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DEPARTMENT OF INTELLIGENT SYSTEMS
ÚSTAV INTELIGENTNÍCH SYSTÉMŮ

STATIC ANALYSIS USING FACEBOOK INFER TO FIND ATOMICITY VIOLATIONS

STATICKÁ ANALÝZA V NÁSTROJI FACEBOOK INFER ZAMĚŘENÁ NA DETEKCI PORUŠENÍ ATOMIČNOSTI

BACHELOR’S THESIS
BAKALÁŘSKÁ PRÁCE

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Zadání bakalářské práce

21689

Student: **Harmim Dominik**
Program: Informační technologie
Název: **Statická analýza v nástroji Facebook Infer zaměřená na detekci porušení atomičnosti**
Static Analysis Using Facebook Infer to Find Atomicity Violations
Kategorie: Analýza a testování softwaru

Zadání:

1. Prostudujte principy statické analýzy založené na abstraktní interpretaci. Zvláštní pozornost věnujte přístupům zaměřeným na odhalování problémů v synchronizaci paralelních procesů.
2. Seznamte se s nástrojem Facebook Infer, jeho podporou pro abstraktní interpretaci a s existujícími analyzátory vytvořenými v prostředí Faceboook Infer.
3. V prostředí Facebook Infer navrhněte a naimplementujte analyzátor zaměřený na odhalování chyb typu porušení atomicity.
4. Experimentálně ověřte funkčnost vytvořeného analyzátoru na vhodně zvolených netriviálních programech.
5. Shrňte dosažené výsledky a diskutujte možnosti jejich dalšího rozvoje v budoucnu.

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Pro udělení zápočtu za první semestr je požadováno:

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Vedoucí ústavu: Hanáček Petr, doc. Dr. Ing.
Datum zadání: 1. listopadu 2018
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Datum schválení: 1. listopadu 2018

Abstract

The goal of this thesis is to propose a *static analyser*, which detects *atomicity violations.* The proposed analyser — *Atomer* — is implemented as an extension for *Facebook Infer*, which is an open-source and extendable static analysis framework that promotes efficient *modular* and *incremental* analysis. The analyser works on the level of *sequences of function calls.* The proposed solution is based on the assumption that sequences executed *once atomically* should probably be executed *always atomically.* The implemented analyser has been successfully verified and evaluated on both smaller programs created for this purpose as well as publicly available benchmarks derived from real-life low-level programs.

Abstrakt

Cílem této práce je navrhnout *statický analyzátor*, který bude sloužit pro detekci *porušení atomicity.* Navržený analyzátor — *Atomer* — je implementován jako rozšíření pro *Facebook Infer*, což je volně šířený a snadno rozšířitelný nástroj, který umožňuje efektivní *modulární* a *inkrementální* analýzu. Analyzátor pracuje na úrovni *sekvencí volání funkcí.* Navržené řešení je založeno na předpokladu, že sekvence, které jsou *jednou zavolány atomicky*, by měly být pravděpodobně volány *atomicky vždy.* Implementovaný analyzátor byl úspěšně ověřen a vyhodnocen jak na malých programech, vytvořených pro tento účel, tak na veřejně dostupných testovacích programech, které vznikly ze skutečných nízko úrovňových programů.

Keywords

static analysis, programs analysis, abstract interpretation, Facebook Infer, atomicity violation, concurrent programs, contracts for concurrency, atomic sequences, atomicity, incremental analysis, modular analysis, compositional analysis, interprocedural analysis

Klíčová slova

statická analýza, analýza programů, abstraktní interpretace, Facebook Infer, porušení atomicity, paralelní programy, kontrakty pro souběžnost, atomické sekvence, atomicita, inkrementální analýza, modulární analýza, kompoziční analýza, interprocedurální analýza

Reference

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Rozšířený abstrakt

[[**TODO**]]

Static Analysis Using Facebook Infer to Find Atomicity Violations

Declaration

Hereby I declare that this bachelor's thesis was prepared as an original author's work under the supervision of professor Tomáš Vojnar. All the relevant information sources, which were used during the preparation of this thesis, are properly cited and included in the list of references.

. . . .
Dominik Harmim
May 15, 2019

Acknowledgements

I would like to thank my supervisor Tomáš Vojnar. Further, I would like to thank Tomáš Fiedor for providing supplementary information and for his assistance. I would also like to thank my colleagues Vladimír Marcin and Ondřej Pavela for helpful discussions about my thesis. Furthermore, I would like to thank Nikos Gorogiannis and Sam Blackshear from Infer team at Facebook for useful discussions about the development of my analyser. Lastly, I thank for the support received from H2020 ECSEL project Aquas.

Contents

Chapter 1

Introduction

Bugs are an integral part of computer programs ever since the inception of the programming discipline. Unfortunately, they are often hidden in unexpected places, and they can lead to unexpected behaviour which may cause significant damage. Nowadays there are many possible ways of catching bugs in the development process. Dynamic analysers or tools for automated testing are often used. These methods are satisfactory in many cases, nevertheless, they can still leave too many bugs undetected, because they are able to analyse only certain program flows, dependent on its input data. An alternative solution is *static analysis* that has its own shortcomings as well. The main issue is the *scalability* on extensive codebases and considerable high rate of incorrectly reported errors (so-called *false positives* or *false alarms*).

Recently, Facebook introduced *Facebook Infer* – a tool for creating *highly scalable compositional*, *incremental*, and *interprocedural* static analysers. Facebook Infer has grown considerably in its possibilities, but it is still under active development by many teams across the globe. It is employed every day not only in Facebook itself, but also in other companies, such as Spotify, Uber, Mozilla, or Amazon. Currently, Facebook Infer provides several analysers implemented as modules in the whole framework. These analysers check for various types of bugs, such as buffer overflows, thread-safety, null-dereferencing, or memory leaks. But most importantly Facebook Infer is a framework for building new analysers quickly and easily. Unfortunately, the current version of Facebook Infer still lacks better support for *concurrency* bugs. While it provides a fairly advanced *data race* analyser, it is limited to Java programs only and fails for C programs, which require more through manipulation with locks.

In *concurrent programs*, there are often *atomicity requirements* for execution of specific sequences of instructions. Violating these requirements may cause many kinds of problems, such as unexpected behaviour, exceptions, segmentation faults, or other failures. *Atomicity violations* are usually not verified by compilers, unlike syntactic or some sorts of semantic rules. Moreover, atomicity requirements, in most cases, are not even documented at all. So in the end, programmers themselves must abide by these requirements and usually lack any tool support. And in general, it is difficult to avoid errors in *atomicity-dependent programs*, especially in large projects, and even harder and time-consuming is finding and fixing them.

In this thesis, there is proposed the *Atomer* — the static analyser for finding atomicity violations — which is implemented as an extension for Facebook Infer. In particular, the concentration is put on an *atomic execution of sequences of function calls*, which is often required, e.g., when using certain library calls. The implementation particularly targets C/C++ programs that use *PThread* locks.

The development of Atomer has been discussed with developers of Facebook Infer, and it is a part of the H2020 ECSEL project Aquas. Parts of this thesis and preliminary results are taken from [13], which was written in collaboration with Vladimír Marcin and Ondřej Pavela.

The rest of the paper is organised as follows. In Chapter 2, there are described all the topics which are necessary to understand before reading the rest of the paper. In particular, Section 2.1 deals with *static analysis* based on *abstract interpretation*. Facebook Infer, which uses abstract interpretation, is described in Section 2.2. And in Section 2.3, there is described the concept of *contracts for concurrency*. A proposal of a static analyser for detection of *atomicity violations*, based on this concept, is described in Chapter 3 together with a description of existing analysers of a similar kind. An implementation of the analyser and its experimental verification and evaluation is presented in Chapter 4. Finally, Chapter 5 concludes the paper. In addition, there are three appendices. Appendix A shows the experimental results. Appendix B lists contents of attached memory media and Appendix C serves as an installation and user manual.

Chapter 2

Preliminaries

This chapter explains the theoretical background on which stands the thesis. It also explains and describes the existing tools used in the thesis. Lastly, the chapter deals with principles which this thesis got inspired by.

The aim of this thesis is to propose a *static analyser* and implement it in *Facebook Infer*. So, in Section 2.1, there is a brief explanation of *static analysis* itself, and then an explanation of *abstract interpretation* that is used in Facebook Infer. Facebook Infer, its principles and features illustrate Section 2.2. A proposal of a solution is based on the concept of *contracts for concurrency*, which is discussed and defined in Section 2.3.

