseteq \mathrm{dom}\ (regPaper)$

Every answer recorded by a student must be for a registered paper.

$\mathrm{dom}\ (questions) \subseteq \mathrm{dom}\ (setter)$

Every paper for which questions are recorded, must have a setter assigned to it.

$\mathrm{dom}\ (questions) \subseteq \mathrm{ran}\, regPaper$

Every question recorded in the system must be for a registered paper.

$\mathrm{dom}\ (ansPaper) \subseteq \mathrm{ran}\, regPaper$

Every answer recorded in the system must be for a registered paper.

A.5.2.d Operations

The operations of the system are formalized as *Circus* actions and described in Table A.14.

Table A.14: Secure electronic examination system - Description of the *Circus* actions

Action	Operation performed by the action
AnnouncePaper	Allows a subject chair to announce a subject examination.
AppointSetter	Allows a subject chair to appoint a subject lecturer to set the exam paper.
ResignSetter	Allows an appointed setter to resign himself or herself from the post.
AppointChecker	Allows a subject chair to appoint a subject lecturer to check the exam paper.
ResignChecker	Allows an appointed checker to resign himself or herself from the post.
AppointMarker	Allows a subject chair to appoint a subject lecturer to set the exam paper.
ResignMarker	Allows an appointed grader to resign himself or herself from the post.
CloseExam	Allows a setter to close the paper to conclude the end of the examination.

CheckPaper	Allows a checker to check the paper and record his approval by changing the paper status to checked.
GradePaper	Allows a grader to record the grade awarded to a particular cnadidate for a particular paper.
PublishGrades	Allows a grader to publish the grades obained by all candidates who set for a paper.
TakePaper	Allows a student to record answers for a particular paper during the examination.
GetMyAnswers	Allows a user to view the answers he/she has recorded in the system.
RegisterforExam	Allows a student to register for a particular paper using his/her candidate number.
CancelRegistration	Allows a student to cancel his/her registration for a particular paper.
GetOwnResult	Allows a student to view his/her grade for a particular paper he/she took.
GetAnyResult	Allows a lecturer to view the grade of any candidate for any paper he/she has sat.
SetPaper	Allows a setter to set a paper by recording questions for that paper.
ReleasePaper	Allows a setter to release the paper for candidates to take the examination.

$[\, ANSWER, QUESTION, PAPER, SUBJECT, USER, EXAMINER \,]$
$[\, CANDIDATE \,]$

$$\begin{aligned} PAPERSTATUS \; ::= \; & paperclosed \mid released \mid checked \mid setting \mid announced \\ \mid \; & gradepublished \mid grading \end{aligned}$$

State

$$\begin{array}{l}
loginUser : USER \\
regStudent : CANDIDATE \twoheadrightarrow\!\!\!\!\!\!\mapsto USER \\
ansPaper : PAPER \leftrightarrow ANSWER \\
ansStudent : CANDIDATE \leftrightarrow ANSWER \\
grader, checker, setter : PAPER \twoheadrightarrow\!\!\!\!\!\!\mapsto USER \\
pStatus : PAPER \twoheadrightarrow\!\!\!\!\!\!\mapsto PAPERSTATUS \\
exams : PAPER \twoheadrightarrow\!\!\!\!\!\!\mapsto SUBJECT \\
chair : SUBJECT \twoheadrightarrow\!\!\!\!\!\!\mapsto USER \\
regPaper : CANDIDATE \twoheadrightarrow\!\!\!\!\!\!\mapsto PAPER \\
users, lecturers, students : \mathbb{F}\, USER \\
theCandidate : CANDIDATE \\
questions : PAPER \leftrightarrow QUESTION \\
result : CANDIDATE \twoheadrightarrow\!\!\!\!\!\!\mapsto \mathbb{N} \\
\hline
\mathrm{dom}\,(ansPaper) \subseteq \mathrm{ran}\, regPaper \\
\mathrm{dom}\,(questions) \subseteq \mathrm{ran}\, regPaper \\
\mathrm{dom}\,(questions) \subseteq \mathrm{dom}\,(setter) \\
\mathrm{dom}\,(ansStudent) \subseteq \mathrm{dom}\,(regPaper) \\
\mathrm{dom}\,(result) \subseteq \mathrm{dom}\,(regPaper) \\
\mathrm{ran}\, regStudent \subseteq students \\
\mathrm{dom}\,(regPaper) \subseteq \mathrm{dom}\,(regStudent) \\
\mathrm{ran}\, regPaper \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(ansPaper) \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(questions) \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(grader) \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(checker) \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(setter) \subseteq \mathrm{dom}\,(pStatus) \\
\mathrm{dom}\,(pStatus) \subseteq \mathrm{dom}\,(exams) \\
loginUser \in users \\
(lecturers \cap students) = \{\} \\
users \subseteq (lecturers \cup students) \\
((\mathrm{ran}\, checker) \cap (\mathrm{ran}\, grader)) = \{\} \\
((\mathrm{ran}\, setter) \cap (\mathrm{ran}\, grader)) = \{\} \\
((\mathrm{ran}\, setter) \cap (\mathrm{ran}\, checker)) = \{\} \\
((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, grader)) = \{\} \\
((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, checker)) = \{\} \\
((\mathrm{ran}\, chair) \cap (\mathrm{ran}\, setter)) = \{\} \\
((\mathrm{ran}\, chair) \cup (\mathrm{ran}\, setter) \cup (\mathrm{ran}\, checker) \cup (\mathrm{ran}\, grader)) \subseteq lecturers
\end{array}$$

HideOthersAnswers

$$\begin{array}{l}
\Xi State \\
\hline
\exists\, State_9 \bullet \\
\quad\;\; ((regStudent)^{\sim})\, loginUser \neq theCandidate \wedge \\
\quad pStatus\,(regPaper\, theCandidate) = released \Rightarrow \\
\qquad\qquad (\mathrm{ran}(\{theCandidate\} \lhd ansStudent) \cap \\
\qquad\qquad\;\; \mathrm{ran}(\{theCandidate_9\} \lhd ansStudent_9)) = \{\}
\end{array}$$

Figure A.6: Specification of Secure electronic examination system - *code block 1 of 6*

channel $gradeAwardedIn, anyResultOut, ownResultOut : \mathbb{N}$
channel $takePaperAnswerIn : ANSWER$
channel $appCheckerSubjectIn, appointPsubjectIn, paperSubjectIn : SUBJECT$
channel $appMarkerSubjectIn : SUBJECT$
channel $resignPsetterIn, appointPSetterIn, newPaperIn : PAPER$
channel $appMarkerPaperIn, resCheckerPaperIn, appCheckerPaperIn : PAPER$
channel $gradePaperIn, chkPaperIn, closePaperIn, resMarkerPaperIn : PAPER$
channel $regExamPaperIn, takePaperIn, pubGradePaperIn : PAPER$
channel $anyResultPaperIn, ownResultPaperIn, cancelRegPaperIn : PAPER$
channel $releasePaperIn, setPaperIn : PAPER$
channel $ownAnswerCandidateIn, takePaperCandidateIn, gradeCandidateIn : CANDIDATE$
channel $ownResultCandidateIn, cancelRegCandidateIn, regExamCandidateIn : CANDIDATE$
channel $anyResultCandidateIn : CANDIDATE$
channel $appMarkerLecturerIn, appCheckerLecturerIn, appointPlecturerIn : USER$
channel $ownAnswerOut : \mathbb{F}\, ANSWER$
channel $setQuestionPaperIn : QUESTION$

channelset $Chair == \{\!|\ appMarkerSubjectIn, appMarkerLecturerIn, resMarkerPaperIn, appCheckerLecturerIn, resCheckerPaperIn, appMarkerPaperIn, resignPsetterIn, appCheckerSubjectIn, appCheckerPaperIn, appointPSetterIn, appointPsubjectIn, appointPlecturerIn\ |\!\}$
channelset $Checker == \{\!|\ resCheckerPaperIn, chkPaperIn\ |\!\}$
channelset $Marker == \{\!|\ gradeCandidateIn, gradeAwardedIn, pubGradePaperIn, gradePaperIn\ |\!\}$
channelset $Setter == \{\!|\ resignPsetterIn, releasePaperIn, closePaperIn, setPaperIn, setQuestionPaperIn\ |\!\}$
channelset $Student == \{\!|\ takePaperCandidateIn, ownAnswerCandidateIn, ownAnswerOut, ownResultOut, takePaperIn, takePaperAnswerIn, cancelRegCandidateIn, ownResultPaperIn, ownResultCandidateIn, regExamPaperIn, regExamCandidateIn, cancelRegPaperIn\ |\!\}$

process $Secure\_electronic\_examination\_system \mathrel{\widehat=}$ **begin**

state $State$

$Init \mathrel{\widehat=} theCandidate := ((regStudent)^{\sim})\ loginUser$

$$
\begin{aligned}
AnnouncePaper \mathrel{\widehat=}\ & \mathbf{var}\ paperSubject : \operatorname{dom}(chair); \\
& newPaper : PAPER \bullet \\
& paperSubjectIn?paperSubject \longrightarrow \\
& newPaperIn?newPaper \longrightarrow \\
& \big((chair\ paperSubject? = loginUser\big) \mathbin{\&} \\
& \quad exams := exams \oplus \{(newPaper? \mapsto paperSubject?)\}; \\
& \quad pStatus := pStatus \oplus \{(newPaper? \mapsto announced)\})
\end{aligned}
$$

$$
\begin{aligned}
AppointSetter \mathrel{\widehat=}\ & \mathbf{var}\ appointPlecturer : lecturers; \\
& appointPsubject : \operatorname{dom}(chair); \\
& appointPSetter : \operatorname{dom}(pStatus) \bullet \\
& appointPlecturerIn?appointPlecturer \longrightarrow \\
& appointPsubjectIn?appointPsubject \longrightarrow \\
& appointPSetterIn?appointPSetter \longrightarrow \\
& \big((loginUser \in lecturers \land (appointPsubject?, loginUser) \in chair\big) \mathbin{\&} \\
& \quad setter := setter \oplus \{(appointPSetter? \mapsto appointPlecturer?)\})
\end{aligned}
$$

Figure A.6 (cont.) : Specification of Secure electronic examination system - *code block 2 of 6*

$$
\begin{array}{lll}
\mathit{ResignSetter} & \widehat{=} & \mathbf{var}\ \mathit{resignPsetter} : \mathrm{dom}\,(\mathit{setter}) \bullet \\
& & \quad \mathit{resignPsetterIn}?\mathit{resignPsetter} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge (\mathit{resignPsetter}?, \mathit{loginUser}) \in \mathit{setter}\big) \,\&\, \\
& & \qquad \mathit{setter} := \mathit{setter} \setminus \{(\mathit{resignPsetter}? \mapsto \mathit{loginUser})\}) \\[2ex]
\mathit{AppointChecker} & \widehat{=} & \mathbf{var}\ \mathit{appCheckerLecturer} : \mathit{lecturers}; \\
& & \quad \mathit{appCheckerSubject} : \mathrm{dom}\,(\mathit{chair}); \\
& & \quad \mathit{appCheckerPaper} : \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{appCheckerLecturerIn}?\mathit{appCheckerLecturer} \longrightarrow \\
& & \quad \mathit{appCheckerSubjectIn}?\mathit{appCheckerSubject} \longrightarrow \\
& & \quad \mathit{appCheckerPaperIn}?\mathit{appCheckerPaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \quad\; (\mathit{appCheckerSubject}?, \mathit{loginUser}) \in \mathit{chair}\big) \,\&\, \\
& & \qquad \mathit{checker} := \mathit{checker} \oplus \\
& & \qquad\qquad \{(\mathit{appCheckerPaper}? \mapsto \mathit{appCheckerLecturer}?)\}) \\[2ex]
\mathit{ResignChecker} & \widehat{=} & \mathbf{var}\ \mathit{resCheckerPaper} : \mathrm{dom}\,(\mathit{checker}) \bullet \\
& & \quad \mathit{resCheckerPaperIn}?\mathit{resCheckerPaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \quad\; (\mathit{resCheckerPaper}?, \mathit{loginUser}) \in \mathit{checker}\big) \,\&\, \\
& & \qquad \mathit{checker} := \mathit{checker} \setminus \{(\mathit{resCheckerPaper}? \mapsto \mathit{loginUser})\}) \\[2ex]
\mathit{AppointMarker} & \widehat{=} & \mathbf{var}\ \mathit{appMarkerLecturer} : \mathit{lecturers}; \\
& & \quad \mathit{appMarkerSubject} : \mathrm{dom}\,(\mathit{chair}); \\
& & \quad \mathit{appMarkerPaper} : \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{appMarkerLecturerIn}?\mathit{appMarkerLecturer} \longrightarrow \\
& & \quad \mathit{appMarkerSubjectIn}?\mathit{appMarkerSubject} \longrightarrow \\
& & \quad \mathit{appMarkerPaperIn}?\mathit{appMarkerPaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \quad\; (\mathit{appMarkerSubject}?, \mathit{loginUser}) \in \mathit{chair}\big) \,\&\, \\
& & \qquad \mathit{grader} := \mathit{grader} \oplus \\
& & \qquad\qquad \{(\mathit{appMarkerPaper}? \mapsto \mathit{appMarkerLecturer}?)\}) \\[2ex]
\mathit{ResignMarker} & \widehat{=} & \mathbf{var}\ \mathit{resMarkerPaper} : \mathrm{dom}\,(\mathit{grader}) \bullet \\
& & \quad \mathit{resMarkerPaperIn}?\mathit{resMarkerPaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge (\mathit{resMarkerPaper}?, \mathit{loginUser}) \in \mathit{grader}\big) \,\&\, \\
& & \qquad \mathit{grader} := \mathit{grader} \setminus \{(\mathit{resMarkerPaper}? \mapsto \mathit{loginUser})\}) \\[2ex]
\mathit{CloseExam} & \widehat{=} & \mathbf{var}\ \mathit{closePaper} : \mathrm{dom}\,(\mathit{setter}) \;\cap\; \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{closePaperIn}?\mathit{closePaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \qquad (\mathit{closePaper}?, \mathit{loginUser}) \in \mathit{setter} \wedge \\
& & \qquad (\mathit{closePaper}?, \mathit{released}) \in \mathit{pStatus}\big) \,\&\, \\
& & \qquad \mathit{pStatus} := \mathit{pStatus} \oplus \{(\mathit{closePaper}? \mapsto \mathit{paperclosed})\}) \\[2ex]
\mathit{CheckPaper} & \widehat{=} & \mathbf{var}\ \mathit{chkPaper} : \mathrm{dom}\,(\mathit{checker}) \;\cap\; \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{chkPaperIn}?\mathit{chkPaper} \longrightarrow \\
& & \quad \big((\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \qquad (\mathit{chkPaper}?, \mathit{loginUser}) \in \mathit{checker} \wedge \\
& & \qquad (\mathit{chkPaper}?, \mathit{setting}) \in \mathit{pStatus}\big) \,\&\, \\
& & \qquad \mathit{pStatus} := \mathit{pStatus} \oplus \{(\mathit{chkPaper}? \mapsto \mathit{checked})\})
\end{array}
$$

