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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF INFORMATION TECHNOLOGY

FAKULTA INFORMAČNÍCH TECHNOLOGIÍ

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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VEDOUCÍ 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.

Literatura:

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Pro udělení zápočtu za první semestr je požadováno:

- Body 1, 2 a alespoň začátek návrhu z bodu 3.

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Vedoucí práce: **Vojnar Tomáš, prof. Ing., Ph.D.**
Vedoucí ústavu: Hanáček Petr, doc. Dr. Ing.
Datum zadání: 1. listopadu 2018
Datum odevzdání: 15. května 2019
Datum schválení: 1. listopadu 2018

Abstract

The goal of this thesis is to propose a *static analyser* of programs, 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* programů, 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

[[Do tohoto odstavce bude zapsán rozšířený výtah (abstrakt) práce v českém jazyce.]]

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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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 8, 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. 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 analysis tools 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 a *static analysis*. Of course, it has some shortages as well. The big issue is *scalability* on extensive codebases and considerable high rate of incorrectly reported errors (so-called *false positives*, also called *false alarms*).

Not long ago, Facebook introduced *Facebook Infer* – a tool for creating *highly scalable compositional*, *incremental*, and *interprocedural* static analysers. Facebook Infer is a live tool and it is still under the development. Anyway, it is in everyday use in Facebook itself, Spotify, Uber, Mozilla, WhatsApp and other well-known companies. Currently, Facebook Infer provides several analysers implemented as modules in the whole framework. These analysers check for various types of bugs, e.g., buffer overflows, thread-safety, null-dereferencing, or memory leaks. Facebook Infer also aims to create a framework for building new analysers quickly and easily. The current version of Facebook Infer still misses 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. Atomicity requirements, in most cases, are not even documented. It means that typically only programmers must take care of following these requirements. In general, it is very difficult to avoid errors in *atomicity-dependent programs*, especially in large projects, and even harder and time-consuming is finding and fixing these errors.

In this thesis, there is described proposal, implementation, and experimental verification and evaluation of *Atomer* — 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 targets to C/C++ programs that use *PThreads* 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 paper are taken over [14], which I wrote together with Vladimír Marcin and Ondřej Pavela. In [14], there were presented preliminary results of my thesis.

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 a *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*. Proposal of a static analyser for detection *atomicity violations*, based on this concept, is described in Chapter 3. Its implementation is in Chapter 4 and experimental results are presented in Chapter 5. Finally, Chapter 6 concludes the paper. Appendix A lists contents of attached memory media and Appendix B 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 a *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. The 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 [19], a *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, a 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. [19]:

- **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?

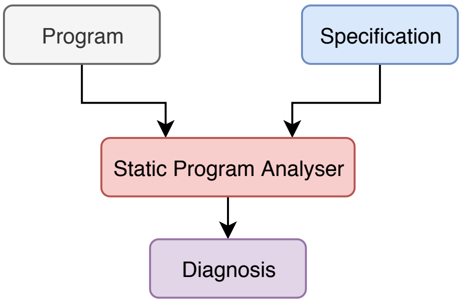


Figure 2.1: A static program analysis [8]

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, a 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 a 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 a static analysis can produce many *false alarms*[1], but it is often resolved by accepting *unsoundness*[2].

Various forms of a static analysis of programs have been invented, for instance [24]: 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 a 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], [15], [16], [10], [20], [19], [25]. 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

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

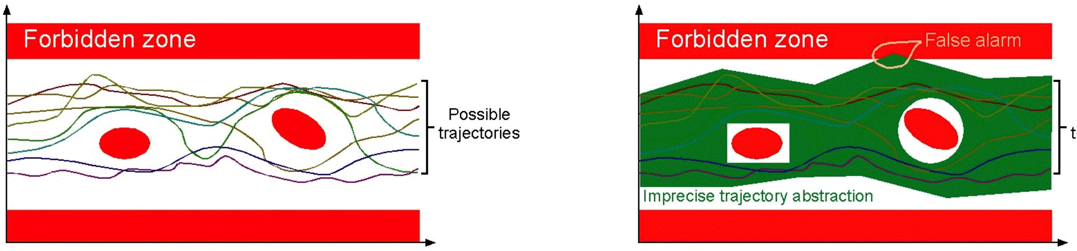
[2] **Soundness** – if a verification method claims that a system is correct according to a given specification, it is truly correct. [24]