2.1 Static Analysis by Abstract Interpretation

According to [18], *static analysis* of programs is reasoning about the behaviour of computer programs without actually executing them. It has been used since the 1970s for optimising compilers for generating effective code. More recently, it has proven valuable also for automatic error detection, verification tools and it is used in other tools that can help programmers. Intuitively, a static program analyser is a program that reasons about the behaviour of other programs, in other words, a static program analyser checks if the *program semantics* of a given program fulfils the given *specification*, as illustrates Figure 2.1 [8]. Nowadays, static analysis is one of the fundamental concepts of *formal verification*. It aims to automatically answer questions about a given program such as e.g. [18]:

- **Are certain operations executed *atomically*?**
- Does the program terminate on every input?
- Can the program *deadlock*?
- Does there exist an input that leads to a *null-pointer dereference*, a *division-by-zero*, or an *arithmetic overflow*?
- Are all variable initialised before they are used?
- Are arrays always accessed within their bound?

- Does the program contain *dead code*?
- Are all resources correctly released after their last use?

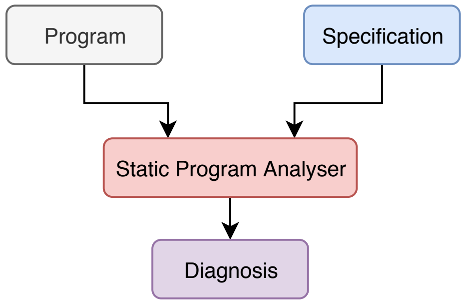


Figure 2.1: Static program analysis [8]

It is well-known that testing, i.e., executing programs with some input data and examining the output, may expose errors, but it can not prove their absence. (It was also famously stated by Edsger W. Dijkstra: "*Program testing can be used to show the presence of bugs, but never to show their absence!*".) However, static program analysis can prove their absence — with some *approximation* — it can check *all possible executions* of the programs and provide guarantees about their properties. Another advantage of static analysis is that the analysis can be performed during the development process, so the program does not have to be executable yet and it already can be analysed. The significant issue is how to ensure high precision and *scalability* to be useful in practice. The biggest disadvantage is that static analysis can produce many *false alarms*[1], but it is often resolved by accepting *unsoundness*[2].

Various forms of static analysis of programs have been invented, for instance [23]: bug pattern searching, data-flow analysis, constraint-based analysis, type analysis, symbolic execution. And one of the essential concept — *abstract interpretation* — is detailed in Section 2.1.1.

There exist numerous tools for static analysis (often proprietary and difficult to openly evaluate or extend), e.g.: Coverity, Klockwork, CodeSonar, Loopus, phpstan, or *Facebook Infer* (described in Section 2.2).

2.1.1 Abstract Interpretation

This section explains and defines the basics of *abstract interpretation*. The description is based on [8], [9], [6], [7], [14], [15], [10], [19], [18], [24]. In these bibliographies, there also can be found more detailed, more formal, and a more theoretical explanation.

The abstract interpretation was introduced and formalised by a French computer scientist Patrick Cousot and his wife Radhia Cousot in the year 1977 at POPL[3] [9]. It is a generic *framework* for static analyses. It is possible to create particular analyses by providing specific components (described later) to the framework. The analysis is guaranteed to be *sound* if certain properties of the components are met. [14], [15]

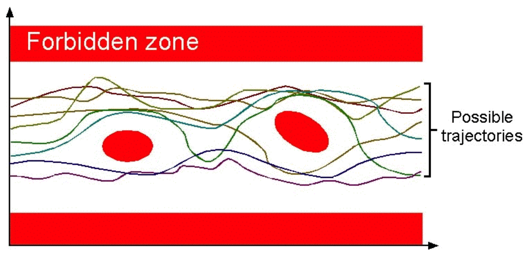
[1]**False alarms** – incorrectly reported an error. Also called *false positives*.

[2]**Soundness** – if a verification method claims that a system is correct according to a given specification, it is truly correct. [23]

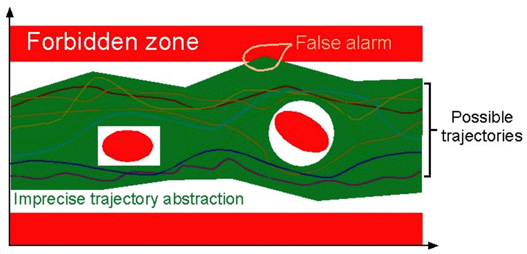
[3]**POPL** – symposium on Principles of Programming Languages.

In general, in the set theory, which is independent on an application setting, abstract interpretation is considered theory for *approximating* sets and set operations. A more restricted formulation of abstract interpretation is to interpret it as a theory of approximation of the behaviour of the *formal semantics* of programs. Those behaviours may be characterised by *fixpoints* (defined below), that is why a primary part of the theory provides efficient techniques for *fixpoint approximation* [19]. So, for a standard semantics, abstract interpretation is used to derive the approximate abstract semantics over an *abstract domain* (defined below), in order to check a given *program specification* using analysation of the abstract semantics. [8]

Patrick Cousot intuitively and informally illustrates abstract interpretation in [6] as follows. Figure 2.2a shows the *concrete semantics* of a program by a set of curves, which represents the set of all possible executions of the program in all possible execution environments. Each curve shows the evolution of the vector $x(t)$ of input values, state, and output values of the program as a function of the time t. *Forbidden zones* on this figure represent a set of erroneous states of the program execution. Proving, that the intersection of the concrete semantics of the program with the forbidden zone is empty, is undecidable because the program concrete semantics is not computable. As demonstrates Figure 2.2b, abstract interpretation deals with an *abstract semantics*, i.e., the *superset* of the concrete program semantics. The abstract semantics includes all possible executions. That implies that if the abstract semantics is safe (i.e. does not intersect the forbidden zone), concrete semantics is safe as well. However, the *over-approximation* of the possible program executions causes that inexisting program executions are considered, that may lead to *false alarms*. It is the case when the abstract semantics intersects the forbidden zone, whereas the concrete semantics does not intersect it.



(a) *Concrete semantics* of programs with *forbidden zones*



(b) *Abstract semantics* of programs with imprecise trajectory abstraction

Figure 2.2: Abstract interpretation demonstration [6]. Horizontal axes: time t. Vertical axes: vector $x(t)$ of input values of programs

Components of Abstract Interpretation

In accordance with [14], [15], basic components of abstract interpretation are as follows:

- **Abstract Domain** [7]

- An abstraction of the *concrete semantics* in the form of *abstract properties*[4] and *abstract operations*[5]. [8]
- Sets of program states at certain locations are represented using *abstract states*.

- **Abstract Transformers**
  - There is a *transform function* for each program operation (instruction) that represents the impact of the operation executed on an abstract state.

- **Join Operator** $\circ$
  - Joins abstract states from individual program branches into a single one.

- **Widening Operator** $\triangledown$ [19], [10], [14]
  - Enforces termination of the abstract interpretation.
  - It is used to approximate the *least fixed points* (it is performed on a sequence of abstract states at a certain location).
  - The later in the analysis is this operator used, the more accurate is the result (but the analysis takes more time).

- **Narrowing Operator** $\triangle$ [19], [10], [14]
  - Encapsulates a termination criterion.
  - Using this operator, the approximation can be refined, i.e., it may be used to refine the result of widening.
  - This operator is used when a *fixpoint* is approximated using widening.

Fixpoints and Fixpoint Approximation

Definition 2.1.1. In [24], there is a *fixpoint* defined as:

- let $(A, \leq_A)$ be a *lattice* [24],
- an element $a \in A$ is a **fixpoint** of a function $f : A \to A$ if and only if $\boldsymbol{f(a) = a}$.

Computation of the *most precise abstract fixpoint* is not generally guaranteed to terminate in certain cases, such as loops. The solution is to approximate the fixpoint using *widening* (over-approximation of a fixpoint) and *narrowing* (improves an approximation of a fixpoint) [14], [15]. Most program properties can be represented as fixpoints. This reduces program analysis to the fixpoint approximation [7]. Further information about fixpoint approximation can be found in [19], [10].

[4] **Abstract properties** approximating *concrete properties behaviours*.
[5] **Abstract operations** include abstractions of the *concrete approximation*, an approximation of the *concrete fixpoint transform function*, etc.

Formal Definition of Abstract Interpretation

Definition 2.1.2. According to [9], [14], **abstract interpretation** $\boldsymbol{I}$ of a program P with the instruction set S is a tuple

$$\boldsymbol{I} = (\boldsymbol{Q}, \circ, \sqsubseteq, \top, \bot, \boldsymbol{\tau})$$

where

- $\boldsymbol{Q}$ is the *abstract domain* (domain of *abstract states*),
- $\circ : Q \times Q \to Q$ is the *join operator* for accumulation of abstract states,
- $(\sqsubseteq) \subseteq Q \times Q$ is *ordering* defined as $x \sqsubseteq y \Leftrightarrow x \circ y = y$ in $(Q, \circ, \top)$,
- $\top \in Q$ is a *supremum* of Q,
- $\bot \in Q$ is an *infimum* of Q,
- $\boldsymbol{\tau} : S \times Q \to Q$ defines the *abstract transformers* for specific instructions,
- $(Q, \circ, \top)$ is a *complete semilattice* [24], [14].