Figure A.6 (cont.) : Specification of Secure electronic examination system - *code block 3 of 6*

$$
\begin{array}{lll}
\mathit{GradePaper} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{gradeAwarded} : \mathbb{N}; \\
& & \quad \mathit{gradePaper} : \mathrm{dom}\,(\mathit{grader}) \ \cap \ \mathrm{dom}\,(\mathit{pStatus}); \\
& & \quad \mathit{gradeCandidate} : \mathrm{dom}\,(\mathit{regPaper}) \bullet \\
& & \quad \mathit{gradeAwardedIn}?\mathit{gradeAwarded} \longrightarrow \\
& & \quad \mathit{gradePaperIn}?\mathit{gradePaper} \longrightarrow \\
& & \quad \mathit{gradeCandidateIn}?\mathit{gradeCandidate} \longrightarrow \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \qquad (\mathit{gradeCandidate}?, \mathit{gradePaper}?) \in \mathit{regPaper} \wedge \\
& & \qquad (\mathit{gradePaper}?, \mathit{paperclosed}) \in \mathit{pStatus} \wedge \\
& & \qquad (\mathit{gradePaper}?, \mathit{loginUser}) \in \mathit{grader}\big) \,\&\, \\
& & \qquad\quad \mathit{result} := \mathit{result} \oplus \{(\mathit{gradeCandidate}? \mapsto \mathit{gradeAwarded}?)\}\big)
\end{array}
$$

$$
\begin{array}{lll}
\mathit{PublishGrades} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{pubGradePaper} : \mathrm{dom}\,(\mathit{grader}) \ \cap \ \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{pubGradePaperIn}?\mathit{pubGradePaper} \longrightarrow \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{lecturers} \wedge \\
& & \qquad (\mathit{pubGradePaper}?, \mathit{paperclosed}) \in \mathit{pStatus} \wedge \\
& & \qquad (\mathit{pubGradePaper}?, \mathit{loginUser}) \in \mathit{grader}\big) \,\&\, \\
& & \qquad\quad \mathit{pStatus} := \mathit{pStatus} \oplus \{(\mathit{pubGradePaper}? \mapsto \mathit{gradepublished})\}\big)
\end{array}
$$

$$
\begin{array}{lll}
\mathit{TakePaper} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{takePaperAnswer} : \mathit{ANSWER}; \\
& & \quad \mathit{takePaperCandidate} : \mathrm{dom}\,(\mathit{regPaper}); \\
& & \quad \mathit{takePaper} : \mathrm{ran}(\mathit{regPaper}) \bullet \\
& & \quad \mathit{takePaperAnswerIn}?\mathit{takePaperAnswer} \longrightarrow \\
& & \quad \mathit{takePaperCandidateIn}?\mathit{takePaperCandidate} \longrightarrow \\
& & \quad \mathit{takePaperIn}?\mathit{takePaper} \longrightarrow \\
& & \quad \mathit{theCandidate} := \mathit{takePaperCandidate}?; \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{students} \wedge \\
& & \qquad ((\mathit{regStudent})^{\sim})\, \mathit{loginUser} = \mathit{takePaperCandidate}? \wedge \\
& & \qquad (\mathit{takePaper}?, \mathit{released}) \in \mathit{pStatus} \wedge \\
& & \qquad (\mathit{takePaperCandidate}?, \mathit{takePaper}?) \in \mathit{regPaper}\big) \,\&\, \\
& & \qquad\quad \mathit{ansPaper} := \mathit{ansPaper} \oplus \{(\mathit{takePaper}? \mapsto \mathit{takePaperAnswer}?)\}\big)
\end{array}
$$

$$
\begin{array}{lll}
\mathit{GetMyAnswers} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{ownAnswerCandidate} : \mathrm{dom}\,(\mathit{ansStudent}) \bullet \\
& & \quad \mathit{ownAnswerCandidateIn}?\mathit{ownAnswerCandidate} \longrightarrow \\
& & \quad \mathit{theCandidate} := \mathit{ownAnswerCandidate}?; \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{students} \wedge \\
& & \qquad ((\mathit{regStudent})^{\sim})\, \mathit{loginUser} = \mathit{ownAnswerCandidate}?\big) \,\&\, \\
& & \qquad\quad \mathit{ownAnswerOut}\,! \\
& & \qquad\qquad\qquad (\mathit{ansStudent}\,(\!|\, \{\mathit{ownAnswerCandidate}?\} \,|\!)) \longrightarrow \mathbf{Skip}\big)
\end{array}
$$

$$
\begin{array}{lll}
\mathit{RegisterforExam} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{regExamCandidate} : \mathrm{dom}\,(\mathit{regStudent}); \\
& & \quad \mathit{regExamPaper} : \mathrm{dom}\,(\mathit{pStatus}) \bullet \\
& & \quad \mathit{regExamCandidateIn}?\mathit{regExamCandidate} \longrightarrow \\
& & \quad \mathit{regExamPaperIn}?\mathit{regExamPaper} \longrightarrow \\
& & \quad \mathit{theCandidate} := \mathit{regExamCandidate}?; \\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{students} \wedge \\
& & \qquad ((\mathit{regStudent})^{\sim})\, \mathit{loginUser} = \mathit{regExamCandidate}?\big) \,\&\, \\
& & \qquad\quad \mathit{regPaper} := \mathit{regPaper} \oplus \\
& & \qquad\qquad\qquad \{(\mathit{regExamCandidate}? \mapsto \mathit{regExamPaper}?)\}\big)
\end{array}
$$

Figure A.6 (cont.) : Specification of Secure electronic examination system - *code block 4 of 6*

$$
\begin{array}{lll}
\mathit{CancelRegistration} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{cancelRegCandidate} : \mathrm{dom}\,(\mathit{regStudent});\\
& & \quad \mathit{cancelRegPaper} : \mathrm{ran}(\mathit{regPaper}) \bullet\\
& & \quad \mathit{cancelRegCandidateIn}?\mathit{cancelRegCandidate} \longrightarrow\\
& & \quad \mathit{cancelRegPaperIn}?\mathit{cancelRegPaper} \longrightarrow\\
& & \quad \mathit{theCandidate} := \mathit{cancelRegCandidate}?;\\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{students} \land\\
& & \qquad ((\mathit{regStudent})^{\sim})\,\mathit{loginUser} = \mathit{cancelRegCandidate}? \land\\
& & \qquad (\mathit{cancelRegCandidate}?, \mathit{cancelRegPaper}?) \in \mathit{regPaper}\big) \&\\
& & \qquad\quad \mathit{regPaper} := \mathit{regPaper} \setminus\\
& & \qquad\qquad\qquad \{(\mathit{cancelRegCandidate}? \mapsto \mathit{cancelRegPaper}?)\}\big)\\
\mathit{GetOwnResult} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{ownResultPaper} : \mathrm{ran}(\mathit{regPaper});\\
& & \quad \mathit{ownResultCandidate} : \mathrm{dom}\,(\mathit{result}) \bullet\\
& & \quad \mathit{ownResultPaperIn}?\mathit{ownResultPaper} \longrightarrow\\
& & \quad \mathit{ownResultCandidateIn}?\mathit{ownResultCandidate} \longrightarrow\\
& & \quad \mathit{theCandidate} := \mathit{ownResultCandidate}?;\\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{students} \land\\
& & \qquad ((\mathit{regStudent})^{\sim})\,\mathit{loginUser} = \mathit{ownResultCandidate}? \land\\
& & \qquad (\mathit{ownResultCandidate}?, \mathit{ownResultPaper}?) \in \mathit{regPaper} \land\\
& & \qquad (\mathit{ownResultPaper}?, \mathit{gradepublished}) \in \mathit{pStatus}\big) \&\\
& & \qquad\quad \mathit{ownResultOut}\,!(\mathit{result}\ \mathit{ownResultCandidate}?) \longrightarrow \mathbf{Skip}\big)\\
\mathit{GetAnyResult} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{anyResultCandidate} : \mathrm{dom}\,(\mathit{result});\\
& & \quad \mathit{anyResultPaper} : \mathrm{ran}(\mathit{regPaper}) \bullet\\
& & \quad \mathit{anyResultCandidateIn}?\mathit{anyResultCandidate} \longrightarrow\\
& & \quad \mathit{anyResultPaperIn}?\mathit{anyResultPaper} \longrightarrow\\
& & \quad \mathit{theCandidate} := \mathit{anyResultCandidate}?;\\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{lecturers} \land\\
& & \qquad (\mathit{anyResultCandidate}?, \mathit{anyResultPaper}?) \in \mathit{regPaper}\big) \&\\
& & \qquad\quad \mathit{anyResultOut}\,!(\mathit{result}\ \mathit{anyResultCandidate}?) \longrightarrow \mathbf{Skip}\big)\\
\mathit{SetPaper} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{setQuestionPaper} : \mathit{QUESTION};\\
& & \quad \mathit{setPaper} : \mathrm{dom}\,(\mathit{setter}) \cap \mathrm{dom}\,(\mathit{pStatus}) \bullet\\
& & \quad \mathit{setQuestionPaperIn}?\mathit{setQuestionPaper} \longrightarrow\\
& & \quad \mathit{setPaperIn}?\mathit{setPaper} \longrightarrow\\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{lecturers} \land\\
& & \qquad (\mathit{setPaper}?, \mathit{loginUser}) \in \mathit{setter} \land\\
& & \qquad (\mathit{setPaper}?, \mathit{checked}) \in \mathit{pStatus}\big) \&\\
& & \qquad\quad \mathit{questions} := \mathit{questions} \oplus\\
& & \qquad\qquad\qquad \{(\mathit{setPaper}? \mapsto \mathit{setQuestionPaper}?)\};\\
& & \qquad\quad \mathit{pStatus} := \mathit{pStatus} \oplus \{(\mathit{setPaper}? \mapsto \mathit{setting})\}\big)\\
\mathit{ReleasePaper} & \mathrel{\widehat=} & \mathbf{var}\ \mathit{releasePaper} : \mathrm{dom}\,(\mathit{setter}) \cap \mathrm{dom}\,(\mathit{pStatus}) \bullet\\
& & \quad \mathit{releasePaperIn}?\mathit{releasePaper} \longrightarrow\\
& & \quad \big(\big(\mathit{loginUser} \in \mathit{lecturers} \land\\
& & \qquad (\mathit{releasePaper}?, \mathit{loginUser}) \in \mathit{setter} \land\\
& & \qquad (\mathit{releasePaper}?, \mathit{checked}) \in \mathit{pStatus}\big) \&\\
& & \qquad\quad \mathit{pStatus} := \mathit{pStatus} \oplus \{(\mathit{releasePaper}? \mapsto \mathit{released})\}\big)\\
\mathit{HideOthersAnswers} & \mathrel{\widehat=} & \mathit{HideOthersAnswers}
\end{array}
$$

$$
\mathit{StudentOptions} \mathrel{\widehat=} \left(\begin{array}{ll}
& \mathit{RegisterforExam}\\
\Box & \mathit{CancelRegistration}\\
\Box & \mathit{TakePaper}\\
\Box & \mathit{GetOwnResult}\\
\Box & \mathit{GetMyAnswers}
\end{array}\right)
$$

Figure A.6 (cont.) : Specification of Secure electronic examination system - *code block 5 of 6*

$$
LecturerOptions \mathrel{\widehat{=}} \left(\begin{array}{ll} & AppointSetter \\ \Box & ResignSetter \\ \Box & AppointChecker \\ \Box & ResignChecker \\ \Box & CloseExam \\ \Box & CheckPaper \\ \Box & AppointMarker \\ \Box & ResignMarker \\ \Box & SetPaper \\ \Box & ReleasePaper \\ \Box & GradePaper \\ \Box & PublishGrades \\ \Box & GetAnyResult \end{array}\right)
$$

$$
Options \mathrel{\widehat{=}} \left(\begin{array}{ll} & LecturerOptions \\ \Box & StudentOptions \end{array}\right) \mathbin{;} HideOthersAnswers
$$

$$
\bullet \langle Init \rangle \mathbin{;} \mu X \bullet \langle Options \mathbin{;} X \rangle
$$

end

Figure A.6 (cont.) : Specification of Secure electronic examination system - *code block 6 of 6*

A.5.3 Case study - ePurse system

A hand-crafted documentation with a formal specification of the ePurse system is presented. A *Circus* action is defined for each use case in the use case diagram of the ePurse system is shown in Figure A.7. The operations performed by these actions are described in Table A.16. It is important to note that the action *Init* in Table A.16 is not in Figure A.7. This is because *Init* initializes system variables and is not executed through external action. The following table of contents may be useful for easy navigation within this case study.

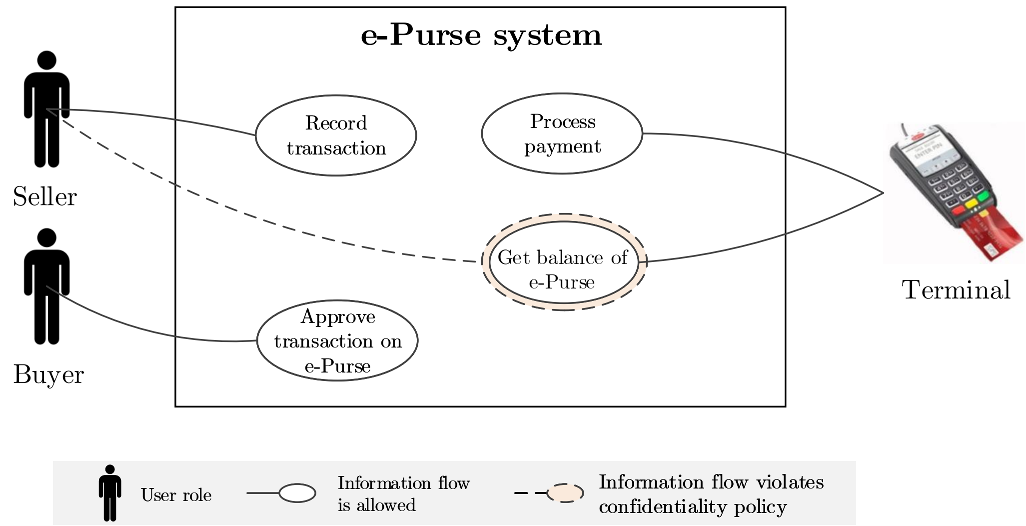


Figure A.7: Use case diagram for the ePurse system

A.5.3.a Operations

The operations of the system are formalized as *Circus* actions and listed in Table A.16.

Table A.16: ePurse system - Description of the *Circus* actions

Action	Operation performed by the action
SelectAgent	Allows the user to select the current agent who is using the system.
RecordTrnsctn	Allows the seller to record the value of a transaction in the system.
ApproveTrnsctn	Allows the ePurse holder to approve charging the value of the transaction from his/her ePurse.
ShowBalSec	Allows only the ePurse owner to check the balance of the ePurse.
DoPayment	Allows the terminal to process the transaction by adjusting value of the transaction from the ePurse.

A.5.3.b Data types of system entities

These basic types declared in the system are described in Table A.17.

Table A.17: ePurse system - Description of the basic types

Basic type	Description
TRANSACTION	set of all possible transaction identifiers
EPURSE	set of all possible epurse identifiers

The free types declared in the system are described in Table A.18.

Table A.18: ePurse system - Description of the free types

Free type	Item	Meaning
AGENT	*buyer*	The current agent is the buyer.
	seller	The current agent is the seller.
	terminal	The current agent is the terminal.
VALIDATED	*yes*	The transaction has been validated.
	no	The transaction has not been validated.

A.5.3.c State variables

A state variable has been declared to represent each organisational component within the system specification. The description of these state variables are included in Table A.19.

Table A.19: ePurse system - Description of the state variables

State variable	Description
owns	A function that identifies the ePurse owned by a buyer, if any.
balance	A function that identifies the balance in an ePurse, if any.

transPurse	A function that identifies the ePurse to which a transaction is charged, if any.
transTerminal	A function that identifies the terminal on which a transaction is recorded, if any.
transAmount	A function that identifies the value of a transaction, if any.
transValid	A function that identifies the validation status of a transaction, if any.
currAgent	The current agent who is using the system.
reqPurse	The ePurse of which a balance is being requested.

A.5.3.d State invariants

We assume certain system constraints that must be respected throughout the life of the system. These constraints reflect the relevant organisational rules that we believe are typical in a phone book system. These constraints are defined as state invariants (Woodcock and Davies, 1996, p. 168) in the system specification.

Table A.20: ePurse system - Description of the state invariants

State invariants	Description
$\mathrm{dom}\ (balance) \subseteq \mathrm{ran}\ owns$	Every ePurse which has a balance must also have an owner.
$\mathrm{ran}\ transPurse \subseteq \mathrm{dom}\ (balance)$	

Every ePurse on to which a transaction is recorded must also have a balance recorded.

$\mathrm{dom}\,(transValid) \subseteq \mathrm{dom}\,(transAmount)$

Every transaction that has a validation status must also have a transation value associated with it.

$\mathrm{dom}\,(transPurse) \subseteq \mathrm{dom}\,(transAmount)$

Every transacation of an ePurse must also have a transation value associated with it.

$\mathrm{dom}\,(transTerminal) \subseteq \mathrm{dom}\,(transAmount)$

Every transacation recorded in a terminal must also have a transation value associated with it.

$reqPurse \in \mathrm{ran}\, owns$

The ePurse of which a balance is being requested must be owned by someone.

$reqPurse \in \mathrm{dom}\,(balance)$

The ePurse of which a balance is being requested must have a balance recorded.