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

specific components (described later) to the framework. The analysis is guaranteed to be *sound* if certain properties of the components are met. [15], [16]

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* [20]. 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 [15], [16], 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** $\triangledown$ [20], [10], [15]

  - 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** $\triangle$ [20], [10], [15]

  - 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 [25], there is a *fixpoint* defined as:

- let $(A, \leq_A)$ be a *lattice* [25],
- 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) [15], [16]. Most program properties can be represented as fixpoints. This reduces a program analysis to the fixpoint approximation [7]. Further information about fixpoint approximation can be found in [20], [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], [15], **abstract interpretation *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 an ordering defined as $x \sqsubseteq y \Leftrightarrow x \circ y = y$ in $(Q, \circ, \top)$,
- $\top \in Q$ is the *supremum* of Q,
- $\bot \in Q$ is the *infimum* of Q,
- $\boldsymbol{\tau} : S \times Q \to Q$ defines the *abstract transformers* for specific instructions,
- $(Q, \circ, \top)$ is a *complete semilattice* [25], [15].

Using so-called *Galois connections* ([20], [10], [15], [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], [16]. Parts of this section are taken over [14].

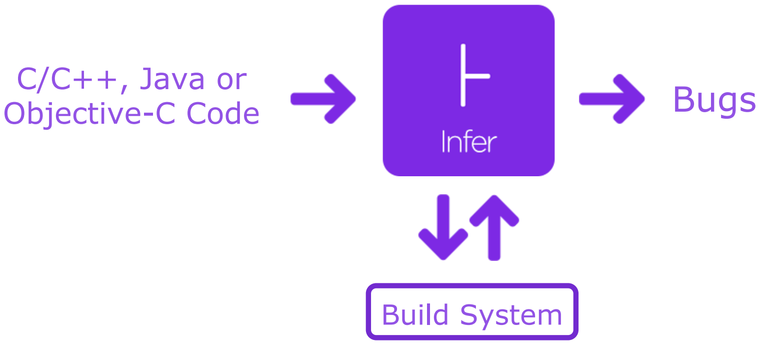


Figure 2.3: A static analysis in Facebook Infer (http://www.codeandyou.com/2015/06/infer-static-analyzer-for-java-c-and.html)

Facebook Infer is an open-source 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

[6] **Facebook Infer** website – https://fbinfer.com.

architecture. Facebook Infer itself is implemented in *OCaml*[7] – functional programming language, also supporting imperative and object-oriented paradigms. Further details about OCaml can be found in [18] or in official documentation[8], tutorials[9]. 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) [26]; *RacerD* (data races) [3], [4], [13]; *RacerX* (race conditions and deadlocks) [12]; and other analyses checks for buffer overflows, thread-safety, null-dereferencing, memory leaks, resource leaks, etc.

2.2.1 Abstract Interpretation in Facebook Infer

Facebook Infer is a general framework for a 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* [20]) 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**)[10] as it is done in classical analyses based on the concepts from [21], [22]. 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. An *abstract domain* Q, i.e., the type of an *abstract state*.
2. Operator $\sqsubseteq$, i.e., an ordering of abstract states.
3. *Join* operator $\circ$, i.e., the way of joining two abstract states.
4. *Widening* operator $\triangledown$, 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 input and produces an abstract state as output.

[7] **OCaml** website – https://ocaml.org.

[8] **OCaml documentation** – http://caml.inria.fr/pub/docs/manual-ocaml.

[9] **OCaml tutorials** – https://ocaml.org/learn/tutorials.