Using so-called *Galois connections* ([19], [10], [14], [7]) can be guaranteed the *soundness* of abstract interpretation.

2.2 Facebook Infer – Static Analysis Framework

This section describes the principles and features of *Facebook Infer*. The description is based on information provided on Facebook Infer website[6] and in [2], [15]. Parts of this section are taken from [13].

Facebook Infer is an open-source[7] static analysis *framework*,which is able to discover various kinds of software bugs of a given program, and the stress is put on *scalability*. Elementary essence of this framework shows Figure 2.3, below is a more detailed explanation of its architecture. Facebook Infer itself is implemented in *OCaml*[8] – *functional* programming language, also supporting *imperative* and *object-oriented* paradigms. Further details about OCaml can be found in [17] or in official documentation[9], tutorials[10]. Facebook Infer was originally a standalone tool focused on *sound verification* of the absence of *memory safety violations*, which has made its breakthrough thanks to a powerful paper [5].

Facebook Infer is able to analyse programs written in several languages. In particular, it supports languages C, C++, Java, and Objective-C. Moreover, it is possible to extend Facebook Infer's *frontend* for supporting another languages. Currently, Facebook Infer contains many analyses focusing on amount sorts of bugs, e.g., *Inferbo* (buffer overruns) [25]; *RacerD* (data races) [3], [4], [12]; and other analyses checks for buffer overflows, thread-safety, null-dereferencing, memory leaks, resource leaks, etc.

[6] **Facebook Infer** website – `https://fbinfer.com`.
[7] **Open-source repository of Facebook Infer** on GitHub – `https://github.com/facebook/infer`.
[8] **OCaml** website – `https://ocaml.org`.
[9] **OCaml documentation** – `http://caml.inria.fr/pub/docs/manual-ocaml`.
[10] **OCaml tutorials** – `https://ocaml.org/learn/tutorials`.

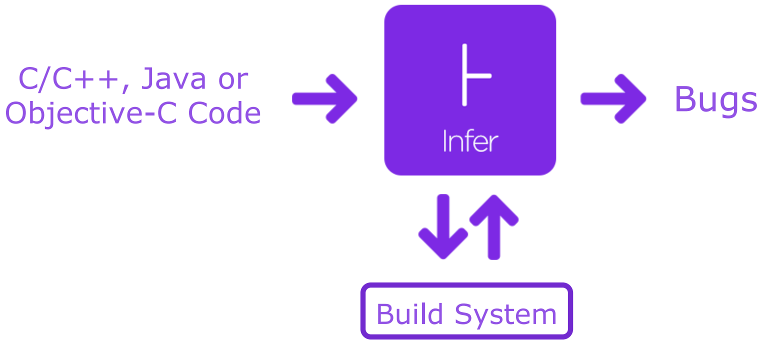


Figure 2.3: Static analysis in Facebook Infer (`http://www.codeandyou.com/2015/06/infer-static-analyzer-for-java-c-and.html`)

2.2.1 Abstract Interpretation in Facebook Infer

Facebook Infer is a general framework for static analysis of programs, it is based on *abstract interpretation*, see Section 2.1.1. It aims to find bugs rather than formal verification. It can be used to quickly develop new sorts of *compositional* and *incremental* analysers (*intraprocedural* or *interprocedural* [19]) based on the concept of function *summaries*. In general, a *summary* is a representation of *preconditions* and *postconditions* of a function. However, in practice, a summary is a custom data structure that may be used for storing any information resulting from the analysis of single functions. Facebook Infer generally does not work out the summaries in the course of the analysis along the *Control Flow Graph* (**CFG**)[11] as it is done in classical analyses based on the concepts from [20], [21]. Instead, Facebook Infer performs the analysis of a program *function-by-function along the call tree*, starting from its leafs (demonstrated later). Therefore a function is analysed and a summary is computed without knowledge of the call context. Since summaries worked out in different contexts are equal, this principle makes the analysis more scalable, but it can lead to a loss of accuracy. Then, the summary of a function is used at all of its call sites. In order to create new intraprocedural analyser in Facebook Infer, it is needed to define (listed items are described in more detail in Section 2.1.1):

1. The *abstract domain* Q, i.e., a type of an *abstract state*.
2. Operator $\sqsubseteq$, i.e., *ordering* of abstract states.
3. The *join* operator $\circ$, i.e., the way of joining two abstract states.
4. The *widening* operator ∇, i.e., the way how to enforce termination of the abstract interpretation of iteration.
5. *Transfer functions* τ, i.e., a transformer that takes an abstract state as an input and produces an abstract state as an output.

And in order to create an interprocedural analyser, it is required to additionally define:

1. A type of function summaries.

[11] **A control flow graph (CFG)** is a directed graph in which the nodes represent basic blocks and the edges represent control flow paths. [1]

2. The logic for using summaries in transfer functions, and the logic for transforming an intraprocedural abstract state to a summary.

The next important feature improving the scalability is *incrementality* of the analysis, it allows to analyse separate code changes only, instead of analysing the whole codebase. It is more suitable for extensive and variable projects, where ordinary analysis is not feasible. The incrementality is based on *re-using summaries* of functions for which there is no change in them neither in the functions transitively invoked from them.

The Architecture of the Abstract Interpretation Framework in Facebook Infer

The architecture of the abstract interpretation framework of Facebook Infer (**Infer.AI**) may be split into three major parts, as demonstrates Figure 2.4: a *frontend*, an *analysis scheduler* (and a *results database*), and a set of *analyser plugins*.

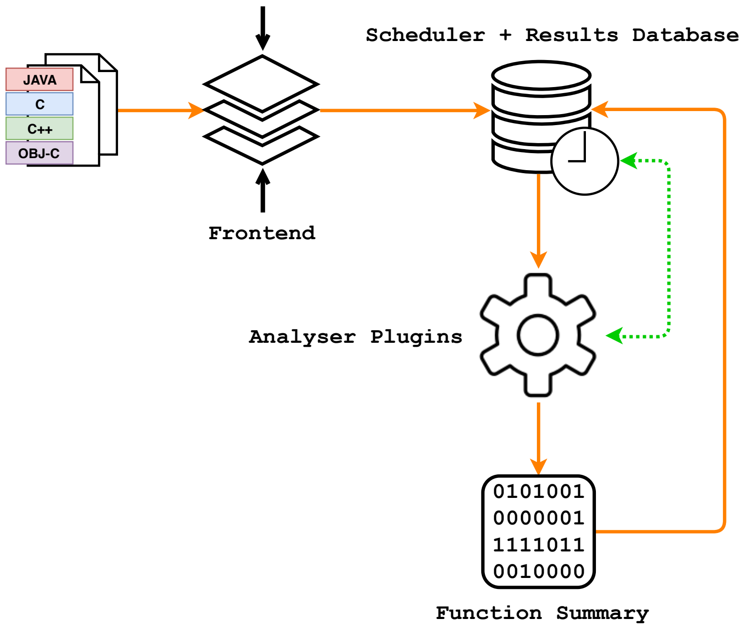


Figure 2.4: The architecture of Facebook Infer's abstract interpretation framework [2], [15]

The frontend compiles input programs into the *Smallfoot Intermediate Language* (SIL) and represents them as the CFG. There is a separate CFG representation for each analysed function. Nodes of this CFG are formed as instructions of SIL. SIL language consists of following underlying instructions:

1. `LOAD` – reading into a temporary variable.
2. `STORE` – writing to a program variable, a field of a structure, or an array.
3. `PRUNE e` (often called `ASSUME`) – a condition `e`.
4. `CALL` – a function call.

The frontend allows one to propose *language-independent* analyses (to a certain extent) because it supports input programs to be written in multiple languages.

The next part of the architecture is the scheduler, which defines the order of the analysis of single functions according to the appropriate *call graph*[12]. The scheduler also checks if it is possible to analyse some functions simultaneously, which allows Facebook Infer to run the analysis in parallel.

Example 2.2.1. For demonstrating the order of the analysis in Facebook Infer and its incrementality, assume a call graph in Figure 2.5. At first, leaf functions `F5` and `F6` are analysed. Further, the analysis goes on towards the root of the call graph – $\texttt{F}_{\texttt{MAIN}}$, while takes into consideration the dependencies denotes by the edges. This order ensures that a summary is available once a nested function call is abstractly interpreted within the analysis. When there is a subsequent code change, only directly changed functions and all the functions up the call path are re-analysed. For instance, if there is a change of source code of function `F4`, Facebook Infer triggers re-analysation of functions `F4`, `F2`, and $\texttt{F}_{\texttt{MAIN}}$ only.