(This page intentionally left blank)

$[\, EPURSE, TRANSACTION \,]$

$$\begin{array}{ll} AGENT & ::= terminal \mid seller \mid buyer \\ VALIDATED & ::= no \mid yes \end{array}$$

$$bmin : \mathbb{N}$$

State

$$\begin{array}{l} transPurse : TRANSACTION \pfun EPURSE \\ transTerminal : TRANSACTION \pfun AGENT \\ currAgent : AGENT \\ transValid : TRANSACTION \pfun VALIDATED \\ balance : EPURSE \pfun \mathbb{N} \\ transAmount : TRANSACTION \pfun \mathbb{N} \\ owns : AGENT \pfun EPURSE \\ reqPurse : EPURSE \\ \hline reqPurse \in \mathrm{dom}\,(balance) \\ reqPurse \in \mathrm{ran}\, owns \\ \mathrm{dom}\,(transTerminal) \subseteq \mathrm{dom}\,(transAmount) \\ \mathrm{dom}\,(transPurse) \subseteq \mathrm{dom}\,(transAmount) \\ \mathrm{dom}\,(transValid) \subseteq \mathrm{dom}\,(transAmount) \\ \mathrm{ran}\, transPurse \subseteq \mathrm{dom}\,(balance) \\ \mathrm{dom}\,(balance) \subseteq \mathrm{ran}\, owns \end{array}$$

HideExactBalance

$$\begin{array}{l} \Xi State \\ \hline \exists\, State_9 \bullet \\ \quad (currAgent \mapsto reqPurse) \notin owns \land \\ \quad currAgent \neq terminal \land \\ \quad reqPurse \in \mathrm{dom}\,(balance) \Rightarrow \\ \qquad (balance\; reqPurse) \neq (balance_9\; reqPurse_9) \end{array}$$

HideMinBalance

$$\begin{array}{l} \Xi State \\ \hline \exists\, State_9 \bullet \\ \quad (currAgent \mapsto reqPurse) \notin owns \land \\ \quad currAgent \neq terminal \land \\ \quad reqPurse \in \mathrm{dom}\,(balance) \land \\ \quad balance\; reqPurse \in \{r : \mathbb{N} \mid r < bmin\} \Rightarrow \\ \qquad balance_9\; reqPurse_9 \notin \{r : \mathbb{N} \mid r < bmin\} \end{array}$$

channel $recordTransAmountIn, showBalEpurseOut, bsout : \mathbb{N}$
channel $epurseOwnerIn, bybIn, approveTransAgentIn, changeAgentIn : AGENT$
channel $payTransEpurseIn, showEpurseIn, epbIn, approveTransEpurseIn : EPURSE$
channel $payTransIn, approveTransIn, recordTransactionIn : TRANSACTION$

$$\begin{array}{lll} \textbf{channelset}\ Buyer & == & \{\!|\, approveTransIn, approveTransAgentIn, approveTransEpurseIn \,|\!\} \\ \textbf{channelset}\ Seller & == & \{\!|\, recordTransAmountIn, recordTransactionIn \,|\!\} \\ \textbf{channelset}\ Terminal & == & \{\!|\, showBalEpurseOut, showEpurseIn, epurseOwnerIn, \\ & & \ payTransIn, payTransEpurseIn \,|\!\} \end{array}$$

Figure A.8: Specification of ePurse system - *code block 1 of 2*

$$
\begin{array}{l}
\textbf{process}\ \mathit{ePurse\_system} \mathrel{\widehat=} \textbf{begin}\\
\quad \textbf{state}\ \mathit{State}\\
\quad \mathit{SelectAgent} \mathrel{\widehat=} \textbf{var}\ \mathit{changeAgent} : \mathit{AGENT} \bullet\\
\qquad \mathit{changeAgentIn}?\mathit{changeAgent} \longrightarrow \mathit{currAgent} := \mathit{changeAgent}?\\
\quad \mathit{RecordTrnsctn} \mathrel{\widehat=} \textbf{var}\ \mathit{recordTransaction} : \mathit{TRANSACTION};\\
\qquad \mathit{recordTransAmount} : \mathbb{N} \bullet\\
\qquad \mathit{recordTransactionIn}?\mathit{recordTransaction} \longrightarrow\\
\qquad \mathit{recordTransAmountIn}?\mathit{recordTransAmount} \longrightarrow\\
\qquad (\big(\mathit{currAgent} = \mathit{seller}\big) \&\\
\qquad\quad \mathit{transAmount} := \mathit{transAmount} \oplus\\
\qquad\qquad \{(\mathit{recordTransaction}? \mapsto \mathit{recordTransAmount}?)\})\\
\quad \mathit{ApproveTrnsctn} \mathrel{\widehat=} \textbf{var}\ \mathit{approveTransEpurse} : \mathit{EPURSE};\\
\qquad \mathit{approveTransAgent} : \mathit{AGENT};\\
\qquad \mathit{approveTrans} : \mathit{TRANSACTION} \bullet\\
\qquad \mathit{approveTransEpurseIn}?\mathit{approveTransEpurse} \longrightarrow\\
\qquad \mathit{approveTransAgentIn}?\mathit{approveTransAgent} \longrightarrow\\
\qquad \mathit{approveTransIn}?\mathit{approveTrans} \longrightarrow\\
\qquad (\big(\mathit{currAgent} = \mathit{buyer} \land \mathit{approveTrans}? \in \operatorname{dom}(\mathit{transAmount})\big) \&\\
\qquad\quad \mathit{transPurse} := \mathit{transPurse} \oplus\\
\qquad\qquad \{(\mathit{approveTrans}? \mapsto \mathit{approveTransEpurse}?)\};\\
\qquad\quad \mathit{transValid} := \mathit{transValid} \oplus \{(\mathit{approveTrans}? \mapsto \mathit{yes})\};\\
\qquad\quad \mathit{transTerminal} := \mathit{transTerminal} \oplus\\
\qquad\qquad \{(\mathit{approveTrans}? \mapsto \mathit{approveTransAgent}?)\})\\
\quad \mathit{ShowBalSec} \mathrel{\widehat=} \textbf{var}\ \mathit{epurseOwner} : \operatorname{dom}(\mathit{owns});\\
\qquad \mathit{showEpurse} : \operatorname{dom}(\mathit{balance}) \cap \operatorname{ran} \mathit{owns} \bullet\\
\qquad \mathit{epurseOwnerIn}?\mathit{epurseOwner} \longrightarrow\\
\qquad \mathit{showEpurseIn}?\mathit{showEpurse} \longrightarrow\\
\qquad \mathit{reqPurse} := \mathit{showEpurse}?;\\
\qquad (\big(\mathit{currAgent} = \mathit{buyer} \land \mathit{currAgent} = \mathit{epurseOwner}? \land\\
\qquad\quad (\mathit{epurseOwner}? \mapsto \mathit{showEpurse}?) \in \mathit{owns}\big) \&\\
\qquad\quad \mathit{showBalEpurseOut}!(\mathit{balance}\ \mathit{showEpurse}?) \longrightarrow \textbf{Skip})\\
\quad \mathit{DoPayment} \mathrel{\widehat=} \textbf{var}\ \mathit{payTransEpurse} : \mathit{EPURSE};\\
\qquad \mathit{payTrans} : \mathit{TRANSACTION} \bullet\\
\qquad \mathit{payTransEpurseIn}?\mathit{payTransEpurse} \longrightarrow\\
\qquad \mathit{payTransIn}?\mathit{payTrans} \longrightarrow\\
\qquad (\big(\mathit{currAgent} = \mathit{terminal} \land \mathit{payTrans}? \in \operatorname{dom}(\mathit{transPurse})\big) \&\\
\qquad\quad \mathit{balance} := \mathit{balance} \oplus\\
\qquad\qquad \{(\mathit{payTransEpurse}? \mapsto\\
\qquad\qquad\quad (\mathit{balance}\ \mathit{payTransEpurse}? - \mathit{transAmount}\ \mathit{payTrans}?))\})\\
\quad \mathit{HideExactBalance} \mathrel{\widehat=} \mathit{HideExactBalance}\\
\quad \mathit{HideMinBalance} \mathrel{\widehat=} \mathit{HideMinBalance}\\
\quad \bullet\ \mu X \bullet \left(\langle \mathit{SelectAgent} \rangle ;\ \left(\begin{array}{ll} & \langle \mathit{ApproveTrnsctn} \rangle \\ \Box & (\langle \mathit{ShowBalSec} \rangle ;\ \langle \mathit{HideExactBalance} \rangle) \\ \Box & \langle \mathit{DoPayment} \rangle \\ \Box & \langle \mathit{RecordTrnsctn} \rangle \end{array} \right) ;\ X \right)\\
\textbf{end}
\end{array}
$$

Figure A.8 (cont.) : Specification of ePurse system - *code block 2 of 2*

Abbreviations

ANTLR	ANother Tool for Language Recognition
ATP	Automatic Theorem Prover
BCF	Banks's Confidentiality Framework
BNF	Backus-Naur Form
CA	Confidentiality Annotation
CML	COMPASS Modelling Language
CNL	Controlled Natural Language
CONCHITA	CONfidentiality CHecker for Incremental Threat Analysis
CSCW	Computer Supported Cooperative Work
CSP	Communicating Sequential Processes
CZT	Community Z Tools
DLP	Data Leak Prevention
DTD	Document Type Definition
E.U.	European Union
FDR	Failures-Divergence Refinement
FTC	Federal Trade Commission

GUI	Graphical user interface
HAZOP	HAZard and OPerability
HiVE	Hierarchical Verification Environment
HOL	Higher-Order Logic
IBAC	Identity-Based Access Control
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KAOS	Knowledge Acquisition in autOmated Specification
LCF	Logic for Computable Functions
LTL	Linear Temporal Logic
ML	Meta Language
OCAML	Object Categorical Abstract Machine Language
OCL	Object Constraint Language
OOPSLA	Object-Oriented Programming Systems Languages & Applications
PII	Personally Identifiable Information
RBAC	Role-Based Access Control
RHODIN	Rigorous Open Development Environment for Complex Systems
SMT	Satisfiability Modulo Theories
SPIN	Simple Promela INterpreter
UML	Unified Modelling Language

UML-RT	Unified Modelling Language - Realtime
UTP	Unifying Theories of Programming
ZF	Zermelo-Fraenkel set theory

List of References

Aagaard, Mark D, Robert B Jones, and Carl-johan H Seger. Lifted-FL : A Pragmatic Implementation of Combined Model Checking and Theorem Proving. page 323, 1999.

Abiteboul, Serge, Richard Hull, and Victor Vianu. *Foundations of databases*. Addison-Wesley Publishing Company, Inc., United States of America, 1995. ISBN 0-201-53771-0. doi: 10.1016/0898-1221(95)90258-9.

Accorsi, Rafael and Claus Wonnemann. InDico: Information Flow Analysis of Business Processes for Confidentiality Requirements. In Cuellar, Jorge, Javier Lopez, and Gilles Barthe Alexander Pretschner, editors, *Proceedings of the 6th international conference on Security and trust management (STM'10)*, pages 194–209. Springer-Verlag Berlin, 2010. ISBN 978-3-642-22443-0, 978-3-642-22444-7. doi: 10.1007/978-3-642-22444-7_13. URL `http://link.springer.com/chapter/10.1007/978-3-642-22444-7_13?null`.

Adolph, S, P Bramble, and A Cockburn. *Patterns for Effective Use Cases*. Crystal collection for software professionals. Addison-Wesley, 2003. ISBN 9780201721843. URL `https://books.google.co.uk/books?id=FGdXBs5uCxMC`.

Ahmed, Tanvir and Anand R. Tripathi. Static verification of security requirements in role based CSCW systems. In *Proceedings of the eighth ACM symposium on Access control models and technologies (SACMAT '03)*, pages 196–203, Como, Italy, 2003. ACM New York, NY, USA. ISBN 1581136811. doi: http://dx.doi.org/10.1145/775412.775438. URL `http://portal.acm.org/citation.cfm?doid=775412.775438`.

Al-Fedaghi, S. S. Privacy as a Base for Confidentiality. *SSRN Electronic Journal*, pages 1–13, 2012. ISSN 1556-5068. doi: 10.2139/ssrn.2012395.

Alexander, Christopher, Sara Ishikawa, and Murray Silverstein. *A Pattern Language: Towns, Buildings, Construction*. Oxford University Press, New York, aug 1977. ISBN 0195019199. URL `http://www.amazon.fr/exec/obidos/ASIN/0195019199/citeulike04-21`.

Alghamdi, Abdullah Sharaf, Tazar Hussain, and Gul Faraz Khan. Enhancing C4I security using threat modeling. *UKSim2010 - UKSim 12th International Conference on Computer Modelling and Simulation*, pages 131–136, 2010. doi: 10.1109/UKSIM.2010.31.

Ambler, Scott W. *Process Patterns: Building Large-scale Systems Using Object Technology*. Cambridge University Press, New York, NY, USA, 1998. ISBN 0-521-64568-9.

Ambysoft, An and Scott W Ambler. An Introduction to Process Patterns. Technical Report September, AmbySoft Inc., 1998.

American National Standard Institute (ANSI), . Procedures for Achieving Content Consistency in ISO/IEC 11179 Metadata Registries. Technical report, Pacific Northwest National Laboratory, Washington, DC, USA, 1999.

Amjad, Hasan. Combining model checking and theorem proving. Technical Report 601, University of Cambridge, Cambridge, 2004. URL `http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Combining+model+checking+and+theorem+proving#0`.

Anderlik, M R and M A Rothstein. Privacy and confidentiality of genetic information: what rules for the new science? *Annual review of genomics and human genetics*, 2: 401–433, 2001. ISSN 1527-8204. doi: 10.1146/annurev.genom.2.1.401.

Andreson, Ross. *Security Engineering*. Number 1. 2014. ISBN 9780874216561. doi: 10.1007/s13398-014-0173-7.2.

Andrews, Paul S, Adam T Sampson, John Markus Bjørndalen, Susan Stepney, Jon Timmis, Douglas N Warren, and Peter H Welch. Investigating Patterns for the Process-Oriented Modelling and Simulation of Space in Complex Systems. *Artificial Life XI Proceedings of the Eleventh International Conference on the Simulation and Synthesis of Living Systems*, pages 17–24, 2008. URL `http://kar.kent.ac.uk/24033/`.

Andronick, J, B Chetali, and O Ly. Using Coq to verify Java Card applet isolation properties. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2758:335–351, 2003. ISSN 0302-9743. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-35248858397&partnerID=40&md5=4aa2672bfb9233176f0682b34540c461`.

Angkasaputra, Niniek and Dietmar Pfahl. Making software process simulation modeling agile and pattern-based. *Simulation*, 11:12, 2004.

Anthem, Inc. 2014 Annual report - Anthem Inc. Technical report, Anthem, Inc., 2014. URL `http://media.corporate-ir.net/media_files/IROL/13/130104/2014AR/export7/pdfs/Anthem_2014AR.pdf`.

Antón, Annie I. and Julia B. Earp. A Taxonomy for Web Site Privacy Requirements. Technical report, North Carolina State University, Raleigh, NC, USA, 2001. URL `http://www4.ncsu.edu/$\sim$jbearp/TSE.pdf`.

Appleton, Brad. Patterns for conducting process improvement. In *Proceedings of PLOP*, volume 97, 1997.

Arkoudas, Konstantine, Sarfraz Khurshid, Darko Marinov, and Martin Rinard. *Integrating Model Checking and Theorem Proving for Relational Reasoning*, pages 21–33. Springer Berlin Heidelberg, Berlin, Heidelberg, 2004. ISBN 978-3-540-24771-5. doi: 10.1007/978-3-540-24771-5_3. URL `https://doi.org/10.1007/978-3-540-24771-5_3`.

Article 29 Working Party, . Opinion 03/2013 on purpose limitation, WP203,. Technical Report April, European Commission, 2013.

Atelier-B, . The industrial tool to efficiently deploy the B Method. 2017. URL http://www.atelierb.eu/en/.

Back, Ralph Johan. *Correctness Preserving Program Refinements: Proof Theory and Applications*. Mathematisch centrum, Amsterdam, 1980. ISBN 9061962072.

Back, Ralph-Johan and Joakim Wright. *Refinement Calculus: A Systematic Introduction*. Springer-Verlag New York, 1998. ISBN 0387984178. URL http://www.springer.com/gb/book/9780387984179.

Baggetun, Rusman E Poggi C, Ellen Rusman, and Caterina Poggi. R. Design patterns for collaborative learning: From practice to theory and back. In *Proceedings of International Conference on Educational Multimedia, Hypermedia and Telecommunications*, volume 53, page 277. Citeseer, 2004.

Banks, Michael J. *On Confidentiality and Formal Methods*. PhD thesis, The University of York, 2012. URL http://etheses.whiterose.ac.uk/2709/.

Banks, Michael J. and Jeremy L. Jacob. Specifying Confidentiality in Circus. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 6664 LNCS:215–230, 2011. ISSN 03029743. doi: 10.1007/978-3-642-21437-0_18.

Banks, Michael J. and Jeremy L. Jacob. On integrating confidentiality and functionality in a formal method. *Formal Aspects of Computing*, 26(5):963–992, 2014. ISSN 0934-5043. doi: 10.1007/s00165-013-0285-4. URL http://link.springer.com/10.1007/s00165-013-0285-4.

Barden, Rosalind, Susan Stepney, and David Cooper. *Z in practice*. BCS practitioner series. Prentice Hall, 1995. ISBN 978-0-13-124934-9.