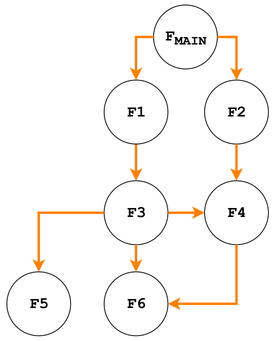


Figure 2.5: A call graph for an illustration of Facebook Infer's analysis process [2], [13], [15]

The last part of the architecture consists of a set of analyser plugins. Each plugin performs the analysis by interpretation of SIL instructions. Result of the analysis of each function (function summary) is stored to the results database. Interpretation of SIL instructions (*commands*) is done using an *abstract interpreter* (also called a *control interpreter*) and *transfer functions* (also called a *command interpreter*). The transfer functions take an actual *abstract state* of an analysed function as an input, and by applying the interpreting command produce a new abstract state. Then, the abstract interpreter interprets the command in *abstract domain* according to the CFG. This workflow is simplified in Figure 2.6.

2.3 Contracts for Concurrency

This section introduces and defines the concept of *contracts for concurrency* described in [22], [11]. Parts of this section are taken from [13]. Listings in this section are pieces of programs written in ANSI C[13].

Respecting the *protocol* of a software module — delineates which *sequences of functions* are legal to invoke — is one of the requirements for the correct behaviour of the module. For example, a module that deals with file system typically requires that a programmer using this module should call function `open` at first, followed by an optional number of functions `read` and `write`, and at last, call function `close`. A program utilising such a module that does not follow this protocol is erroneous. The methodology of *design by contract* (described in [16]) requires programs to meet such well-defined behaviours. [22]

[12] **A call graph** is *directed graph* describing call dependencies among functions.
[13] **ANSI C** – standard for the C programming language published by the *ANSI* (American National Standards Institute).

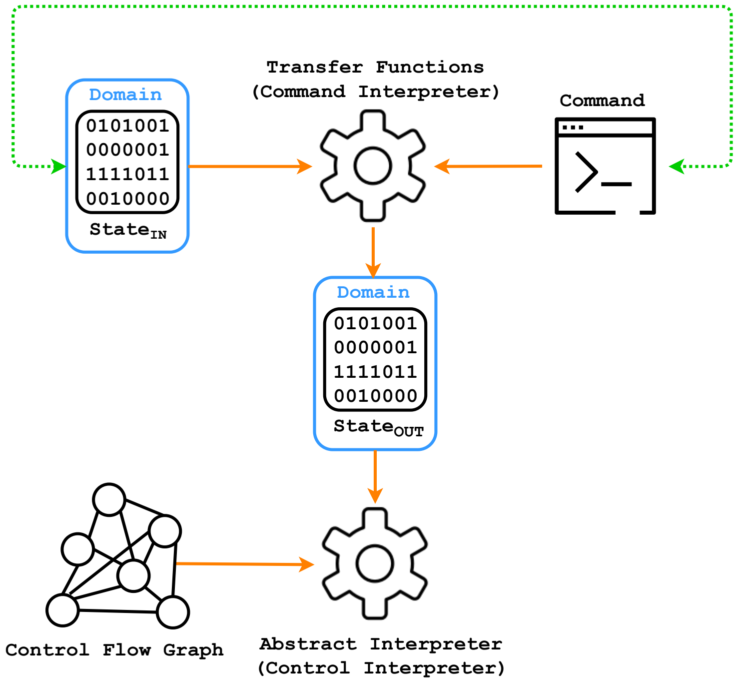


Figure 2.6: Facebook Infer's abstract interpretation process [2], [15]

In *concurrent programs*, contracts for concurrency allow one to specify *sequences of functions* that are needed to be *executed atomically*, in order to avoid *atomicity violations*. Such contracts may be manually specified by a developer or it may be automatically generated by a program (analyser). These contracts can be used to verify the correctness of programs as well as they can serve as helpful documentation. A program is safe from atomicity violations if the program follows the contract and the contract is well-defined and complete.

Section 2.3.1 defines the notion of *basic contracts for concurrency*. Further, Section 2.3.2 defines contracts extended to consider the *data flow* between functions (i.e., a sequence of function calls must be atomic only if they handle the same data). Above that, paper [11] extends the idea of basic contracts with *spoilers* (i.e., extending by *contextual information*).

2.3.1 Basic Contracts

Definition 2.3.1. In [11], [22], a *basic contract* is formally defined as follows. Let $\Sigma_{\mathbb{M}}$ be a set of all function names of a software module. A contract is a set $\mathbb{R}$ of *clauses* where each clause $\varrho \in \mathbb{R}$ is a *star-free regular expression*[14] over $\Sigma_{\mathbb{M}}$. A *contract violation* occurs if any of the sequences expressed by the contract clauses are interleaved with the execution of functions from $\Sigma_{\mathbb{M}}$, in other words, each sequence specified by any clause ϱ must be executed atomically, otherwise, there is a violation of the contract. The number of sequences defined by a contract is finite since the contract is the union of *star-free languages*.

Example 2.3.1. Consider the following example from [11], [22]. There is a module with the implementation of a resizable array with the listed functions:

[14] **Star-free regular expressions** are regular expressions using only the *concatenation operators* and the *alternative operators* (|), without the *Kleene star operator* (∗).

f_1: `void add(char *array, char element)`

f_2: `bool contains(char *array, char element)`

f_3: `int index_of(char *array, char element)`

f_4: `char get(char *array, int index)`

f_5: `void set(char *array, int index, char element)`

f_6: `void remove(char *array, int index)`

f_7: `int size(char *array)`

The module's contract contains the following clauses:

(ϱ_1) `contains index_of`

The execution of `contains` followed by the execution of `index_of` should be atomic. Otherwise, the program may fail to get the index, because after verification of the presence of an element in an array, it can be concurrently, e.g., removed.

(ϱ_2) `index_of (get | set | remove)`

The execution of `index_of` follow by the execution of `get`, `set`, or `remove` should be atomic. Otherwise, the received index may be outdated when it is applied to address an element, because a concurrent modification of an array may shift the position of the element.

(ϱ_3) `size (get | set | remove)`

The execution of `size` followed by the execution of `get`, `set`, or `remove` should be atomic. Otherwise, the size of an array may be void when accessing an array, because of a concurrent change of the array. This can be an issue since a given index is not in a valid range anymore (e.g., testing `index < size`).

(ϱ_4) `add (get | index_of)`

The execution of `add` followed by the execution of `get` or `index_of` should be atomic. Otherwise, the added element does not have to longer exist or its position in an array can be changed, when the program attempts to obtain information about it.

The above definition of contracts for concurrency is quite limited in some circumstances and can consider valid concurrent programs as erroneous (reports *false alarms*). Hence, in Section 2.3.2, there is defined an extension of contracts for concurrency with *parameters*, which takes into consideration the data flow within function calls. And in [11], [22], there is defined another extension with *spoilers*, which considering contextual information of function calls.

2.3.2 Contracts with Parameters

Example 2.3.2. Consider the following example from [11], [22], as demonstrates Listing 2.1. There is a function `replace` that replaces item `a` in an array by item `b`. Implementation of this function comprises two atomicity violations:

(i) when `index_of` is invoked, item `a` does not need to be in the array anymore;

(ii) the acquired index can be obsolete when `set` is invoked.

A basic contract defined in Section 2.3.1 could cover this scenario by clause ϱ_5:

(ϱ_5) `contains index_of set`

Nevertheless, it is too restrictive because it is required to be executed atomically only if `contains` and `index_of` have the same arguments `array` and `element`, `index_of` and `set` have the same argument `array`, and the returned value of `index_of` is used as the argument `index` of function `set`.

```c
void replace(char *array, char a, char b)
{
    if (contains(array, a))
    {
        int index = index_of(array, a);
        set(array, index, b);
    }
}
```

Listing 2.1: An example of an atomicity violation with data dependencies [11]

In order to respect function call *parameters* and *return values* of functions in contracts, the basic contracts are further extended by dependencies among functions in [11], [22] as follows. Function call parameters and return values are expressed as *meta-variables*. Further, if a contract should be required exclusively if the same object emerges as an argument or as the return value of multiple calls in a given call sequence, it may be denoted by using the same meta-variable at the position of all these occurrences of parameters and return values.

Clause ϱ_5 can be extended as follows (repeated application of meta-variables `X/Y/Z` requiring the same objects $\mathtt{o}_1/\mathtt{o}_2/\mathtt{o}_3$ to be used at the positions of `X/Y/Z`):

(ϱ'_5) `contains(X,Y) Z=index_of(X,Y) set(X,Z,_)`

The underscore indicates a *free meta-variable* that does not restrict the contract clause.

With the extension described above, it is possible to extend the contract from Section 2.3.1 as follows:

(ϱ'_1) `contains(X,Y) index_of(X,Y)`

(ϱ'_2) `Y=index_of(X,_) (get(X,Y) | set(X,Y,_) | remove(X,Y))`

Chapter 3

Atomicity Violations Detector

This chapter describes a proposal of a static program analyser for detection of *atomicity violations*. The proposed analyser — **Atomer** — has been proposed as an extension for *Facebook Infer*, introduced in Section 2.2. In particular, the proposal concentrates on an *atomic execution of sequences of function calls*, which is often required. The proposed principle is based on the assumption that sequences executed *once atomically* should probably be executed *always atomically*. The chapter also assessments already existing solutions in this area.

At first, Section 3.1 deals with existing approaches and tools for finding atomicity violations, their advantages, disadvantages, features, availability, and so on. Then, the proposal itself is introduced in Section 3.2. Parts of this chapter are taken from [13]. Listings in this chapter are pieces of exemplary programs written in ANSI C (assume *PThread* locks and the existence of an initialised global variable `lock` of a type `pthread_mutex_t`).

3.1 Related Work

The proposed solution is slightly inspired by ideas from [11], [22]. In these papers, there is described a proposal and implementation of a *static validation* for finding *atomicity violations*, which is based on *grammars* and *parsing trees*. In paper [11], there is also described and implemented a dynamic approach to this validation. The authors of [11] and [22] implemented a stand-alone prototype tool[1] for analysing programs written in Java. It led to some promising experimental results but the *scalability* of the tool was still limited. Moreover, the tool from [11] and [22] is no more developed. That is why was made the decision to get inspired by [11] and [22] and reimplement the analysis in *Facebook Infer* redesigning it in accordance with the principles of Facebook Infer (described in Section 2.2), which should make it more scalable. In the end, due to adapting the analysis for the context of Facebook Infer, implementation of the analysis within this thesis is significantly different from [11] and [22], as it is presented in Chapter 4. Furthermore, unlike [11] and [22], the implementation aims at programs written in C/C++ languages using *POSIX Thread (PThread)* locks for a *synchronisation of concurrent threads*.

[1] **Gluon** — a tool for static verification of *contracts for concurrency* (see Section 2.3) in Java programs — https://github.com/trxsys/gluon.

In Facebook Infer, there is already implemented analysis called *Lock Consistency Violation*[2]. It is part of *RacerD* [3], [4], [12]. This analysis finds atomicity violations for writes/reads on single variables that are required to be executed atomically. Atomer is different, it finds atomicity violations for *sequences of functions* that are required to be executed atomically, i.e., it checks whether *contracts for concurrency* (see Section 2.3) hold.

3.2 Analysis and Design

The proposal of the analyser is based on the concept of *contracts for concurrency* described in Section 2.3. In particular, the proposal considers only *basic contracts* described in Section 2.3.1. Parameters of functions and their return values — expressed in *contracts with parameters* (see Section 2.3.2) — are not taken into consideration.

In general, basic contracts for concurrency allow one to define *sequences of functions* that are required to be *executed atomically*, as it is explained in more detail in Section 2.3. Atomer is able to automatically derive candidates for such contracts, and then to verify whether the contracts are fulfilled. Both of these operations are done statically. The proposed analysis is divided into two parts (*phases of the analysis*):

Phase 1: Detection of *atomic sequences*, which is described in Section 3.2.1.

Phase 2: Detection of *atomicity violations* (violations of the atomic sequences), which is described in Section 3.2.2.

These phases of the analysis and its workflow illustrate Figure 3.1.

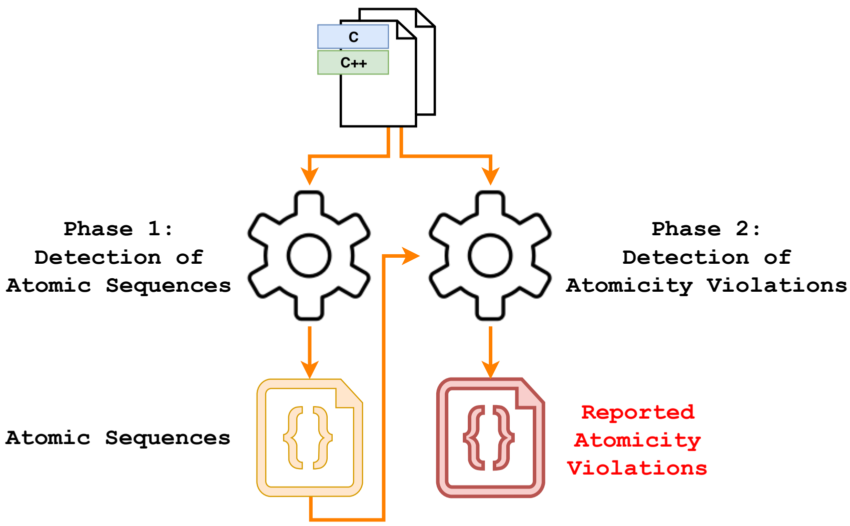


Figure 3.1: Phases of the proposed analyser

[2]**Lock Consistency Violation** — atomicity violations analysis in Facebook Infer — https://fbinfer.com/docs/checkers-bug-types.html#LOCK_CONSISTENCY_VIOLATION.

3.2.1 Phase 1: Detection of Atomic Sequences

Before the detection of *atomicity violations* (Section 3.2.2) may begin, it is required to have contracts introduced in Section 2.3. **Phase 1** of Atomer is able to produce such contracts, i.e., it detects *sequences of functions* that should be *executed atomically*. Intuitively, the detection is based on looking for sequences of functions that are executed atomically on some path through a program. The assumption is that if it is once needed to execute a sequence atomically, it should probably be always executed atomically.

The detection of sequences of calls to be executed atomically is based on analysing all paths through the CFG of a function and generating all pairs **(A, B)** of sets of function calls such that: **A** is a *reduced sequence* of function calls that appear between the beginning of the function being analysed and the first lock or between an unlock and a subsequent lock (or between an unlock and the end of the function being analysed), and **B** is a reduced sequence of function calls that follow the calls from **A** and that appear between a lock and an unlock (or between a lock and the end of the function being analysed). Here, by a reduced sequence, it is meant a sequence in which the first appearance of each function is recorded only. The reason is to ensure *finiteness* of the sequences and of the analysis. The *summary* of a function then consists of:

(i) the set of all the **B** sequences and

(ii) the set of *concatenations* of all the **A** and **B** sequences with the removal of duplicate function calls.

The latter is recorded for the purpose of analysing functions higher in the *call hierarchy* since locks/unlocks can appear in such a *higher-level function*.

Example 3.2.1. For instance, the analysis of the function `g` from Listing 3.1 produces the following sequences:

$$\overbrace{\texttt{f1}\ \cancel{\texttt{f1}}}^{\mathbf{A_1}}\overbrace{(\texttt{f1}\ \cancel{\texttt{f1}}\ \texttt{f2})}^{\mathbf{B_1}}\,|\,\overbrace{\texttt{f1}\ \cancel{\texttt{f1}}}^{\mathbf{A_2}}\overbrace{(\texttt{f1}\ \texttt{f3})}^{\mathbf{B_2}}\,|\,\overbrace{\cancel{\texttt{f1}}}^{\cancel{\mathbf{A_3}}}\ \overbrace{(\cancel{\texttt{f1}\ \texttt{f3}\ \texttt{f3}})}^{\cancel{\mathbf{B_3}}}$$

The parentheses are used to indicate an atomic sequence. The strikethrough of the functions `f1` and `f3` denotes the removal of already recorded function calls in the **A** and **B** sequences. The strikethrough of the entire sequence `f1` (`f1 f3 f3`) means discarding sequences already seen before. The derived sets for the function `g` are then as follows:

(i) {(`f1 f2`), (`f1 f3`)}, i.e., $\mathbf{B_1}$ and $\mathbf{B_2}$;

(ii) {`f1 f2 f3`}, i.e., concatenation of $\mathbf{A_1}$, $\mathbf{B_1}$, $\mathbf{A_2}$, and $\mathbf{B_2}$ with the removal of duplicate function calls.