Barrett, Clark and Cesare Tinelli. CVC3. In Damm, Werner and Holger Hermanns, editors, *Computer Aided Verification: 19th International Conference, CAV 2007, Berlin, Germany, July 3-7, 2007. Proceedings*, pages 298–302. Springer Berlin Heidelberg, Berlin, Heidelberg, 2007. ISBN 978-3-540-73368-3. doi: 10.1007/978-3-540-73368-3_34. URL `http://dx.doi.org/10.1007/978-3-540-73368-3_34`.

Barrett, Clark, Christopher L Conway, Morgan Deters, Liana Hadarean, Dejan Jovanović, Tim King, Andrew Reynolds, and Cesare Tinelli. CVC4. In Gopalakrishnan, Ganesh and Shaz Qadeer, editors, *Computer Aided Verification: 23rd International Conference, CAV 2011, Snowbird, UT, USA, July 14-20, 2011. Proceedings*, pages 171–177. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-22110-1. doi: 10.1007/978-3-642-22110-1_14. URL `http://dx.doi.org/10.1007/978-3-642-22110-1_14`.

Barrocas, S L M and M V M Oliveira. JCircus 2.0: an Extension of an Automatic Translator from Circus to Java. *Communicating Process Architectures*, 34(55):15–36, 2012.

Barthe, Gilles and Guillaume Dufay. Formal Methods for Smartcard Security. In Aldini, Alessandro, Roberto Gorrieri, and Fabio Martinelli, editors, *Foundations of Security Analysis and Design III*, chapter Formal Met, pages 133–177. Springer-Verlag, Berlin, Heidelberg, 2005. ISBN 3-540-28955-0, 978-3-540-28955-5. URL `http://dl.acm.org/citation.cfm?id=2137760.2137767`.

Basin, David, Jürgen Doser, and Torsten Lodderstedt. Model driven security for process-oriented systems. *Proceedings of the eighth ACM symposium on Access control models and technologies - SACMAT '03*, page 100, 2003. doi: 10.1145/775423.775425. URL `http://portal.acm.org/citation.cfm?doid=775412.775425`.

BBC News, . Adobe hack: At least 38 million accounts breached. Http://www.bbc.co.uk/news/technology-24740873, 2013. URL `http://www.bbc.co.uk/news/technology-24740873`.

BBC News, . Ashley Madison faces huge class-action lawsuit. http://www.bbc.co.uk/news/business-34032760, 2015. URL `http://www.bbc.co.uk/news/business-34032760`.

Becker, Moritz Y. Information governance in NHS's NPfIT: A case for policy specification. *International Journal of Medical Informatics*, 76(5-6):432–437, 2007. ISSN 13865056. doi: 10.1016/j.ijmedinf.2006.09.008.

Benzmüller, Christoph, Lawrence C Paulson, Frank Theiss, and Arnaud Fietzke. LEO-II - A Cooperative Automatic Theorem Prover for Classical Higher-Order Logic (System Description). In Armando, Alessandro, Peter Baumgartner, and Gilles Dowek, editors, *Automated Reasoning: 4th International Joint Conference, IJCAR 2008 Sydney, Australia, August 12-15, 2008 Proceedings*, pages 162–170. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. ISBN 978-3-540-71070-7. doi: 10.1007/978-3-540-71070-7_14. URL `http://dx.doi.org/10.1007/978-3-540-71070-7_14`.

Bevan, N and M Azuma. Quality in use: incorporating human factors into the software engineering lifecycle. In *Proceedings of IEEE International Symposium on Software Engineering Standards*, pages 169–179, jun 1997. doi: 10.1109/SESS.1997.595963.

Bézivin, Jean, Frédéric Jouault, and Jean Paliès. Towards model transformation design patterns. In *Proceedings of the First European Workshop on Model Transformations (EWMT 2005)*, page 116, 2005.

Bjørner, Nikolaj S, Zohar Manna, Henny B Sipma, and Tomás E Uribe. *Deductive verification of real-time systems using STeP*, pages 22–43. Springer Berlin Heidelberg, Berlin, Heidelberg, 1997. ISBN 978-3-540-69058-0. doi: 10.1007/3-540-63010-4_3. URL `https://doi.org/10.1007/3-540-63010-4_3`.

Black, Jennifer Ann. *CARNEGIE INSTITUTE OF TECHNOLOGY SYSTEM SAFETY AS AN EMERGENT PROPERTY IN COMPOSITE SYSTEMS*. PhD thesis, CARNEGIEMELLON UNIVERSITY, 2009.

Blanchet, Bruno. Automated Verification of Selected Equivalences for Security Protocols. *The Journal of Logic and Algebraic Programming*, 75(1):3–51, 2008. URL `http://www.sciencedirect.com/science/article/pii/S1567832607000549`.

Blanchette, Jasmin Christian and Lawrence C Paulson. Hammering Away: A User's Guide to Sledgehammer for Isabelle/HOL, 2016. URL `http://isabelle.in.tum.de/dist/doc/sledgehammer.pdf`.

Bobot, François, Sylvain Conchon, Evelyne Contejean, and Stéphane Lescuyer. Implementing polymorphism in SMT solvers. In *Proceedings of the Joint Workshops of the 6th International Workshop on Satisfiability Modulo Theories and 1st International Workshop on Bit-Precise Reasoning*, pages 1–5. ACM, 2008.

Böhme, Sascha and Tjark Weber. Fast LCF-style proof reconstruction for Z3. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 6172 LNCS:179–194, 2010. ISSN 03029743. doi: 10.1007/978-3-642-14052-5_14.

Bote-Lorenzo, Miguel L, Davinia Hernández Leo, Yannis Dimitriadis, Juan I Asensio-Pérez, Eduardo Gómez-Sánchez, Guillermo Vega-Gorgojo, and Luis M Vaquero-Gónzalez. Towards reusability and tailorability in collaborative learning systems using IMS-LD and Grid Services. *Advanced Technology for Learning. 2004; 1 (3): 129-138*, 2004.

Bouaziz, Rahma, Brahim Hamid, and Nicolas Desnos. Towards a Better Integration of Patterns in Secure Component-based Systems Design. In *Proceedings of the 2011 International Conference on Computational Science and Its Applications - Volume Part V*, ICCSA'11, pages 607–621, Berlin, Heidelberg, 2011. Springer-Verlag. ISBN 978-3-642-21933-7. URL `http://dl.acm.org/citation.cfm?id=2029427.2029483`.

Bouton, Thomas, Diego Oliveirade , David Déharbe, and Pascal Fontaine. veriT: An Open, Trustable and Efficient SMT-Solver. In Schmidt, Renate A, editor, *Automated Deduction – CADE-22: 22nd International Conference on Automated Deduction, Montreal, Canada, August 2-7, 2009. Proceedings*, pages 151–156. Springer Berlin Heidelberg, Berlin, Heidelberg, 2009. ISBN 978-3-642-02959-2. doi: 10.1007/978-3-642-02959-2_12. URL `http://dx.doi.org/10.1007/978-3-642-02959-2_12`.

Bovet, Jean and Terence Parr. ANTLRWorks: an ANTLR grammar development environment. *Software: Practice and Experience*, 38(12):1305–1332, 2008.

Bowen, Jonathan and Mike Gordon. Z and HOL. In Bowen, J. P. and J. A. Hall, editors, *Z User Workshop, Cambridge 1994*, pages 141–167. Springer London, Cambridge, 1994. ISBN 3-540-19884-9.

Bowen, Jonathan P. Formal Specification and Documentation using Z: A Case Study Approach. *Citeseer*, 1996. URL `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.14.8627&rep=rep1&type=pdf`.

Bresciani, Paolo, Anna Perini, Paolo Giorgini, Fausto Giunchiglia, and John Mylopoulos. Tropos: An agent-oriented software development methodology. *Autonomous Agents and Multi-Agent Systems*, 8(3):203–236, 2004. ISSN 13872532. doi: 10.1023/B:AGNT.0000018806.20944.ef.

Brown, Chad E. Satallax: An Automatic Higher-Order Prover. In Gramlich, Bernhard, Dale Miller, and Uli Sattler, editors, *Automated Reasoning: 6th International Joint Conference, IJCAR 2012, Manchester, UK, June 26-29, 2012. Proceedings*, pages 111–117. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012. ISBN 978-3-642-31365-3. doi: 10.1007/978-3-642-31365-3_11. URL `http://dx.doi.org/10.1007/978-3-642-31365-3_11`.

Brucker, Achim D., Stefan Friedrich, Frank Rittinger, and Burkhart Wolff. HOL-Z 2.0: A Proof Environment for Z-Specifications. *Journal of Universal Computer Science*, 9(2): 152—-172, 2003.

Büchi, J Richard. On a decision method in restricted second order arithmetic. In *Proceedings of the International Congress on Logic, Method, and Philosophy of Science*, pages 1–12. Stanford University Press, 1960.

Burgemeestre, Brigitte, Joris Hulstijn, and Yao Hua Tan. Value-based argumentation for designing and auditing security measures. *Ethics and Information Technology*, 15(3): 153–171, 2013. ISSN 13881957. doi: 10.1007/s10676-013-9325-2.

Burnette, Ed. *Eclipse IDE Pocket Guide*. O'Reilly Media, Inc., 2005. ISBN 0596100655.

Buschmann, Frank, Regine Meunier, Hans Rohnert, Peter Sommerlad, and Michael Stal. *Pattern-Oriented Software Architecture - Volume 1: A System of Patterns*. Wiley Publishing, 1996. ISBN 0471958697, 9780471958697.

Butler, Michael and Stefan Hallerstede. The Rodin Formal Modelling Tool. *BCSFACS Christmas 2007 Meeting Formal Methods In Industry London*, pages 1–5, 2007. URL `http://eprints.ecs.soton.ac.uk/14949/`.

Cabral, Gustavo and Augusto Sampaio. Automated formal specification generation and refinement from requirement documents. *Journal of the Brazilian Computer Society*, 14(1):87–106, mar 2008. ISSN 1678-4804. doi: 10.1007/BF03192554. URL `https://doi.org/10.1007/BF03192554`.

Campbell, Jeffrey D. Interaction in collaborative computer supported diagram development. *Computers in Human Behavior*, 20(2):289–310, 2004. ISSN 0747-5632. doi: http://dx.doi.org/10.1016/j.chb.2003.10.019. URL `http://www.sciencedirect.com/science/article/pii/S0747563203000918`.

Cant, A. Program Verification using Higher Order Logic. Technical report, Australian Government, 1992. URL `http://dspace.dsto.defence.gov.au/dspace/handle/1947/9036`.

Cant, Tony, Brendan Mahony, and Jim McCarthy. Design Oriented Verification and Evaluation : The Dove Project. Technical report, DSTO Information Sciences Laboratory, Edinburgh, South Australia, Australia 5111, 2002. URL http://dspace.dsto.defence.gov.au/dspace/handle/1947/4378.

Cao, Longbing and Philip S. Yu. *Behavior Computing*. Springer-Verlag, London, 2012. ISBN 9781447129684. doi: 10.1007/978-1-4471-2969-1.

Cao, Xiao Ming and Xiangrui Wang. A computer- assisted assessment and diagnosis system for arts students-oriented computer education. *2009 International Conference on Education Technology and Computer, ICETC 2009*, pages 289–293, 2009. doi: 10.1109/ICETC.2009.53.

Casset, Ludovic. *Development of an Embedded Verifier for Java Card Byte Code Using Formal Methods*, pages 290–309. Springer Berlin Heidelberg, Berlin, Heidelberg, 2002. ISBN 978-3-540-45614-8. doi: 10.1007/3-540-45614-7_17.

Cast Software .Inc, . Study finds seven out of ten retailer and finance applcations vulnerable to Heartbleed-style attacks. Technical report, Cast Software .Inc, New York, NY 10016, 2014. URL http://www.castsoftware.com/discover-cast/press-releases.

CAUSE, . Privacy and the Handling of Student Information in the Electronic Networked Environments of Colleges and universities. Technical report, CAUSE, Boulder, Colorado, 1997. URL https://library.educause.edu/$\sim$/media/files/library/1997/1/pub3102-pdf.pdf.

Cavalcanti, Ana and Marie-Claude Gaudel. Data Flow Coverage for Circus-Based Testing. In Gnesi, Stefania and Arend Rensink, editors, *Fundamental Approaches to Software Engineering: 17th International Conference, FASE 2014, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2014, Grenoble, France, April 5-13, 2014, Proceedings*, pages 415–429. Springer Berlin Heidelberg, Berlin, Heidelberg, 2014. ISBN 978-3-642-54804-8. doi: 10.1007/978-3-642-54804-8_29. URL http://dx.doi.org/10.1007/978-3-642-54804-8_29.

Cavalcanti, Ana and Jim Woodcock. A Predicate Transformer Semantics for a Concurrent Language of Refinement. *Communicating Process Architectures*, pages 147–166, 2002.

Cavalcanti, Ana and Jim Woodcock. A tutorial introduction to CSP in unifying theories of programming. *Refinement Techniques in Software Engineering*, pages 220–268, 2006. ISSN 03029743. doi: 10.1007/11889229_6. URL http://eprints.whiterose.ac.uk/70560/.

Cavalcanti, Ana, Augusto Sampaio, and Jim Woodcock. Procedures and Recursion in the Refinement Calculus. *Journal of the Brazilian Computer Society*, 5:0, 1998. ISSN 0104-6500. URL http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-65001998000200002&nrm=iso.

Cavalcanti, Ana, Phil Clayton, and Colin O'Halloran. Control Law Diagrams in Circus. In Fitzgerald, John, Ian J Hayes, and Andrzej Tarlecki, editors, *FM 2005: Formal Methods: International Symposium of Formal Methods Europe, Newcastle, UK, July 18-22, 2005. Proceedings*, pages 253–268. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005. ISBN 978-3-540-31714-2. doi: 10.1007/11526841_18. URL http://dx.doi.org/10.1007/11526841_18.

Cavalcanti, Ana, Will Harwood, and Jim Woodcock. Pointers and Records in the Unifying Theories of Programming. In Dunne, Steve and Bill Stoddart, editors, *Unifying Theories of Programming: First International Symposium, UTP 2006, Walworth Castle, County Durham, UK, February 5-7, 2006, Revised Selected Papers*, pages 200–216. Springer Berlin Heidelberg, Berlin, Heidelberg, 2006. ISBN 978-3-540-34752-1. doi: 10.1007/11768173_12. URL http://dx.doi.org/10.1007/11768173_12.

Cavalcanti, Ana, Phil Clayton, and Colin O'Halloran. From control law diagrams to Ada via Circus. *Formal Aspects of Computing*, 23(4):465–512, 2011. ISSN 1433-299X. doi: 10.1007/s00165-010-0170-3. URL http://dx.doi.org/10.1007/s00165-010-0170-3.

Cavalcanti, Ana L C, Augusto C A Sampaio, and Jim Woodcock. A unified language of classes and processes. In *St Eve: State-Oriented vs. Event-Oriented Thinking in Requirements Analysis, Formal Specification and Software Engineering*, Satellite Workshop at FM'03, 2003. URL `http://kar.kent.ac.uk/13842/`.

Cavoukian, Ann. Privacy by Design. Technical report, Information and Privacy Commissioner of Ontario, Ontario, Canada, 2009.

Cavoukian, Ann and Mark Dixon. Privacy and Security by Design: A Convergence of Paradigms. In Cavoukian, Ann, editor, *Privacy by Design. From rhetoric to reality*, pages 209–226. Information and Privacy Commissioner of Ontario, Ontario, Canada, 2013.

Cerny, Pavol and Rajeev Alur. Automated Analysis of Java Methods for Con dentiality. *Computer Aided Verification*, pages 173–187, 2009a.

Cerny, Pavol and Rajeev Alur. Automated Analysis of Java Methods for Confidentiality. *Computer Aided Verification*, pages 173–187, 2009b.

Chandra, S. and R.A Khan. Confidentiality checking an object-oriented class hierarchy. *Network Security*, 2010(3):16–20, 2010. ISSN 13534858. doi: 10.1016/S1353-4858(10)70037-4.

Cheng, Shang-wen and David Garlan. Mapping Architectural Concepts to UML-RT. In *International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'2001)*, 2001.

Chetali, Boutheina and Quang-huy Nguyen. Industrial Use of Formal Methods for a High-Level Security Evaluation. *FM 2008: Formal Methods*, pages 198–213, 2008. doi: 10.1007/978-3-540-68237-0_15.

Chivers, Howard Robert. *Security Design Analysis*. PhD thesis, University of York, UK, 2006.

Churchill, Andrew. 'Privacy and public policy delivery - Dichotomy or design'. *Information Security Technical Report*, 14(3):131–137, 2009. ISSN 13634127. doi: 10.1016/j.istr.2009.10.009. URL `http://dx.doi.org/10.1016/j.istr.2009.10.009`.

Clark, David, Chris Hankin, and Sebastian Hunt. Information flow for Algol-like languages. *Computer Languages, Systems and Structures*, 28(1):3–28, 2002. doi: http://dx.doi.org/10.1016/S0096-0551(02)00006-1.

Clark, Peter, Philip Harrison, Thomas Jenkins, John A Thompson, and Richard H Wojcik. Acquiring and Using World Knowledge Using a Restricted Subset of English. *FLAIRS Conference*, pages 506–511, 2005.

Cofer, Darren. Model checking: Cleared for take off. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 6349 LNCS:76–87, 2010. ISSN 03029743. doi: 10.1007/978-3-642-16164-3_6.

Coleman, JoeyW., Luis Diogo Couto, Kenneth Lausdahl, Claus Ballegaard Nielsen, Anders Kaels Malmos, Peter Gorm Larsen, Richard Payne, Simon Foster, Alvaro Miyazawa, Uwe Schulze, Adalberto Cajueiro, and Andre Didier. Fourth Release of the COMPASS Tool Symphony IDE User Manual, 2014. URL `http://www.compass-research.eu/Project/Deliverables/D31.4a.pdf`.

Computing Research Association, . Four Grand Challenges in Trustworthy Computing: Second in a Series of Conferences on Grand Research Challenges in Computer Science and Engineering. Technical report, Computing Research Association, 2003. URL `http://archive.cra.org/reports/trustworthy.computing.pdf`.

Condamines, Anne and Maxime Warnier. Linguistic Analysis of Requirements of a Space Project and Their Conformity with the Recommendations Proposed by a Controlled Natural Language. In Davis, Brian, Kaarel Kaljurand, and Tobias Kuhn, editors, *Controlled Natural Language: 4th International Workshop, CNL 2014, Galway, Ireland, August 20-22, 2014. Proceedings*, pages 33–43. Springer International Publishing, Cham, 2014. ISBN 978-3-319-10223-8. doi: 10.1007/978-3-319-10223-8_4. URL `http://dx.doi.org/10.1007/978-3-319-10223-8_4`.

Coplien, J. Patterns of engineering. *IEEE Potentials*, 23(2):4–8, apr 2004. ISSN 0278-6648. doi: 10.1109/MP.2004.1289991.

Crocker, David. Perfect Developer: A tool for Object-Oriented Formal Specification and Refinement. In *Tools Exhibition Notes at Formal Methods Europe*. Escher Technologies Ltd., Mallard House, Hillside Road, Ash Vale, Aldershot GU12 5BJ, UK, 2003.

Cruanes, Simon. *Extending Superposition with Integer Arithmetic, Structural Induction, and Beyond*. Theses, École polytechnique, sep 2015. URL `https://hal.archives-ouvertes.fr/tel-01223502`.

Dabaghchian, Maryam and Mohammad Abdollahi Azgomi. Model checking the observational determinism security property using PROMELA and SPIN. *Formal Aspects of Computing*, 27(5-6):789–804, 2015. ISSN 1433299X. doi: 10.1007/s00165-014-0331-x.

Dam, Mads and Pablo Giambiagi. Confidentiality for mobile code: the case of a simple payment protocol. *Proceedings 13th IEEE Computer Security Foundations Workshop. CSFW-13*, pages 233–244, 2000. ISSN 10636900. doi: 10.1109/CSFW.2000.856940. URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=856940`.

David, Julie Smith and Marilyn Prosch. Extending the value chain to incorporate privacy by design principles. *Identity in the Information Society*, 3(2):295–318, 2010. ISSN 18760678. doi: 10.1007/s12394-010-0059-6. URL `http://www.springerlink.com/index/10.1007/s12394-010-0059-6`.

De Capitani di Vimercati, Sabrina, Robert F. Erbacher, Sara Foresti, Sushil Jajodia, Giovanni Livraga, and Pierangela Samarati. Encryption and fragmentation for data confidentiality in the cloud. In Aldini, Alessandro, Javier Lopez, and Fabio Martinelli, editors, *Foundations of Security Analysis and Design VII: FOSAD 2012/2013 Tutorial Lectures*, pages 212–243. Springer International Publishing, Cham, Switzerland, 2014. ISBN 978-3-319-10081-4, 978-3-319-10082-1. doi: 10.1007/978-3-319-10082-1_8. URL `http://link.springer.com/chapter/10.1007/978-3-319-10082-1_8`.

De Landtsheer, Renaud and Axel Van Lamsweerde. Reasoning about confidentiality at requirements engineering time. *Proceedings of the 10th European software engineering conference held jointly with 13th ACM SIGSOFT international symposium on Foundations of software engineering*, pages 41–49, 2005. doi: 10.1145/1081706.1081715. URL `http://portal.acm.org/citation.cfm?id=1081715`.

Defence Science and Technology Organisation, . The PARTI Architecture Assurance. Technical report, Defence Science and Technology Organisation, Department of Defence, Government of Australia, Edinburgh, South Australia 5111, Australia, 2008.

Denning, Dorothy. The limits of formal security models. *National Computer Systems Security Award Acceptance Speech*, 18, 1999.

Denning, Dorothy E. A lattice model of secure information flow. *Communications of the ACM*, 19(5):236–243, 1976. ISSN 00010782. doi: 10.1145/360051.360056.

Depaula, Nic. A Sophistication Index for Evaluating Security Breaches. *Symposium on information assurance*, (11):26–31, 2016.

Derrick, John, Siobhán North, and Anthony J H Simons. Z2SAL: a translation-based model checker for Z. *Formal Aspects of Computing*, 23(1):43–71, 2011. ISSN 1433-299X. doi: 10.1007/s00165-009-0126-7. URL `http://dx.doi.org/10.1007/s00165-009-0126-7`.

Dijkstra, Edsger W. Notes on Structured Programming. In Dahl, Ole-Johan, C.A.R. Hoare, and Edsger W. Dijkstra, editors, *Structured programming*, chapter Notes on S, pages 1–82. Academic Press Ltd. London, UK, UK, 1972. ISBN 0-12-200550-3.

Dijkstra, Edsger W. Guarded commands, non-determinacy and formal derivation of programs. *ACM SIGPLAN Notices*, 18(6):453–457, 1975. ISSN 03621340. doi: 10.1145/390016.808417.

Dijkstra, Edsger W. *A Discipline of Programming*. Prentice Hall PTR, Upper Saddle River, NJ, USA, 1st edition, 1997. ISBN 013215871X.

Dijkstra, Edsger W and Carel S Scholten. *Predicate Calculus and Program Semantics*. Springer-Verlag New York, Inc., New York, NY, USA, 1990. ISBN 0-387-96957-8.

Dingel, Jürgen and Thomas Filkorn. *Model checking for infinite state systems using data abstraction, assumption-commitment style reasoning and theorem proving*, pages 54–69. Springer Berlin Heidelberg, Berlin, Heidelberg, 1995. ISBN 978-3-540-49413-3. doi: 10.1007/3-540-60045-0_40. URL `https://doi.org/10.1007/3-540-60045-0_40`.

Durr, E and J Katwijkvan . VDM++, a formal specification language for object-oriented designs. In *CompEuro 1992 Proceedings Computer Systems and Software Engineering*, pages 214–219, may 1992. doi: 10.1109/CMPEUR.1992.218511.

Dutertre, Bruno. *Yices 2.2*. Lecture Notes in Computer Science. Springer International Publishing, 2014. doi: 10.1007/978-3-319-08867-9_49.

Dwyer, Matthew B., George S. Avrunin, and James C. Corbett. Property specification patterns for finite-state verification. *Proceedings of the second workshop on Formal methods in software practice - FMSP '98*, pages 7–15, 1998. doi: 10.1145/298595.298598. URL `http://dl.acm.org/citation.cfm?id=298598`.

Dwyer, M.B., G.S. Avrunin, and J.C. Corbett. Patterns in property specifications for finite-state verification. *Proceedings of the 1999 International Conference on Software Engineering (IEEE Cat. No.99CB37002)*, pages 411–420, 1999. ISSN 0270-5257. doi: 10.1145/302405.302672.

Easterbrook, Steve, Janice Singer, Margaret-Anne Storey, and Daniela Damian. Selecting Empirical Methods for Software Engineering Research. In Shull, Forrest, Janice Singer, and Dag I. K. Sjøberg, editors, *Guide to Advanced Empirical Software Engineering*, volume 53, pages 296–297. Springer-Verlag, London, 2008. ISBN 9788578110796. doi: 10.1017/CBO9781107415324.004. URL https://doi.org/10.1007/978-1-84800-044-5_11.

Eckel, Bruce. *Thinking in Java (4th Edition)*. Prentice Hall PTR, Upper Saddle River, NJ, USA, 2005. ISBN 0131872486.

Edelkamp, Stefan. *Data structures and learning algorithms in state space search*. PhD thesis, PhD thesis, University of Freiburg, 1999. Infix, 1999.

Edelkamp, Stefan, Alberto Lluch Lafuente, and Stefan Leue. Protocol Verification with Heuristic Search. Technical report, Association for the Advancement of Artificial Intelligence, 2001. URL http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.26.6752.

El-Hadary, Hassan and Sherif El-Kassas. Capturing security requirements for software systems. *Journal of Advanced Research*, 5(4):463–472, 2014. ISSN 20901232. doi: 10.1016/j.jare.2014.03.001. URL http://linkinghub.elsevier.com/retrieve/pii/S2090123214000332.

Elahi, Golnaz, Eric Yu, and Nicola Zannone. A Vulnerability-centric Requirements Engineering Framework: Analyzing Security Attacks, Countermeasures, and Requirements Based on Vulnerabilities. *Requir. Eng.*, 15(1):41–62, mar 2010. ISSN 0947-3602. doi: 10.1007/s00766-009-0090-z. URL http://dx.doi.org/10.1007/s00766-009-0090-z.

Ellis, Timothy J. and Yair Levy. A guide for novice researchers: Design and development research methods. In *Proceeding of the Informing Science and Information Technology Education Conference (InSITE) 2010*, pages 108–118. Nova Southeastern University, 2010. URL http://nsuworks.nova.edu/gscis_facpres/111/.

European Digital Rights, . Key aspects of the proposed General Data Protection Regulation explained : What are they ? Why are they important ? What are common misconceptions ? What can be improved ? Technical report, European Digital Rights, Brussels, 2012. URL https://edri.org/files/GDPR-key-issues-explained.pdf.

European Parliament, . Protection of individuals with regard to the processing of personal data (General Data Protection Regulation Draft). *European Parliament Texts Adopted*, 2014. URL http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P7-TA-2014-0212+0+DOC+XML+V0//EN.

Farkas, Csilla and Sushil Jajodia. The Inference Problem: A Survey. *SIGKDD Explor. Newsl.*, 4(2):6–11, dec 2002. ISSN 1931-0145. doi: 10.1145/772862.772864. URL http://doi.acm.org/10.1145/772862.772864.

Federal Trade Commision (FTC), . Protecting Consumer in an Era of Rapid Change: Recommendations for businesses and policymakers. *Federal Trade Commision*, (March): 1– 112, 2012.

Federal Trade Commission, . Protecting Consumer Privacy in an Era of Rapid Change: A proposed framework for businesses and policymakers. *Preliminary FTC Staff Report*, (December), 2010.

Feliachi, Abderrahmane, Marie-Claude Gaudel, and Burkhart Wolff. *Isabelle/Circus: A Process Specification and Verification Environment*, pages 243–260. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012. ISBN 978-3-642-27705-4. doi: 10.1007/978-3-642-27705-4_20. URL https://doi.org/10.1007/978-3-642-27705-4_20.

Feliachi, Abderrahmane, Marie-claude Gaudel, and Makarius Wenzel. The Circus Testing Theory Revisited in Isabelle / HOL. In *International Conference on Formal Engineering Methods*, Lecture Notes in Computer Science, pages 131–147. Springer Berlin Heidelberg, 2013.

Ferraiolo, David and Richard Kuhn. Role-Based Access Control. In *In 15th NIST-NCSC National Computer Security Conference*, pages 554–563, Baltimore, MD, oct 1992. ISBN 1580533701. doi: 10.1109/2.485845.

Feuto Njonko, Paul Brillant, Sylviane Cardey, Peter Greenfield, and Walid El Abed. RuleCNL: A Controlled Natural Language for Business Rule Specifications. In Davis, Brian, Kaarel Kaljurand, and Tobias Kuhn, editors, *Controlled Natural Language: 4th International Workshop, CNL 2014, Galway, Ireland, August 20-22, 2014. Proceedings*, pages 66–77. Springer International Publishing, Cham, 2014. ISBN 978-3-319-10223-8. doi: 10.1007/978-3-319-10223-8_7. URL `http://dx.doi.org/10.1007/978-3-319-10223-8_7`.

Fiadeiro, J L and L F Andrade. Interconnecting objects via contracts. In *Proceedings Technology of Object-Oriented Languages and Systems. TOOLS 38*, pages 182–183, 2001. doi: 10.1109/TOOLS.2001.911771.

Foley, S.N. and J. Jacob. Specifying security for CSCW systems. In *Proceedings The Eighth IEEE Computer Security Foundations Workshop*, pages 136–145, jun 1995. ISBN 0-8186-7033-9. doi: 10.1109/CSFW.1995.518559. URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=518559`.

Foster, Simon and Richard Payne. COMPASS Theorem Proving Support - Developers Manual. Technical Report September, European Commission, 2013. URL `http://www.compass-research.eu/Project/Deliverables/D332b.pdf`.

Fowler, M. *Analysis Patterns: Reusable Object Models*. Addison-Wesley series in object-oriented software engineering. Addison-Wesley, 1997. ISBN 9780201895421. URL `https://books.google.co.uk/books?id=4V8pZmpwmBYC`.

Freitas, Angela and Ana Cavalcanti. Automatic Translation from Circus to Java. In Misra, Jayadev, Tobias Nipkow, and Emil Sekerinski, editors, *FM 2006: Formal Methods: 14th International Symposium on Formal Methods, Hamilton, Canada, August 21-27, 2006. Proceedings*, pages 115–130. Springer Berlin Heidelberg, Berlin, Heidelberg, 2006. ISBN 978-3-540-37216-5. doi: 10.1007/11813040_9. URL http://dx.doi.org/10.1007/11813040_9.

Freitas, Leo. *Model checking Circus*. PhD thesis, University of York, 2005.

Freitas, Leo and Iain Whiteside. Proof patterns for formal methods. In *International Symposium on Formal Methods*, pages 279–295. Springer, 2014.

Freitas, Leonardo. Proving Theorems with Z/Eves. Technical Report July, University of Kent, 2004.

Fuchs, Norbert E, Kaarel Kaljurand, and Tobias Kuhn. *Attempto Controlled English for Knowledge Representation*, pages 104–124. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. ISBN 978-3-540-85658-0. doi: 10.1007/978-3-540-85658-0_3. URL https://doi.org/10.1007/978-3-540-85658-0_3.

Gamma, Erich, Richard Helm, Ralph Johnson, and John Vlissides. *Design Patterns: Elements of Reusable Object-oriented Software*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1995. ISBN 0-201-63361-2.

Gangemi, A, A Gómez-Pérez, V Presutti, and Mari Carmen Suárez-Figueroa. Towards a Catalog of OWL-based Ontology Design Patterns. In *Actas de la XII Conferencia de la Asociación Española para la Inteligencia Artificial*, 2007. URL http://oa.upm.es/5212/.

Garvey, T D, T F Lunt, and M E Stickel. Abductive and approximate reasoning models for characterizing inference channels. In *Proceedings Computer Security Foundations Workshop IV*, pages 118–126, jun 1991. doi: 10.1109/CSFW.1991.151578.

Gemalto, . First Half Review 2015 - Findings from the BREACH LEVEL INDEX. Technical report, Gemalto, 2015.

General Services Administration, . Federal Acquisition Regulation. https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf, 2005. URL https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf.

Giorgini, Paolo, Fabio Massacci, John Mylopoulos, and Nicola Zannone. Requirements engineering meets trust management. Technical report, UNIVERSITY OF TRENTO, 2004.

Goguen, Joseph A and José Meseguer. Security Policies and Security Models. *Security and Privacy, IEEE Symposium on*, page 11, 1982. doi: 10.1109/SP.1982.10014.

Goldsmith, Michael, Bill Roscoe, and Philip Armstrong. Failures-Divergence Refinement-FDR2 User Manual, 2005.

Gomes, Artur Oliveira. *Formal Specification of the ARINC 653 Architecture Using Circus*. PhD thesis, The University of York, 2012. URL http://etheses.whiterose.ac.uk/id/eprint/2683.

Gordon, Peter. Data Leakage - Threats and Mitigation. Technical report, SANS Institute, 2007.

Gormish, Michael J, Edward L Schwartz, Alexander F Keith, Martin P Boliek, and Ahmad Zandi. Lossless and nearly lossless compression for high-quality images, 1997. URL http://dx.doi.org/10.1117/12.270058.