Analysing Functions Using Results of the Analysis of Nested Functions

Further, it is demonstrated how the results of the analysis of *nested functions* are used during the detection of atomic sequences. The result of the analysis of a nested function is used as follows. When calling an already analysed function, one plugs all the sequences from the second component of its summary into the current **A** or **B** sequence.

```c
void g(void)
{
    f1(); f1();

    pthread_mutex_lock(&lock);
    f1(); f1(); f2();
    pthread_mutex_unlock(&lock);

    f1(); f1();

    pthread_mutex_lock(&lock);
    f1(); f3();
    pthread_mutex_unlock(&lock);

    f1();

    pthread_mutex_lock(&lock);
    f1(); f3(); f3();
    pthread_mutex_unlock(&lock);
}
```

Listing 3.1: An example of a code for an illustration of the derivation of sequences of functions called atomically

Example 3.2.2. This example shows how the function h from Listing 3.2 would be analysed using the result of the analysis of the function g from Listing 3.1. So the analysis of the function h produces the following sequence:

f1 g ~~f1~~ f2 f3 (g f1 f2 f3)

The derived sets for the function h are then as follows:

(i) {(g f1 f2 f3)};

(ii) {f1 g f2 f3}.

```c
void h(void)
{
    f1(); g();

    pthread_mutex_lock(&lock);
    g();
    pthread_mutex_unlock(&lock);
}
```

Listing 3.2: An example of a code for an illustration of the derivation of sequences of functions called atomically with a nested function call (function g is defined in Listing 3.1)

Cases Where Lock/Unlock Calls Are Not Paired in a Function

For treating cases where lock/unlock calls are *not paired* in a function — as demonstrates Listing 3.3 — two solutions have been proposed:

1. At the end of a function, everything is unlocked, i.e., append an unlock to the end of the function if it is necessary. Then for the function `x` from Listing 3.3, the first component of its summary (i.e., atomic sequences) would be {(`a`)}. Subsequently, all unlock calls not preceded by a lock are ignored. So the first component of a summary of the function `y` from Listing 3.3 would be an empty set.

2. Addition of two further items to the summaries:

   (a) function calls with missing an unlock call,

   (b) function calls with missing a lock call.

   For the example from Listing 3.3, this would give:

   - for `x`: {(`f1`},
   - for `y`: {`f2`)}.

   The above sequences would have to be glued to the sequences captured higher in the call hierarchy. Calls of the functions `f1` and `f2` will also appear in the second component of the function summaries (i.e., the sequences of all functions called).

```c
void x(void)
{
    pthread_mutex_lock(&lock);
    f1();
}

void y(void)
{
    f2();
    pthread_mutex_unlock(&lock);
}

void main(void)
{
    x(); y();
}
```

Listing 3.3: An example of a code for an illustration of treating cases where lock/unlock calls are not paired in a function

In the end, the first approach of treating such cases described above has been chosen. The reason is that it is much easier for implementation. However, in future, the analysis can be improved by implementing the second approach.

Summary of Detection of Atomic Sequences and Future Work

The above detection of atomic sequences has been implemented, as it is described in Section 4.1. Furthermore, it has been successfully verified on a set of sample programs created for this purpose. The verification is presented in Section 4.3 and in Section A.1 of Appendix A. The derived sequences of calls assumed to execute atomically, i.e., the **B** sequences, from the summaries of all analysed functions are stored into a file, which is used during **Phase 2**, described below in Section 3.2.2. There are some possibilities for further extending and improving **Phase 1**, e.g., working with *nested locks*; distinguishing the *different locks* used (currently, it is not distinguished between the locks at all); consider *contracts for concurrency with parameters* defined in Section 2.3.2 or other extensions of contracts for concurrency discussed in Section 2.3; or extending the detection for *other types of locks* for a synchronisation of concurrent threads/processes. On the other hand, to further enhance the *scalability*, it seems promising to replace working with the **A** and **B** sequence by working with sets of calls: sacrificing some precision but gaining the speed.

3.2.2 Phase 2: Detection of Atomicity Violations

In the second phase of the analysis, i.e., when *detecting violations* of the atomic sequences obtained from **Phase 1** (see Section 3.2.1), the analysis looks for pairs of functions that should be called atomically (or just for single functions if there is only one function call in an atomic sequence) while this is not the case on some path through the CFG.

Example 3.2.3. For example, assume that the result of the first phase is the following set of functions called atomically:

$$\{(\texttt{f1 f2 f3}), (\texttt{f1 f3 f4})\}$$

Then the analysis will look for the following pairs of functions that are not called atomically:

- `f1 f2`
- `f2 f3`
- `f1 f3`
- `f3 f4`

The analysis of functions with nested function calls and cases where lock/unlock calls are not paired in a function are handled the analogical way as it is handled in **Phase 1** described in Section 3.2.1. For detailed examples see verification experiments in Section A.2 of Appendix A.

Example 3.2.4. For a demonstration of the detection of an atomicity violation, assume the functions `a` and `b` from Listing 3.4. The set of atomic sequences of the function `a` is $\{(\texttt{f2 f3})\}$. In the function `b`, an atomicity violation is detected because the functions `f2` and `f3` are not called atomically (under a lock).

```
void a(void)
{
    f1();

    pthread_mutex_lock(&lock);
    f2(); f3();
    pthread_mutex_unlock(&lock);

    f4();
}

void b(void)
{
    f1(); f2(); f3(); f4();
}
```

Listing 3.4: Example of an atomicity violation

Summary of Detection of Atomicity Violations and Future Work

As well as the first phase of the analysis, **Phase 2** has been implemented, as it is described in Section 4.2. And it has been also successfully verified on a set of sample purposeful programs. This verification is described in Section 4.3 and in Section A.2 of Appendix A. **Phase 2** also has the potential for further enhancing. It is possible to extend this phase with all the improvements discussed in Section 3.2.1. Moreover, it is possible to improve this phase by working with sets instead of pairs, when looking for functions that should be called atomically. The next idea is to consider atomic sequences from the first phase only if they appear in an *atomic block* more than, e.g., three times. It would strengthen certainty that this sequence should be called atomically.

Chapter 4

Implementation and Evaluation

This chapter describes the implementation of the *static analyser* proposed in Chapter 3. The analyser is implemented as an extension for *Facebook Infer* introduced in Section 2.2. The implementation is demonstrated using algorithms in *pseudocode* and using listings with codes written in *OCaml*, which is an implementation language of Facebook Infer. Section 4.1, respectively Section 4.2, then describes an implementation of the *detection of atomic sequences* defined in Section 3.2.1, respectively an implementation of the *detection of atomicity violations* defined in Section 3.2.2. Subsequently, Section 4.3 covers experimental verification and evaluation of the analyser.

The implementation of the analyser can be found publicly on GitHub[1]. The implementation is done in OCaml and it is exploited its *functional* and *imperative* paradigm. Facebook Infer supports analysis of programs written in Java, C, C++, and Objective-C. However, the implementation aims at programs written in C/C++ languages using *POSIX Thread (PThread)* locks, which is a low-level mechanism for *synchronisation of concurrent threads*. So, as a lock, it is considered a function with a name `pthread_mutex_lock` and as an unlock, it is considered a function with a name `pthread_mutex_unlock`. It is also possible to run the analysis on programs written in Java or Objective-C languages but the result of the analysis would be likely wrong since these languages use a different mechanism for synchronisation.

Phase 1, i.e., the detection of atomic sequences and **Phase 2**, i.e., the detection of atomicity violations (these phases are described in Chapter 3.2) are implemented as separated analysers in Facebook Infer. The output of the first phase is the input of the second phase (as demonstrates Figure 3.1). Both of these analysers are registered as extensions of Facebook Infer in a file `infer/src/checkers/registerCheckers.ml`. These analyses run only if a particular command line argument of Facebook Infer is specified. Implementations of individual phases are stated in sections below (Section 4.1 and Section 4.2).

In order to make the analysis *interprocedural*, it is necessary to define a type of function *summaries* for each phase. The types of summaries are defined in *abstract domains* of each phase. But the summaries are accessed globally using a structure (so-called *summary payload*). Fields of the payload that refer to the summaries of analyses are defined in a file `infer/src/backend/Payloads.ml[i]`.

[1]**The implementation of the analyser** in a GitHub repository, which is a *fork* of the official repository of Facebook Infer, in a branch `atomicity` – `https://github.com/harmim/infer/tree/atomicity`.