Guardian News, . Experian hack exposes 15 million people's personal information. https://www.theguardian.com/business/2015/oct/01/experian-hack-t-mobile-credit-checks-personal-information, 2014. URL https://www.theguardian.com/business/2015/oct/01/experian-hack-t-mobile-credit-checks-personal-information.

Gulati, Ms and Ms Singh. Analysis of Three Formal Methods-Z, B and VDM. *International Journal of Engineering*, 1(4):1–5, 2012. URL http://www.ijert.org/browse/june-2012-edition?download=297:analysis-of-three-formal-methods-z-b-and-vdm&start=120.

Gurgel, Alessandro Cavalcante, Cristiano Gurgel Castro, and Marcel Vinicius Oliveira. Tool Support for the Circus Refinement Calculus. In *Proceedings of the 1st International Conference on Abstract State Machines, B and Z*, ABZ '08, page 349, Berlin, Heidelberg, 2008. Springer-Verlag. ISBN 978-3-540-87602-1. doi: 10.1007/978-3-540-87603-8_37. URL http://dx.doi.org/10.1007/978-3-540-87603-8_37.

Gurses, Seda, Jens H Jahnke, Christina Obry, Adeniyi Onabajo, Thomas Santen, and Morgan Price. Eliciting confidentiality requirements in practice. *Proceedings of the 2005 conference of the Centre for Advanced Studies on Collaborative research*, pages 101–116, 2005. ISSN 1705-7361. URL http://dl.acm.org/citation.cfm?id=1105634.1105642.

Hadj-alouane, Nejib Ben, John Mullins, Nejib Ben Hadj-alouane, Stéphane Lafrance, Feng Lin, John Mullins, and Mohamed Moez Yeddes. On the Verification of Intransitive Noninterference in Mulitlevel Security. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 35(5):948–958, 2005. doi: 10.1109/TSMCB.2005.847749. URL http://ieeexplore.ieee.org/document/1510770/.

Hagen, Mariele and Volker Gruhn. Towards flexible software processes by using process patterns. In *IASTED Conf. on Software Engineering and Applications*, pages 436–441, 2004.

Hahsler, Michael and Wirtschaftsuniversität Wien Informationswirtschaft. Software Engineering with Analysis Patterns. Technical report, Technical Report of WU-Wien, 2001.

Hakeem, Hossam Hassan. *A compositional framework for determining pattern applicability.* Phd thesis, De Montfort University, 2010. URL http://hdl.handle.net/2086/4401.

Hall, Anthony and Roderick Chapman. Correctness by construction: Developing a commercial secure system. *IEEE Software*, 19(1):18–25, 2002. ISSN 07407459. doi: 10.1109/52.976937.

Hansen, M. H. Insuring confidentiality of individual records in data storage and retrieval for statistical purposes. *Managing Requirements Knowledge, International Workshop on*, page 579, 1971. doi: http://doi.ieeecomputersociety.org/10.1109/AFIPS.1971.100. URL `http://doi.acm.org/10.1145/1479064.1479167%5Cnhttp://portal.acm.org/citation.cfm?doid=1479064.1479167`.

Hayashi, Koichiro. Social Issues of Big Data and Cloud: Privacy, Confidentiality, and Public Utility. *2013 International Conference on Availability, Reliability and Security*, pages 506–511, 2013. doi: 10.1109/ARES.2013.66. URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6657282`.

Henties, Thomas, James J Hunt, Doug Locke, Kelvin Nilsen, Martin Schoeberl, and Jan Vitek. Java for Safety-Critical Applications. In *2nd International Workshop on the Certification of Safety-Critical Software Controlled Systems (SafeCert 2009)*. Elsevier Science B. V, 2009.

Henz, Martin, Gert Smolka, and Jorg Wurtz. Object-Oriented Concurrent Constraint Programming in Oz. In Herzog, Otthein, Thomas Christaller, and Dieter Schutt, editors, *Grundlagen und Anwendungen der Künstlichen Intelligenz*, number April in Informatik aktuell. Springer Berlin Heidelberg, 1993. doi: 10.1007/978-3-642-78545-0_3.

Hillenbrand, Thomas, Arnim Buch, Roland Vogt, and Bernd Löchner. WALDMEISTER - High-Performance Equational Deduction. *Journal of Automated Reasoning*, 18(2): 265–270, 1997. ISSN 1573-0670. doi: 10.1023/A:1005872405899. URL `http://dx.doi.org/10.1023/A:1005872405899`.

Hoare, C. A. R. and Jifeng He. *Unifying Theories of Programming*. Prentice Hall Englewood Cliffs, 1998. ISBN 978-0134587615. doi: 10.1007/978-3-319-14806-9. URL http://www.amazon.com/Unifying-Theories-Programming-C-Hoare/dp/0134587618.

Hoare, C.A.R. An Axiomatic Basis for Computer Programming. *Communications of the ACM*, 12(10):576–580, 1969. ISSN 00010782. doi: 10.1145/363235.363259.

Hoare, C.A.R. A model for communicating sequential process. 1980. URL http://ro.uow.edu.au/compsciwp/14/.

Hoare, C.A.R. Unified theories of programming. *Mathematical methods in program development. NATO ASI Series F Computer and Systems Science*, 158:313–368, 1997.

Hoder, Kryštof and Andrei Voronkov. Sine Qua Non for Large Theory Reasoning. In Bjørner, Nikolaj and Viorica Sofronie-Stokkermans, editors, *Automated Deduction – CADE-23: 23rd International Conference on Automated Deduction, Wrocław, Poland, July 31 - August 5, 2011. Proceedings*, pages 299–314. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-22438-6. doi: 10.1007/978-3-642-22438-6_23. URL http://dx.doi.org/10.1007/978-3-642-22438-6_23.

Holzmann, Gerard J. The Model Checker SPIN. *Ieee Transactions on Software Engineering*, 23(5):279–295, 1997. ISSN 00985589. doi: 10.1109/32.588521.

Holzmann, Gerard J and Rajeev Joshi. Model-Driven Software Verification. In Graf, S. and L. Mounier, editors, *Model Checking Software*, pages 76–91. Springer-Verlag Berlin Heidelberg, 2004. URL http://link.springer.com/chapter/10.1007%2F978-3-540-24732-6_6.

Howitt, Anthony. *The formal specification of the Tees Confidentiality Model*. PhD thesis, Teesside University, 2008.

Hubbard, B S, S A Walker, and R R Henning. Database Systems and the Criteria: Do They Relate? In *9th National Computer Security Conference*, pages 21–24, 1986.

Hudson, S, F Flannery, S Ananian, D Wang, and A Appel. JavaCup User's Manual, 1998.

IDG Communications, Inc. Target breach happened because of a basic network segmentation error, 2013. URL `https://www.computerworld.com/article/2487425/cybercrime-hacking/target-breach-happened-because-of-a-basic-network-segmentation-error.html`.

Ion, Mihaela, Giovanni Russello, and Bruno Crispo. Supporting publication and subscription confidentiality in pub/sub networks. *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, 50 LNICST: 272–289, 2010. ISSN 18678211. doi: 10.1007/978-3-642-16161-2_16.

ISO/IEC, . Information technology–Z formal specification notation–Syntax, type system and semantics. Technical report, International Organization for Standardization International Electrotechnical Commission, 2002. URL `ftp://195.215.30.152/jtc1/sc22/def/n3399.pdf`.

Jacob, Jeremy L. Security specifications. *Proceedings. 1988 IEEE Symposium on Security and Privacy*, pages 14–23, 1988. doi: 10.1109/SECPRI.1988.8094.

Jajodia, Sushil and Catherine Meadows. Inference problems in multilevel secure database management systems. *Information Security: An integrated collection of essays*, 1:570–585, 1995. URL `http://www.acsa-admin.org/secshelf/book001/24.pdf`.

Jamal, Leila, Julie C Sapp, Katie Lewis, Tatiane Yanes, Flavia M Facio, Leslie G Biesecker, and Barbara B Biesecker. Research participants' attitudes towards the confidentiality of genomic sequence information. *European journal of human genetics : EJHG*, 22(8): 964–8, 2014. ISSN 1476-5438. doi: 10.1038/ejhg.2013.276. URL `http://www.ncbi.nlm.nih.gov/pubmed/24281371`.

Jensen, Kurt. Coloured Petri nets. *Petri Nets: Central Models and Their Properties SE - 10*, 254:248–299, 1987. doi: 10.1007/BFb0046842. URL http://dx.doi.org/10.1007/BFb0046842.

JetBrains, . IntelliJ IDEA, 2017. URL https://www.jetbrains.com/idea/.

Johnson, Stephen C. *Yacc: Yet another compiler-compiler*, volume 32. Bell Laboratories Murray Hill, NJ, 1975.

Juan, Beatriz Martín De, Miguel Ángel, Valero Duboy, Diana Soler, José Manuel Azorín, and Rafael Conde. Design and Validation of a Secure Communication Platform for Mobile Health. *Temp 2013*, pages 24–31, 2011.

Kanav, Sudeep, Peter Lammich, and Andrei Popescu. A Conference Management System with Verified Document Confidentiality. In Biere, Armin and Roderick Bloem, editors, *Computer Aided Verification: 26th International Conference, CAV 2014, Held as Part of the Vienna Summer of Logic, VSL 2014, Vienna, Austria, July 18-22, 2014. Proceedings*, pages 167–183. Springer International Publishing, Cham, Switzerland, 2014. ISBN 978-3-319-08867-9. doi: 10.1007/978-3-319-08867-9_11. URL https://doi.org/10.1007/978-3-319-08867-9_11.

Kerckhoffs, Auguste. La Cryptographie Militaire. *Journal des Sciences Militaires*, IX, jan 1883. URL http://www.cl.cam.ac.uk/$\sim$fapp2/kerckhoffs/la_cryptographie_militaire_i.htm.

Khabsa, M and C. Lee Giles. The Number of Scholarly Documents on the Public Web. *PLoS ONE*, 9:e93949, may 2014. doi: 10.1371/journal.pone.0093949.

Kimber, Tim G. Object-Z to Perfect Developer. Technical Report September, Imperial College London, 2007.

Kirby, J, M Archer, and C Heitmeyer. SCR: a practical approach to building a high assurance COMSEC system. In *Computer Security Applications Conference, 1999. (ACSAC '99) Proceedings. 15th Annual*, pages 109–118, 1999. doi: 10.1109/CSAC.1999.816018.

Kletz, Trevor A. *Hazop and hazan : identifying and assessing process industry hazards*. Institution of Chemical Engineers (Great Britain), Philadelphia, PA, 4th ed edition, 1999. ISBN 1560328584 (alk. paper).

Kodaganallur, Viswanathan and Sung Shim. Analysis Patterns: A Taxonomy and its Implications. *Information Systems Management*, 23(3):52–61, 2006. doi: 10.1201/1078.10580530/46108.23.3.20060601/93707.6. URL `http://dx.doi.org/10.1201/1078.10580530/46108.23.3.20060601/93707.6`.

Kolyang, , T. Santen, and B. Wolff. A Structure Preserving Encoding of Z in Isabelle/HOL. *Theorem Proving in Higher Order Logics*, pages 1–16, 1996.

Konrad, Sascha, Betty H.C. Cheng, Laura a. Campbell, and Ronald Wassermann. Using Security Patterns to Model and Analyze Security Requirements. *2nd International Workshop on Requirements Engineering for High Assurance Systems*, pages 13–22, 2003.

Korovin, Konstantin. iProver – An Instantiation-Based Theorem Prover for First-Order Logic (System Description). In Armando, Alessandro, Peter Baumgartner, and Gilles Dowek, editors, *Automated Reasoning: 4th International Joint Conference, IJCAR 2008 Sydney, Australia, August 12-15, 2008 Proceedings*, pages 292–298. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. ISBN 978-3-540-71070-7. doi: 10.1007/978-3-540-71070-7_24. URL `http://dx.doi.org/10.1007/978-3-540-71070-7_24`.

Korovin, Konstantin and Christoph Sticksel. iProver-Eq: An Instantiation-Based Theorem Prover with Equality. In Giesl, Jürgen and Reiner Hähnle, editors, *Automated Reasoning: 5th International Joint Conference, IJCAR 2010, Edinburgh, UK, July 16-19, 2010. Proceedings*, pages 196–202. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010. ISBN 978-3-642-14203-1. doi: 10.1007/978-3-642-14203-1_17. URL `http://dx.doi.org/10.1007/978-3-642-14203-1_17`.

Lamsweerde, a. Van. Elaborating security requirements by construction of intentional anti-models. *Proceedings. 26th International Conference on Software Engineering*, 2004. ISSN 0270-5257. doi: 10.1109/ICSE.2004.1317437.

Lapadula, Alessandro, Rosario Pugliese, and Francesco Tiezzi. Specifying and analysing SOC applications with COWS. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 5065 LNCS: 701–720, 2008. ISSN 03029743. doi: 10.1007/978-3-540-68679-8_43.

Latham, Donald C. Trusted computer system evaluation criteria. *Department of Defense*, 1986.

Lawson, N. Side-Channel Attacks on Cryptographic Software. *IEEE Security Privacy*, 7 (6):65–68, nov 2009. ISSN 1540-7993. doi: 10.1109/MSP.2009.165.

Le M'etayer, Daniel. Privacy by Design: A Matter of Choice. In Gutwirth, Serge, Yves Poullet, and Paul De Hert, editors, *Data Protection in a Profiled World*, pages 323–334. Springer Netherlands, Dordrecht, 2010. ISBN 978-90-481-8865-9. doi: 10.1007/978-90-481-8865-9_20. URL `https://doi.org/10.1007/978-90-481-8865-9_20`.

Le Métayer, Daniel. Formal methods as a link between software code and legal rules. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 7041 LNCS:3–18, 2011. ISSN 03029743. doi: 10.1007/978-3-642-24690-6_2.

Lemma 1 Ltd., . ProofPower. Technical report, Lemma 1 Ltd., 2006.

Leone, Nicola, Gerald Pfeifer, Wolfgang Faber, Thomas Eiter, Georg Gottlob, Simona Perri, and Francesco Scarcello. The DLV system for knowledge representation and reasoning. *ACM Trans. Comput. Logic*, 7(3):499–562, 2006. ISSN 1529-3785. doi: 10.1145/1149114.1149117. URL `http://doi.acm.org/10.1145/1149114.1149117`.

Leuschel, Michael and Michael Butler. ProB: A Model Checker for B. In Keijiro, Araki, Stefania Gnesi, and Mandrio Dino, editors, *FME 2003: Formal Methods: International Symposium of Formal Methods Europe, Pisa, Italy, September 8-14, 2003. Proceedings*, pages 855–874. Springer Berlin Heidelberg, 2003. ISBN 978-3-540-45236-2. doi: 10.1007/978-3-540-45236-2_46. URL `https://doi.org/10.1007/978-3-540-45236-2_46`.

Lindblad, Fredrik. A Focused Sequent Calculus for Higher-Order Logic. In Demri, Stéphane, Deepak Kapur, and Christoph Weidenbach, editors, *Automated Reasoning: 7th International Joint Conference, IJCAR 2014, Held as Part of the Vienna Summer of Logic, VSL 2014, Vienna, Austria, July 19-22, 2014. Proceedings*, pages 61–75. Springer International Publishing, Cham, 2014. ISBN 978-3-319-08587-6. doi: 10.1007/978-3-319-08587-6_5. URL http://dx.doi.org/10.1007/978-3-319-08587-6_5.

Lockton Inc., . Anthem Breach Overview. Technical Report February, Lockton Inc., 2015.

Lucena, Norka B, Grzegorz Lewandowski, and Steve J Chapin. *Covert Channels in IPv6*, pages 147–166. Springer Berlin Heidelberg, Berlin, Heidelberg, 2006. ISBN 978-3-540-34746-0. doi: 10.1007/11767831_10. URL https://doi.org/10.1007/11767831_10.

Lukosch, Stephan and Till Schümmer. Groupware Development Support with Technology Patterns. *Int. J. Hum.-Comput. Stud.*, 64(7):599–610, jul 2006. ISSN 1071-5819. doi: 10.1016/j.ijhcs.2006.02.006. URL http://dx.doi.org/10.1016/j.ijhcs.2006.02.006.

Lunt, T.F. Aggregation and inference: facts and fallacies. In *Proceedings. 1989 IEEE Symposium on Security and Privacy*, pages 102–109. IEEE Comput. Soc. Press, 1989. ISBN 0-8186-1939-2. doi: 10.1109/SECPRI.1989.36284. URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=36284.

Mahony, B. and Jin Song Dong Jin Song Dong. Blending Object-Z and Timed CSP: an introduction to TCOZ. *Proceedings of the 20th International Conference on Software Engineering*, 1998. ISSN 0270-5257. doi: 10.1109/ICSE.1998.671106.

Mahony, Brendan, Jim McCarthy, Linh Vu, and Kylie Williams. Z Support in the HiVe Mathematical Toolkit. Technical report, Defence Science and Technology Organisation, Edinburgh, South Australia 5111, Australia, 2009.

Maiden, N. CREWS validation frames: validating systems requirements. In *IEE Colloquium on Understanding Patterns and Their Application to Systems Engineering (Digest No. 1998/308)*, pages 2/1–2/6, apr 1998. doi: 10.1049/ic:19980542.

Malik, Petra and Mark Utting. CZT: A Framework for Z Tools. *ZB 2005: Formal Specification and Development in Z and B*, 3455:315–352, 2005. ISSN 03029743. doi: 10.1007/11415787_5. URL `http://dx.doi.org/10.1007/11415787-5`.

Margheri, Andrea, Rosario Pugliese, and Francesco Tiezzi. On Properties of Policy-Based Specifications. *Electronic Proceedings in Theoretical Computer Science*, 188:33–50, 2015. ISSN 2075-2180. doi: 10.4204/EPTCS.188.5. URL `http://arxiv.org/abs/1508.03903`.

MarketWatch, Inc. Annual Financials for Home Depot Inc. http://www.marketwatch.com/investing/stock/hd/financials/balance-sheet, 2014. URL `http://www.marketwatch.com/investing/stock/hd/financials/balance-sheet`.

Mayer, Nicolas, André Rifaut, and Eric Dubois. Towards a Risk-Based Security Requirements Engineering Framework. *11th International Workshop on Requirements Engineering: Foundation for Software Quality (REFSQ 05)*, pages 83–97, 2005. doi: 10.1.1.109.7452. URL `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.109.7452&rep=rep1&type=pdf`.

Mayer, T. S. Privacy and Confidentiality Research and the U.S. Census Bureau Recommendations Based on a Review of the Literature. Technical report, U.S. Bureau of the Census, Washington D.C. 20233, 2002. URL `http://www.census.gov/srd/papers/pdf/rsm2002-01.pdf`.

McClelland, R. Confidentiality and security of clinical information in mental health practice. *Advances in psychiatric Treatment*, 8(4):291, 2002.

Mccullough, Daryl. Why Care About Composability ? *Odyssey*, 1988.

McDermott, John and Chris Fox. Using Abuse Case Models for Security Requirements Analysis. In *Proceedings of the 15th Annual Computer Security Applications Conference*, ACSAC '99, pages 55—-, Washington, DC, USA, 1999. IEEE Computer Society. ISBN 0-7695-0346-2. URL `http://dl.acm.org/citation.cfm?id=784590.784691`.

McLean, John. Security Models, 1994.

McMillan, Kenneth L. Verification of Infinite State Systems by Compositional Model Checking. In *Proceedings of the 10th IFIP WG 10.5 Advanced Research Working Conference on Correct Hardware Design and Verification Methods*, CHARME '99, pages 219–234, London, UK, UK, 1999. Springer-Verlag. ISBN 3-540-66559-5. URL `http://dl.acm.org/citation.cfm?id=646704.702020`.

Melnik, Grigori, Frank Maurer, and Mike Chiasson. Executable Acceptance Tests for Communicating Business Requirements: Customer Perspective. In *Proceedings of the Conference on AGILE 2006*, AGILE '06, pages 35–46, Washington, DC, USA, 2006. IEEE Computer Society. ISBN 0-7695-2562-8. doi: 10.1109/AGILE.2006.26. URL `https://doi.org/10.1109/AGILE.2006.26`.

Mendeley Ltd., . Mendeley. https://www.mendeley.com, 2016. URL `https://www.mendeley.com`.

Meyrowitz, Norman, editor. *OOPSLA '86: Conference Proceedings on Object-oriented Programming Systems, Languages and Applications*, New York, NY, USA, 1986. ACM. ISBN 0-89791-204-7.

Miyazawa, Alvaro and Ana Cavalcanti. SCJ-Circus: a refinement-oriented formal notation for Safety-Critical Java. In Derrick, John, Eerke A Boiten, and Steve Reeves, editors, *Proceedings 17th International Workshop on Refinement, Refine@FM 2015, Oslo, Norway, 22nd June 2015.*, volume 209 of *EPTCS*, pages 71–86, 2015. doi: 10.4204/EPTCS.209.6. URL `http://dx.doi.org/10.4204/EPTCS.209.6`.

Mlinek, E J and J Pierce. Confidentiality and privacy breaches in a university hospital emergency department. *Academic emergency medicine : official journal of the Society for Academic Emergency Medicine*, 4(12):1142–1146, 1997. ISSN 1069-6563. doi: 10.1111/j.1553-2712.1997.tb03697.x. URL http://www.ncbi.nlm.nih.gov/pubmed/9408430.

Moore, Helen and Wilfred McSherry. Ethical implications of consent in translational research. *Cancer Nursing Practice*, 12(10):22–26, 2013. doi: http://dx.doi.org/10.7748/cnp2013.12.12.10.22.e1002. URL http://rcnpublishing.com/doi/abs/10.7748/cnp2013.12.12.10.22.e1002.

Morgan, Carroll. *Programming from Specification*. Prentice Hall International (UK) Ltd, 1998.

Morgan, Carroll. The Shadow Knows: Refinement and security in sequential programs. *Science of Computer Programming*, 74(September 2007):629–653, 2009. ISSN 01676423. doi: 10.1016/j.scico.2007.09.003.

Morris, Joseph M. A theoretical basis for stepwise refinement and the programming calculus. *Science of Computer Programming*, 9(3):287–306, 1987. ISSN 01676423. doi: 10.1016/0167-6423(87)90011-6.

Moura, Leonardo De, Sam Owre, and Natarajan Shankar. The SAL Language Manual. Technical Report 650, Computer Science Laboratory, SRI International, Menlo Park, Tech. Rep. CSL-01-01, 2003.

Mouratidis, Haralambos, Paolo Giorgini, and Gordon Manson. Integrating Security and Systems Engineering: Towards the Modelling of Secure Information Systems. *Proceedings of CAiSE 2003, 15th International Conference on Advanced Information Systems Engineering*, 2681:63–78, 2003.

Mouratidis, Haralambos, Paolo Giorgini, and Gordon Manson. When security meets software engineering: A case of modelling secure information systems. *Information Systems*, 30(8):609–629, 2005. ISSN 03064379. doi: 10.1016/j.is.2004.06.002.

Nakagawa, Hiroyuki, Kenji Taguchi, and Shinichi Honiden. Formal Specification Generator for KAOS: Model Transformation Approach to Generate Formal Specifications from KAOS Requirements Models. In *Proceedings of the Twenty-second IEEE/ACM International Conference on Automated Software Engineering*, ASE '07, pages 531–532, New York, NY, USA, 2007. ACM. ISBN 978-1-59593-882-4. doi: 10.1145/1321631.1321729. URL `http://doi.acm.org/10.1145/1321631.1321729`.

Nipkow, Tobias, Lawrence C Paulson, and Markus Wenzel. *A Proof Assistant for Higher-Order Logic*. Springer-Verlag Berlin, 2014.

Oehlert, P. Violating assumptions with fuzzing. *IEEE Security Privacy*, 3(2):58–62, mar 2005. ISSN 1540-7993. doi: 10.1109/MSP.2005.55.

Office for National Statistics, . National Statistics Code of Practice: Statement of Principles. Technical report, Office for National Statistics, United Kingdom, 2002. URL `http://calls.ac.uk/wp-content/uploads/2013/06/protdataaccessconfidentiality_tcm77-179254.pdf`.

Office of Parliamentary Counsel, . Privacy Act 1988, 1988.

O'Halloran, Colin. A Calculus of Information Flow. In *ESORICS*, volume 90, pages 147–159, 1990.

Olan, Michael. Unit Testing: Test Early, Test Often. *J. Comput. Sci. Coll.*, 19(2):319–328, dec 2003. ISSN 1937-4771. URL `http://dl.acm.org/citation.cfm?id=948785.948830`.

Oliveira, M, Alessandro Cavalcante Gurgel, and CG Castro. *CRefine: Support for the Circus Refinement Calculus*. IEEE, 2008.

Oliveira, M V M, A L C Cavalcanti, and J C P Woodcock. Refining Industrial Scale Systems in lCircus. In East, Ian, Jeremy Martin, Peter Welch, David Duce, and Mark Green, editors, *Communicating Process Architectures*, volume 62 of *Concurrent Systems Engineering Series*, pages 281–309. IOS Press, sep 2004.

Oliveira, Marcel. *Formal Derivation of State-Rich Reactive Programs using Circus*. PhD thesis, University of York, 2005.

Oliveira, Marcel, Jim Woodcock, and Ana Cavalcanti. Formal development of industrial-scale systems in Circus. *Innovations in Systems and Software Engineering*, 1:125–146, 2005. ISSN 16145046. doi: 10.1007/s11334-005-0014-0.

Oliveira, Marcel, Jim Woodcock, and Ana Cavalcanti. A denotational semantics for Circus. *Electronic Notes in Theoretical Computer Science*, 187:107–123, 2006. URL `http://www.sciencedirect.com/science/journal/15710661`.

Oliveira, Marcel, Ana Cavalcanti, and Jim Woodcock. A UTP semantics for Circus. *Formal Aspects of Computing*, 21:3–32,17, 2009. ISSN 09345043. doi: 10.1007/s00165-007-0052-5.

Onabajo, Adeniyi. *Analysis of multilateral software confidentiality requirements*. PhD thesis, University of Victoria, 2009. URL `http://hdl.handle.net/1828/1689`.

Onabajo, Adeniyi and Jens H. Jahnke. Properties of confidentiality requirements. *Proceedings - IEEE Symposium on Computer-Based Medical Systems*, 2006:841–846, 2006a. ISSN 10637125. doi: 10.1109/CBMS.2006.133.

Onabajo, Adeniyi and Jens H. Jahnke. Modelling and reasoning for confidentiality requirements in software development. *Proceedings of the International Symposium and Workshop on Engineering of Computer Based Systems*, pages 460–467, 2006b. doi: 10.1109/ECBS.2006.50.

Onunkun, Temitope Jos. *Confidentiality Properties and the B Method*. PhD thesis, Kings College London, 2012.

Orb, Angelica, Laurel Eisenhauer, and Dianne Wynaden. Ethics in Qualitative Research. *Journal of Nursing Scholarship*, 33(1):93–96, 2001. ISSN 1547-5069. doi: 10.1111/j.1547-5069.2001.00093.x. URL `http://dx.doi.org/10.1111/j.1547-5069.2001.00093.x`.

Parr, Terence. *The definitive ANTLR 4 reference*. Pragmatic Bookshelf, 2013.

Parveen, Nikhat, Md. Rizwan Beg, and M. H. Khan. Model to Quantify Confidentiality at Requirement Phase. *Proceedings of the 2015 International Conference on Advanced Research in Computer Science Engineering and Technology (ICARCSET 2015) - ICARCSET '15*, pages 1–4, 2015. doi: 10.1145/2743065.2743117. URL `http://dl.acm.org/citation.cfm?doid=2743065.2743117`.

Pearce, Jon. Requirements Modeling. http://www.cs.sjsu.edu/∼pearce/uml/usecases.htm, 2017. URL `http://www.cs.sjsu.edu/$\sim$pearce/uml/usecases.htm`.

Peine, Holger, Marek Jawurek, and Stefen Mandel. Security goal indicator trees: A model of software features that supports efficient security inspection. *Proceedings of IEEE International Symposium on High Assurance Systems Engineering*, pages 9–18, 2008. ISSN 15302059. doi: 10.1109/HASE.2008.57.

Pnueli, Amir. The Temporal Logic of Programs. *The 18th IEEE Symposium on Foundation of Computer Science*, pages 46–57, 1977. ISSN 0272-5428. doi: 10.1109/SFCS.1977.32.

Ponemon Institute LLC, . 2014 Cost of Data Breach Study : Global Analysis. Technical Report May, Ponemon Institute LLC, 2014.

Porambage, Pawani, Mika Ylianttila, Corinna Schmitt, Pardeep Kumar, Andrei Gurtov, and Athanasios V. Vasilakos. The Quest for Privacy in the Internet of Things. *IEEE Cloud Computing*, 3(2):36–45, 2016. ISSN 2325-6095. doi: 10.1109/MCC.2016.28. URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7478541`.

Potter, Ben, David Till, and Jane Sinclair. *An Introduction to Formal Specification and Z*. Prentice Hall PTR, Upper Saddle River, NJ, USA, 2nd edition, 1996a. ISBN 0132422077.

Potter, Ben, David Till, and Jane Sinclair. *An introduction to formal specification and Z*. Prentice Hall PTR, 1996b.

Prisaznuk, PaulJ. ARINC Specification 653, Avionics Application Software Standard Interface. In *Avionics*, Electrical Engineering Handbook, pages 14–17. CRC Press, dec 2006. ISBN 978-0-8493-8438-7. doi: doi:10.1201/9780849384394.ch14. URL `http://dx.doi.org/10.1201/9780849384394.ch14`.

Purao, Sandeep, Veda C Storey, and Taedong Han. Improving Analysis Pattern Reuse in Conceptual Design: Augmenting Automated Processes with Supervised Learning. *Info. Sys. Research*, 14(3):269–290, sep 2003. ISSN 1526-5536. doi: 10.1287/isre.14.3.269.16559. URL `http://dx.doi.org/10.1287/isre.14.3.269.16559`.

Rajan, S, N Shankar, and M K Srivas. *An integration of model checking with automated proof checking*, pages 84–97. Springer Berlin Heidelberg, Berlin, Heidelberg, 1995. ISBN 978-3-540-49413-3. doi: 10.1007/3-540-60045-0_42. URL `https://doi.org/10.1007/3-540-60045-0_42`.

Ramos, Rodrigo, Augusto Sampaio, and Alexandre Mota. A Semantics for UML-RT Active Classes via Mapping into Circus. In Steffen, Martin and Gianluigi Zavattaro, editors, *Formal Methods for Open Object-Based Distributed Systems: 7th IFIP WG 6.1 International Conference, FMOODS 2005, Athens, Greece, June 15-17, 2005. Proceedings*, pages 99–114. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005. ISBN 978-3-540-31556-8. doi: 10.1007/11494881_7. URL `http://dx.doi.org/10.1007/11494881_7`.

Riazanov, Alexandre and Andrei Voronkov. The Design and Implementation of VAMPIRE. *AI Commun.*, 15(2,3):91–110, aug 2002. ISSN 0921-7126. URL `http://dl.acm.org/citation.cfm?id=1218615.1218620`.

Ribó, Josep M and Xavier Franch. Supporting Process Reuse in PROMENADE. *Barcelona: LSI-Universitat Politècnica de Catalunya*, 2002.

Roscoe, a W. CSP and determinism in security modelling. *Security and Privacy, 1995. Proceedings., 1995 IEEE Symposium on*, pages 114–127, 1995. ISSN 10637109. doi: 10.1109/SECPRI.1995.398927.

Rotenberg, Marc. Communications privacy: implications for network design. *Communications of the ACM*, 36(8):61–68, 1993.

Rubinstein, Ira S. Regulating Privacy By Design. *Berkeley Technology Law Journal*, 26(3):1409–1456, 2011. ISSN 10863818. doi: 10.15779/Z38368N. URL http://ra.ocls.ca/ra/login.aspx?url=http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=74237061&site=eds-live.

Rumbaugh, James, Ivar Jacobson, and Grady Booch. *The Unified Modeling Language Reference Manual*. Pearson Higher Education, 2004.

Sabelfeld, Andrei and Andrew C Myers. Language-Based Information-Flow Security. *IEEE Journal on Selected Areas in Communications*, 21(1):5–19, 2003. doi: 10.1109/JSAC.2002.806121.

Salter, David and Rhawi Dantas. *NetBeans IDE 8 Cookbook*. Packt Publishing, 2014. ISBN 1782167765, 9781782167761.

Sampaio, Augusto, Jim Woodcock, and Ana Cavalcanti. Refinement in Circus. *FME 2002:Formal Methods-Getting IT Right*, 2391:1–15, 2002. doi: 10.1007/3-540-45614-7_26. URL http://dx.doi.org/10.1007/3-540-45614-7-26.

Sampaio, Augusto, Jim Woodcock, and Ana Cavalcanti. A Refinement Strategy for Circus. *Formal Aspects of Computing*, 15:146–181, 2003. ISSN 09345043. doi: 10.1007/s00165-003-0006-5.

Santen, T. Stepwise Development of Secure Systems. *Proc. 25th International Conference on Computer Safety, Reliability and Security (SAFECOMP 2006). Gdansk, Poland*, pages 142–155, 2006. ISSN 16113349. doi: 10.1007/11875567_11.