For both phases of the analysis, the analyser is implemented as an *abstract interpreter* using the `LowerHil` module which transforms *SIL instructions* into *HIL instructions*. (Abstract interpretation in Facebook Infer, as well as SIL instructions, are described in Section 2.2.1.) HIL instructions just wrap SIL instructions and simplify their utilisation. For representing functions, *forward CFG with no exceptional control-flow* is used. It corresponds to the `ProcCfg.Normal` module in Facebook Infer. *Transfer functions* of both phases are implemented in the same essence, as illustrates Listing 4.1. In general, transfer functions take an *abstract state* as an input and produce an abstract state as an output for specific instructions. In this case, it modifies an abstract state when a function is called (`CALL` instruction). When the called function is a lock or an unlock, the abstract state is appropriately updated in the abstract domain of the analysis. Otherwise, the abstract state is updated with the called function and then, if the called function has already been analysed, it is used its summary to update the abstract state again.

```
let exec_instr astate procData _ instr =
  match instr with
  | Call (_, Direct procName, _, _, _) ->
    let procNameS = Procname.to_string procName in

    if is_lock procNameS then
      Domain.update_astate_on_lock astate
    else if is_unlock procNameS then
      Domain.update_astate_on_unlock astate
    else
    (
      let astate =
        Domain.update_astate_on_function_call astate procNameS
      in

      match Payload.read procData.pdesc procName with
      | Some summary ->
        Domain.update_astate_on_function_call_with_summary astate summary
      | None -> astate
    )
  | _ -> astate
```

Listing 4.1: *Transfer functions* of the analysers

The abstract domains of both phases are altogether dissimilar. But essential *operators* of the abstract domains are practically the same. Implementation of these operators is put forward in Listing 4.2, where `TSet` is a module representing a set of specific structures. The abstract state is then of a type of `TSet`. Each phase of the analysis define its own `TSet`, i.e., fields of structures in this set are different for each phase. So particular operators are defined as follows (see also Listing 4.2):

- *Ordering* operator $\sqsubseteq$ (in Facebook Infer, it is `<=`) is defined as follows. Let `lhs` be a left-hand side of this operator and `rhs` a right-hand side of this operator. Then, `lhs <= rhs` (`lhs` is less or equal to `rhs`) if and only if `lhs` is a *subset* of `rhs`.

- The *join* operator ∘ (in Facebook infer, it is `join`) is defined as a *union* of two abstract states.
- The *widening* operator ▽ (in Facebook Infer, it is `widen`) is defined as `join` of the previous and next abstract states.

```
let ( <= ) ~lhs:leftSide ~rhs:rightSide =
  TSet.is_subset leftSide ~of_:rightSide

let join astate1 astate2 =
  TSet.union astate1 astate2

let widen ~prev:prevAstate ~next:nextAstate ~num_iters:_ =
  join prevAstate nextAstate
```

Listing 4.2: Essential *operators of abstract domains* of the analysers

4.1 Implementation of Detection of Atomic Sequences

The proposal of this phase is described in Section 3.2.1. It runs only if it is specified a command line argument `--atomic-sequences`. It detects *sequences of functions* that should be *executed atomically*. These sequences are printed into a file, it is explained in Section 4.1.2.

The main function of the analyser of this phase is `analyse_procedure`, which is shown in Listing 4.3. Facebook Infer invokes this function for every function in an analysed program. It produces a *summary* for a given function. The function computes an *abstract state* for the analysed function using the created abstract interpreter `Analyser` on an *abstract domain*. As a *precondition*, an initial abstract state `initialAstate` from the abstract domain is used. If the computation succeeds, the abstract state is appropriately updated and converted to the function summary by applying functions in the abstract domain. In the end, the *summary payload* is updated with the resulting summary.

The abstract domain of this phase is described in Section 4.1.1. It includes the definition of an abstract state, summary, and functions working with them. *Ordering* of abstract states, the *join operator*, and the *widening operator* are defined at the beginning of Chapter 4.

4.1.1 Abstract Domain of the Detection of Atomic Sequences

In this section, at first, it is described the definition of an *abstract state* of the *abstract domain* along with functions working with the abstract state. Furthermore, it is described a *summary* of functions in this phase of the analysis and corresponding functions working with the summary.

```
let analyse_procedure args =
  let procData = ProcData.make_default args.proc_desc args.tenv in

  match Analyser.compute_post procData ~initial:Domain.initialAstate with
  | Some astate ->
    let summary =
      let astate = Domain.update_astate_at_the_end_of_function astate in
      Domain.convert_astate_to_summary astate
    in

    Payload.update_summary summary args.summary
  | None -> Logging.(die InternalError) "Analysis failed."
```

Listing 4.3: The analysis of a function in the analyser of **Phase 1**

Abstract State of the Domain of the Detection of Atomic Sequences

The abstract state is of a type of `TSet`. `TSet` is a module representing a **set of structures**. This structure has the following fields:

- `firstOccurrences` – it is of a type of a **list of strings**. It captures the *first occurrences* of function calls in the **A** or **B** sequences defined in Section 3.2.1. In other words, it captures the first occurrences of function calls inside or outside *atomic blocks*.
- `callSequence` – it is of a type of a **list of strings**. It is used for storing the **A** sequences followed by the **B** sequences. In other words, it stores function calls outside atomic blocks followed by function calls inside atomic blocks. For instance, `f1 f2 (f3)`.
- `finalCalls` – it is of a type of a **set of lists of strings**. It is used for storing a set of sequences of calls `callSequence`. For instance, {`f1 f2 (f3)`, `f2 (f1 f3)`}.
- `isInLock` – it is of a type of a **boolean**. Determines whether the current state of a function is inside or outside an atomic block, i.e., it is or it is not under a lock.

The *initial abstract state* is then a set with a single empty element. An empty element is an element where `firstOccurrences` and `callSequence` are empty strings, `finalCalls` is an empty set, and `isInLock` is `false`.

According to Listings 4.1 and 4.3, there are several functions working with the abstract state. The functions are described below (all of these functions modifies all elements of the abstract state):

- `update_astate_on_function_call` – it is invoked when any function (except a lock or an unlock) is called. It captures the first occurrence of the called function.
- `update_astate_on_lock` – it is invoked when a lock is called. When the state is not under a lock, it sets a flag indicating the start of an atomic sequence. Moreover, capturing the first occurrences of function calls inside the atomic sequence begins.

- `update_astate_on_unlock` – it is invoked when an unlock is called. When the state is under a lock, it unsets a flag indicating the start of an atomic sequence. Moreover, capturing of the first occurrences of function calls followed this unlock call begins, and the last captured function calls, i.e., the last captured **A** and **B** sequences, are moved into the set of all such captured sequences within an analysed function.

- `update_astate_at_the_end_of_function` – it is invoked at the end of the analysis of a function. It moves the last captured function calls, i.e., the last captured **A** and **B** sequences, into the set of all such captured sequences within an analysed function.

Function Summary of the Domain of the Detection of Atomic Sequences

The summary is of a type of **structure**. The structure has the following fields:

- `atomicSequences` – it is of a type of a **list of lists of strings**. It is a list of all captured atomic sequences within an analysed function. For instance, (`f3`) (`f1 f3`). It is used for printing the atomic sequences to a file at the end of the entire analysis.

- `allOccurrences` – it is of a type of a **list of strings**. It is a list of all called functions within an analysed function. It is used for the purpose of analysing functions higher in the *call hierarchy*.

According to Listings 4.1 and 4.3, there are some functions working with the summary. These functions are described below:

- `update_astate_on_function_call_with_summary` – it is invoked when the called function has already been analysed so that the abstract state could be updated with its summary. Therefore, occurrences of all called functions within the called function are appended to the first occurrences of an analysed function. It is demonstrated on Algorithm 4.1.

- `convert_astate_to_summary` – it is invoked at the end of the analysis of an analysed function. It transforms the abstract state of a given function to the summary. In particular, it derives all atomic sequences and all called functions within an analysed function from the abstract state, as demonstrates Algorithm 4.2.

Algorithm 4.1: Updating the abstract state with the summary of a called function

```
def update_astate_on_function_call_with_summary(astate, sum):
    if sum.allOccurrences ≠ [] then
        for e ∈ astate do
            for o ∈ sum.allOccurrences do
                e.firstOccurrences ← AddUniq(e.firstOccurrences, o);
            end for
        end for
    end if
    return astate;
end
```

Algorithm 4.2: Converting the abstract state to the function summary

```
def convert_astate_to_summary(astate):
    atomicSeq ← [];
    allOccur ← [];
    for e ∈ astate do
        for c ∈ e.finalCalls do
            atomicSeq ← AddUniq(atomicSeq, GetAtomicSeq(c));
            allOccur ← AddUniq(allOccur, GetAllCalls(c));
        end for
    end for
    return {atomicSeq, allOccur};
end
```

4.1.2 Output of the Detection of Atomic Sequences

The output of **Phase 1** are sequences of functions that should be executed atomically for each analysed function in a program. These sequences are derived from summaries of all analysed functions. At the end of the entire analysis, the sequences are printed into a file `infer-atomicity-out/atomic-sequences` in the following format. Each line of the file contains a list of the detected atomic sequences within a particular function. It starts by a function name of an analysed function followed by a colon and whitespace. Then, there are listed atomic sequences (function names separated by whitespace) separated by whitespace. Example of the output:

```
functionA:␣(f1␣f2)␣(f3␣f1)

functionB:␣

functionC:␣(f3␣f4)␣(f6)
```

The principle of the derivation of the atomic sequences and their printing is demonstrated on Algorithm 4.3. The atomic sequences are then further processed in the second phase of the analysis, see Section 4.2.

Algorithm 4.3: Printing atomic sequences from summaries of all analysed functions

Input: A set F of all analysed functions

for $f \in F$ **do**
    `printf('%s:␣', GetFunName(`f`));`
    $S \leftarrow$ `ReadSummary(`f`);`
    for $q \in S.atomicSequences$ **do**
        `printf('(%s)␣', SeqToString(`q`));`
    end for
end for

4.2 Implementation of the Detection of Atomicity Violations

The proposal of this phase is described in Section 3.2.2. It runs only if it is specified a command line argument `--atomicity-violations`. It detects *atomicity violations*, i.e., violations of the *atomic sequences* obtained from **Phase 1**. The atomic sequences are read from the file `infer-atomicity-out/atomic-sequences` (see Section 4.1.2). If this file does not exist, i.e., the previous phase of the analysis has not run yet, this phase will fail.

As well as it is with the first phase of the analysis, the main function of the analyser of this phase is `analyse_procedure`, which is shown in Listing 4.4. Facebook Infer invokes this function for every single function in an analysed program. And it produces a summary for a given function. This function, at first, initialises an abstract domain of this phase, and then it computes an abstract state for an analysed function using the created abstract interpreter `Analyser` upon the abstract domain. As a *precondition*, an initial abstract state `initialAstate` from the abstract domain is used. If the computation succeeds, the abstract state is converted to the function summary by application of functions in the abstract domain. Further, atomicity violations within the analysed function are reported based on the abstract state. This reporting is in more detail described in Section 4.2.2. In the end, the *summary payload* is updated with the resulting summary.

```
let analyse_procedure args =
  Domain.initialise true;
  let procData = ProcData.make_default args.proc_desc args.tenv in

  match Analyser.compute_post procData ~initial:Domain.initialAstate with
  | Some astate ->
    let summary = Domain.convert_astate_to_summary astate in

    Domain.report_atomicity_violations astate ( fun loc msg ->
      Reporting.log_error
        args.summary ~loc:loc IssueType.atomicity_violation msg );

    Payload.update_summary summary args.summary
  | None -> Logging.(die InternalError) "Analysis failed."
```

Listing 4.4: The analysis of a function in the analyser of **Phase 2**

The abstract domain of this phase is described in Section 4.2.1. It includes an initialisation of the domain, the definition of an abstract state, summary, and functions working with them. *Ordering* of abstract states, the *join operator*, and the *widening operator* are defined at the beginning of Chapter 4.

4.2.1 Abstract Domain of the Detection of Atomicity Violations

In this section, at first, it is explained how the abstract domain of this phase is initialised. Then it is described the definition of an abstract state along with functions working with it. In the end, it is described a summary of functions in this phase of the analysis and corresponding functions working with the summary.

Initialisation of the Domain of the Detection of Atomicity Violations

Before analysing each function, i.e., at the beginning of the function `analyse_procedure`, the abstract domain is initialised. The initialisation servers for processing the input file with atomic sequences and storing these sequences into internal data structures in the appropriate format. In the abstract domain, there is a reference for a global data structure `globalData`. The structure contains the following fields:

- `initialised` – it is of a type of a **boolean**. It is used for a determination whether the input file has already been processed.
- `atomicPairs` – it is of a type of a **set of pairs of strings**. It stores pairs of functions that should be called atomically. For instance, {(`f1 f2`), (`f2 f3`)}.

The initialisation process is then done the following way. The input file with atomic sequences is read and it is parsed using the *regular expressions*. Each pair of functions that should be called atomically, i.e., any pair of functions in any of the atomic sequences from the input file, is stored into the field `atomicPairs` of the structure `globalData`. Single functions may be also stored into this structure when the atomic sequence contains just one function call. This structure is globally accessible throughout the analysis.

Abstract State of the Domain of the Detection of Atomicity Violations

The abstract state is of a type of `TSet`. `TSet` is a module representing a **set of structures**. This structure has the following fields:

- `firstCall` – it is of a type of a **string**. Captures the first function call within an analysed function. It is used for detection of atomicity violation of pair (a, b), where a is the last call of a function higher in the *call hierarchy* when calling the analysed function and b is the first function call of the analysed function.
- `lastPair` – is of a type of a **pair of strings**. Captures last two function calls. And it is used for detecting whether this pair violates atomicity. For instance, (`f1 f2`).
- `nastedLastCalls` – is of a type of a **list of strings**. Captures the all possible last function calls of the last nested function. It is used for detection of atomicity violation

of pair (a, b), where a is one of the last calls of the last nested function and b is the analysed function.

- `atomicityViolations` – is of a type of a **set of pairs of strings**. It is used for capturing pairs of function calls that violate atomicity. So it can be reported at the end of the analysis of a function. For instance, {(`f1 f2`), (`f2 f3`)}.
- `isInLock` – it is of a type of a **boolean**. Determines whether the current state of a function is inside or outside an atomic block, i.e., it is or it is not under a lock.

The *initial abstract state* is then a set with a single empty element. An empty element is an element where `firstCall` is an empty string, `lastPair` is a pair of two empty strings, `nastedLastCalls` is an empty list, `atomicityViolations` is an empty set, and `isInLock` is `false`.

According to Listings 4.1, there are several functions working with the abstract state. The functions are described below (all of these functions modifies all elements of the abstract state):

- `update_astate_on_function_call` – it is invoked when any function (except a lock or an unlock) is called. When the state is not under a lock, a pair of last two function calls is updated, and it is checked whether this pair (or any pair created from `nastedLastCalls`) violates atomicity. The simplified implementation of the function shows Algorithm 4.4.
- `update_astate_on_lock` – it is invoked when a lock is called. It sets a flag indicating the start of an atomic sequence and it clears the stored last function calls.
- `update_astate_on_unlock` – it is invoked when an unlock is called. It unsets a flag indicating the start of an atomic sequence and it clears the stored last function calls.

Algorithm 4.4: Simplified updating of the abstract state with a called function and checking of atomicity violation

Require: An initialised global data structure *globalData* with a field *atomicPairs* with pairs of functions that should be called atomically

def `update_astate_on_function_call`(*astate, f*)**:**
    for $e \in astate$ **do**
        if $\neg(e.isInLock)$ **then**
            $(x, y) \leftarrow e.lastPair$;
            $e.lastPair \leftarrow (a, b) \leftarrow (y, f)$;
            if $(a, b) \in globalData.atomicPairs$ **then**
                $e.atomicityViolations \leftarrow \texttt{Add}(e.atomicityViolations, (a, b))$;
            end if
        end if
    end for
    return *astate*;
end

Function Summary of the Domain of the Detection of Atomicity Violations

The summary is of a type of **structure**. This structure contains the following fields:

- `firstCalls` – it is of a type of a **list of strings**. It is a list of all possible first function calls of an analysed function.
- `lastCalls` – it is of a type of a **list of strings**. It is a list of all possible last function calls of an analysed function.

Both of the summary fields are used for the purpose of detecting atomicity violating pairs across nested function calls.

According to Listings 4.1 and 4.4, there are some functions working with the summary. The functions are described below:

- `update_astate_on_function_call_with_summary` – it is invoked when the called function has already been analysed. And it performs checks for an atomicity violation of pairs across nested function calls.
- `convert_astate_to_summary` – it is invoked at the end of the analysis of an analysed function. It transforms the abstract state of a given function to the summary. In particular, it derives all the first function calls and all the last function calls within an analysed function from the abstract state.

4.2.2 Reporting of Atomicity Violations

As demonstrates Listing 4.4, at the end of the analysis of a function, atomicity violations within the function are reported. Reporting is achieved by the `Reporting` module implemented in Facebook Infer. For reporting errors using this module, it is necessary to assign an error to the function summary along with a location of the error (a file and line). It is also required to specify a type of the error through the `IssueType` module. The error is then printed to a command line as well as logged to logging files.

Reported atomicity violations are deduced from the abstract state of an analysed function. A simplified reporting process illustrates Algorithm 4.5.

Algorithm 4.5: Reporting of atomicity violations from the abstract state of an analysed function

Input: The abstract state *astate* of an analysed function

for $e \in astate$ **do**
    for $(a, b) \in e.atomicityViolations$ **do**
        `LogError('„%s" and „%s" should be called atomically.'`, a, b);
    end for
end for

4.3 Experimental Verification and Evaluation

[[TODO]]

Chapter 5

Conclusion

[[TODO]]

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Appendix A

Results of Experimental Verification

[[TODO]]

A.1 Experimental Verification of Detection of Atomic Sequences

[[TODO]]

A.2 Experimental Verification of Detection of Atomicity Violations

[[TODO]]

Appendix B

Contents of Attached Memory Media

[[TODO]]

Appendix C

Installation and User Manual

[[TODO]]

C.1 Installation Manual

[[TODO]]

C.2 User Manual

[[TODO]]