Schneider, Steve. *Concurrent and Real Time Systems: the CSP approach*. John Wiley and Sons, Ltd., 1999.

Schulz, Stephan. E - a Brainiac Theorem Prover. *AI Commun.*, 15(2,3):111–126, aug 2002. ISSN 0921-7126. URL http://dl.acm.org/citation.cfm?id=1218615.1218621.

Schumacher, Markus. *Security Engineering with Patterns*. Springer-Verlag Berlin Heidelberg, 1 edition, 2001. ISBN 3540407316. doi: 10.1007/b11930. URL http://eprints.lancs.ac.uk/60581/.

Schumacher, Markus, Eduardo Fernandez, Duane Hybertson, Frank Buschmann, and Peter Sommerland. *Security Patterns : Integrating Security and Systems Engineering*. John Wiley and Sons Inc., The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, 2005. ISBN 9780470858844.

Schwitter, Rolf. Controlled Natural Languages for Knowledge Representation. In *Proceedings of the 23rd International Conference on Computational Linguistics: Posters*, COLING '10, pages 1113–1121, Stroudsburg, PA, USA, 2010. Association for Computational Linguistics. URL http://dl.acm.org/citation.cfm?id=1944566.1944694.

Seffah, Ahmed, Mohammad Donyaee, Rex B Kline, and Harkirat K Padda. Usability measurement and metrics: A consolidated model. *Software Quality Journal*, 14(2): 159–178, jun 2006. ISSN 1573-1367. doi: 10.1007/s11219-006-7600-8. URL https://doi.org/10.1007/s11219-006-7600-8.

Shabtai, Asaf, Yuval Elovici, and Lior Rokach. *A survey of data leakage detection and prevention solutions*. Springer-Verlag, New York, 1 edition, 2012. ISBN 978-1-4614-2052-1. doi: 10.1007/978-1-4614-2053-8. URL http://www.springer.com/gb/book/9781461420521.

Shankar, N. *PVS: Combining specification, proof checking, and model checking*, pages 257–264. Springer Berlin Heidelberg, Berlin, Heidelberg, 1996. ISBN 978-3-540-49567-3. doi: 10.1007/BFb0031813. URL https://doi.org/10.1007/BFb0031813.

Shaw, Mary and David Garlan. *Software Architecture: Perspectives on an Emerging Discipline*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1996. ISBN 0-13-182957-2.

Sherif, Adnan and He Jifeng. Towards a Time Model for Circus. In George, Chris and Huaikou Miao, editors, *Formal Methods and Software Engineering: 4th International Conference on Formal Engineering Methods, ICFEM 2002 Shanghai, China, October 21–25, 2002 Proceedings*, pages 613–624. Springer Berlin Heidelberg, Berlin, Heidelberg, 2002. ISBN 978-3-540-36103-9. doi: 10.1007/3-540-36103-0_62. URL `http://dx.doi.org/10.1007/3-540-36103-0_62`.

Sindre, Guttorm and Andreas L. Opdahl. Eliciting security requirements with misuse cases. *Requirements Engineering*, 10:34–44, 2005. ISSN 09473602. doi: 10.1007/s00766-004-0194-4.

Siregar, M U, J Derrick, S North, and A J H Simons. Experiences using Z2SAL. In *2014 International Conference on Advanced Computer Science and Information System*, pages 225–231, oct 2014. doi: 10.1109/ICACSIS.2014.7065856.

Skon, Jim. Use Case Example Solution, 2016. URL `http://cs.mvnu.edu/twiki/bin/view/Main/SsE12014Prob1Sol`.

Sommerville, I. *Software Engineering, Global Edition*. Pearson Education Limited, 10th edition, 2016. ISBN 9781292096148. URL `https://books.google.co.uk/books?id=W_LjCwAAQBAJ`.

Sommerville, Ian. *Software Engineering*. Addison-Wesley, Boston, Massachusetts 02116, 9 edition, 2010. ISBN 9780137035151. doi: 10.1111/j.1365-2362.2005.01463.x.

Spivey, J M. *Understanding Z: A Specification Language and Its Formal Semantics*. Cambridge University Press, New York, NY, USA, 1988. ISBN 0-521-33429-2.

Spivey, Jhon. M. *The Z notation: A reference manual*. Prentice-Hall, Inc. Upper Saddle River, NJ, USA, 1989. ISBN 0-13-978529-9. doi: 10.1016/0167-6423(90)90091-Q.

Srivatanakul, Thitima. *Security Analysis with Deviational Techniques*. Phd thesis, The University of York, UK, 2005. URL `https://pdfs.semanticscholar.org/c1b5/0c6687e6feae1ca07187dea358eb9a42bdbf.pdf`.

Stickel, Mark, Richard Waldinger, Michael Lowry, Thomas Pressburger, and Ian Underwood. Deductive composition of astronomical software from subroutine libraries. In Bundy, Alan, editor, *Automated Deduction — CADE-12: 12th International Conference on Automated Deduction Nancy, France, June 26 – July 1, 1994 Proceedings*, pages 341–355. Springer Berlin Heidelberg, Berlin, Heidelberg, 1994. ISBN 978-3-540-48467-7. doi: 10.1007/3-540-58156-1_24. URL http://dx.doi.org/10.1007/3-540-58156-1_24.

Sutherland, David. A model of Information. In *Proceeding of the 9th National Computer Security Conference*, pages 175–183. DTIC Document, Baltimore, 9th edition, 1986.

Swaminathan, Ashwin, Yinian Mao, Guan-Ming Su, Hongmei Gou, Avinash L Varna, Shan He, Min Wu, and Douglas W Oard. Confidentiality-preserving rank-ordered search. *StorageSS*, pages 7–12, 2007.

The Association of Data Protection Officers, . The Biggest Data Breaches of All Time. https://www.dpo.ie/news/view/1539, 2015. URL https://www.dpo.ie/news/view/1539.

The European Parliament and The European Council, . General Data Protection Regulation. Technical report, European Union (EU), 2016. URL http://eur-lex.europa.eu/eli/reg/2016/679/oj.

The Hillside Group, . Pattern Languages of Programs (PLoP), 2017. URL https://conf.researchr.org/series/PLOP.

The Home Depot, . 2014 Annual Report - The Home Depot. Technical report, The Home Depot, 2014.

The Home Depot, . 2015 Annual Report - The Home Depot. Technical report, The Home Depot, 2015. URL http://investor.resmed.com/investor-relations/financials/default.aspx?section=annual.

The New York Times Company, . Ways to Protect Yourself After the JPMorgan Hacking. http://www.nytimes.com/2014/10/04/your-money/jpmorgan-chase-hack-ways-to-protect-yourself.html, 2014. URL http://www.nytimes.com/2014/10/04/your-money/jpmorgan-chase-hack-ways-to-protect-yourself.html.

The New York Times Company, . Yahoo Says Hackers Stole Data on 500 Million Users in 2014. http://www.nytimes.com/2016/09/23/technology/yahoo-hackers.html, 2016. URL http://www.nytimes.com/2016/09/23/technology/yahoo-hackers.html.

Tran, Hanh Nhi, Bernard Coulette, and Bich Thuy Dong. A UML-based Process Meta-model Integrating a Rigorous Process Patterns Definition. In *Proceedings of the 7th International Conference on Product-Focused Software Process Improvement*, PROFES'06, pages 429–434, Berlin, Heidelberg, 2006. Springer-Verlag. ISBN 3-540-34682-1, 978-3-540-34682-1. doi: 10.1007/11767718_39. URL http://dx.doi.org/10.1007/11767718_39.

Trouessin, Gilles. Dependability Requirements and Security Architectures for the Healthcare / Medical Sector 1. In Felici, Massimo and Karama Kanoun, editors, *Computer Safety, Reliability and Security: 18th International Conference, SAFECOMP'99 Toulouse, France, September 27–29, 1999 Proceedings*, pages 445–458. Springer Berlin Heidelberg, Berlin, Heidelberg, 1999. ISBN 978-3-540-48249-9. doi: 10.1007/3-540-48249-0_38. URL https://doi.org/10.1007/3-540-48249-0_38.

Tschantz, Michael Carl and Jeannette M. Wing. Extracting conditional confidentiality policies. *Proceedings - 6th IEEE International Conference on Software Engineering and Formal Methods, SEFM 2008*, pages 107–116, 2008. doi: 10.1109/SEFM.2008.46.

Ulutas, Mustafa, Güzin Ulutas, and Vasif V. Nabiyev. Medical image security and EPR hiding using Shamir's secret sharing scheme. *Journal of Systems and Software*, 84(3):341–353, 2011. ISSN 01641212. doi: 10.1016/j.jss.2010.11.928. URL http://dx.doi.org/10.1016/j.jss.2010.11.928.

U.S. National Institute of Standards and Technology, . Guidelines for Smart Grid Cybersecurity NISTIR 7628 Revision 1. *U.S. Department of Commerce NISTIR*, 1 (September):668, 2014. doi: 10.6028/NIST.IR.7628r1.

Van Lamsweerde, Axel, Anne Dardenne, Bruno Delcourt, Françoise Dubisy, and Others. The KAOS project: Knowledge acquisition in automated specification of software. In *Proceedings of the AAAI Spring Symposium Series*, 1991.

Varghese, Praveen Thomas Methrayil. *Parity and Generalised Büchi Automata Determinisation and Complementation*. PhD thesis, University of Liverpool, 2014.

Verizon, . 2015 Data Breach Investigations Report. *Information Security*, pages 58,57, 2015.

Verizon Enterprise Solutions, . 2014 Data Breach Investigations Report. Technical Report 1, Verizon Enterprise Solutions, 2014. URL `www.verizonenterprise.com/resources/reports/rp_Verizon-DBIR-2014_en_xg.pdf`.

Verma, Ankit. Mechanising Programs in Isabelle/HOL. Technical report, University of York, 2011.

Viswanathan, Kapali, Colin Boyd, and Ed Dawson. A Three Phased Schema for sealed bid auction system design. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 1841:412–426, 2000. ISSN 16113349. doi: 10.1007/10718964_34.

Wang, Da W., Churn Jung Liau, and Tsan Sheng Hsu. Granulation as a privacy protection mechanism. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 4400 LNCS(PART 2): 256–273, 2007. ISSN 03029743. URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-38149084088&partnerID=tZOtx3y1`.

Wang, Wenli, Zoltán Hidvégi, Andrew D. Bailey, and Andrew B. Whinston. E-process design and assurance using model checking. *Computer*, 33:48–53, 2000. ISSN 00189162. doi: 10.1109/2.876292.

Wegner, Peter. The Ada Language and Environment. *SIGSOFT Softw. Eng. Notes*, 5(2):8–14, apr 1980. ISSN 0163-5948. doi: 10.1145/1010792.1010793. URL `http://doi.acm.org/10.1145/1010792.1010793`.

Wei, K, J Woodcock, and A Burns. A Timed Model of Circus with the Reactive Design Miracle. In *2010 8th IEEE International Conference on Software Engineering and Formal Methods*, pages 315–319, sep 2010. doi: 10.1109/SEFM.2010.40.

Wei, Kun. New Circus Time. Technical Report April, University of York, York, UK, 2013. URL `https://www.cs.york.ac.uk/circus/publications/techreports/reports/CircusTime.pdf`.

Wei, Kun, Jim Woodcock, and Alan Burns. Timed circus: Timed CSP with the miracle. *Proceedings - 2011 16th IEEE International Conference on Engineering of Complex Computer Systems, ICECCS 2011*, pages 55–64, 2011. doi: 10.1109/ICECCS.2011.13.

Weidenbach, Christoph, Dilyana Dimova, Arnaud Fietzke, Rohit Kumar, Martin Suda, and Patrick Wischnewski. SPASS Version 3.5. In Schmidt, Renate A, editor, *Automated Deduction – CADE-22: 22nd International Conference on Automated Deduction, Montreal, Canada, August 2-7, 2009. Proceedings*, pages 140–145. Springer Berlin Heidelberg, Berlin, Heidelberg, 2009. ISBN 978-3-642-02959-2. doi: 10.1007/978-3-642-02959-2_10. URL `http://dx.doi.org/10.1007/978-3-642-02959-2_10`.

Weiss, M. and H. Mouratidis. Selecting security patterns that fulfill security requirements. *Proceedings of the 16th IEEE International Requirements Engineering Conference, RE'08*, pages 169–172, 2008. ISSN 1090-705X. doi: 10.1109/RE.2008.32.

Wenzel, Makarius. The Isabelle / Isar Reference Manual. Technical report, Technische Universität München, Garching, Germany, 2013. URL `http://isabelle.in.tum.de/doc/isar-ref.pdf`.

White, Stephen a. Introduction to BPMN. *BPTrends*, pages 1–11, 2004. ISSN 09636897. doi: 10.3727/000000006783982421.

Williams, Mary Anne. Privacy management, the law and business strategies: A case for privacy driven design. *Proceedings - 12th IEEE International Conference on Computational Science and Engineering, CSE 2009*, 3:60–67, 2009. doi: 10.1109/CSE.2009.478.

Wing, J M. A specifier's introduction to formal methods. *Computer*, 23(9):8–22, sep 1990. ISSN 0018-9162. doi: 10.1109/2.58215.

Wirth, Niklaus. Program development by stepwise refinement. *Communications of the ACM*, 14(4):221–227, 1971. ISSN 00010782. doi: 10.1145/362575.362577.

Woodcock, Jim and Ana Cavalcanti. A Concurrent Language for Refinement. In *Proceedings of the 5th Irish Conference on Formal Methods*, pages 93–115. BCS Learning & Development Ltd., Swindon, UK, 2001a. URL http://dl.acm.org/citation.cfm?id=2227391.2227398.

Woodcock, Jim and Ana Cavalcanti. The Steam Boiler in a Unified Theory of Z and CSP. In *Proceedings of the Eighth Asia-Pacific on Software Engineering Conference*, APSEC '01, pages 291—-, Washington, DC, USA, 2001b. IEEE Computer Society. URL http://dl.acm.org/citation.cfm?id=872020.872420.

Woodcock, Jim and Ana Cavalcanti. The Semantics of Circus. In Bert, Didier, Jonathan P. Bowen, Martin C. Henson, and Ken Robinson, editors, *Zb 2002: Formal Specification and Development in Z and B: 2nd International Conference of B and Z Users Grenoble*, pages 184–203, Berlin, 2002. Springer Berlin Heidelberg. ISBN 3-540-43166-7. doi: 10.1007/3-540-45648-1_10. URL http://link.springer.com/chapter/10.1007/3-540-45648-1_10.

Woodcock, Jim and Jim Davies. *Using Z. Specification, Refinement and Proof*. Prentice-Hall, Inc., 1996. ISBN 0139484728. URL www.usingz.com/text/zedbook.pdf.

Woodcock, Jim and Alvaro Miyazawa. CML Definition 0. Technical report, COMPASS, 2012. URL http://www.compass-research.eu/Project/Deliverables/D231.pdf.

Woodcock, Jim, Simon Foster, and Frank Zeyda. Isabelle/UTP: A Mechanised Theory Engineering Framework. *Springer*, pages 21–41,31, 2015. doi: 10.1007/978-3-319-14806-9_2.

Ye, Kangfeng and Jim Woodcock. Model checking of state-rich formalism Circus by linking to CSP||B. *International Journal on Software Tools for Technology Transfer*, 19 (1):73–96, feb 2017. ISSN 1433-2787. doi: 10.1007/s10009-015-0402-1. URL https://doi.org/10.1007/s10009-015-0402-1.

Yu, Eric and Lin Liu. Modelling Trust for System Design Using the i * Strategic Actors Framework. *Trust in Cyber-Societies*, pages 175–194, 2001. ISSN 03029743. doi: 10.1007/3-540-45547-7_11.

Yu, Yijun, Virginia N L Franqueira, Thein Than Tun, Roel J. Wieringa, and Bashar Nuseibeh. Automated analysis of security requirements through risk-based argumentation. *Journal of Systems and Software*, 106:102–116, 2015. ISSN 01641212. doi: 10.1016/j.jss.2015.04.065. URL http://dx.doi.org/10.1016/j.jss.2015.04.065.

Z Standards Panel, . Formal Specification - Z Notation - Syntax , Type and Semantics. Technical report, International Organization for Standardization and International Electrotechnical Commission, 2000. URL http://www.open-std.org/jtc1/sc22/open/n3187.pdf.

Zakinthinos, Aris and E.S. Lee. A general theory of security properties. *Proceedings. 1997 IEEE Symposium on Security and Privacy (Cat. No.97CB36097)*, pages 94–102, 1997. ISSN 1081-6011. doi: 10.1109/SECPRI.1997.601322.

Zeyda, Frank, Julian Ouy, Simon David Foster, and Ana Lucia Caneca Cavalcanti. *Formalised Cosimulation Models*. 2017. URL http://eprints.whiterose.ac.uk/121804/.