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

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

1. The type of function summaries.
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

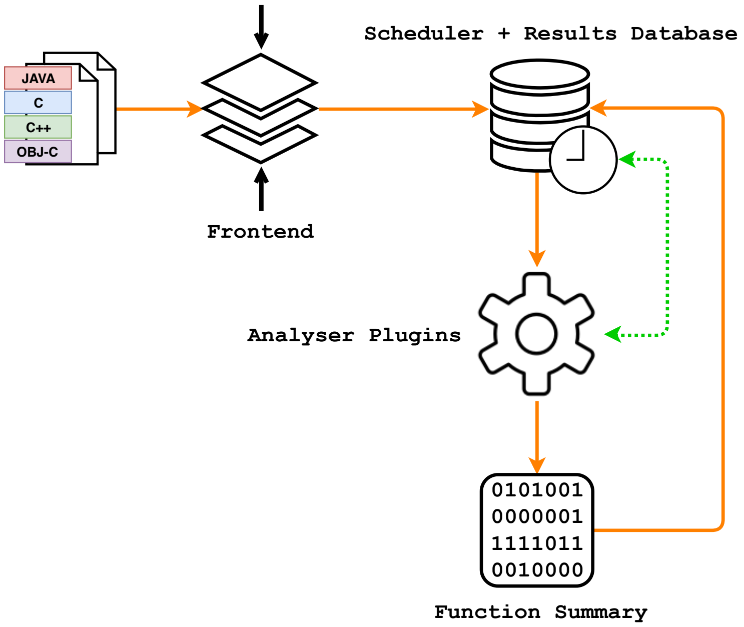


Figure 2.4: The architecture of Facebook Infer's abstract interpretation framework [2], [16]

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*.

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*[11]. 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.

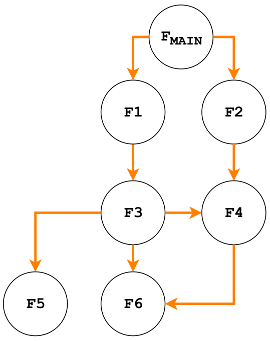


Figure 2.5: A call graph for an illustration of Facebook Infer's analysis process [2], [14], [16]

The last part of the architecture consists of the 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 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 [23], [11]. Parts of this section are taken over [14]. Listings in this section are pieces of programs written in ANSI C[12].

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

[11] **A call graph** is *directed graph* describing call dependencies among functions.

[12] **ANSI C** – standard for the C programming language published by the *ANSI* (American National Standards Institute).

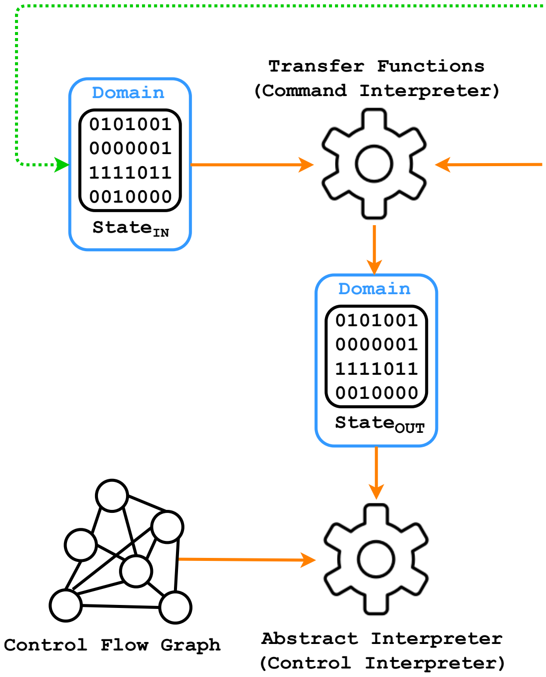


Figure 2.6: Facebook Infer's abstract interpretation process [2], [16]

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 [17]) requires programs to meet such well-defined behaviours. [23]

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], [23], 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*[13] 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

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

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], [23]. There is a module with the implementation of a resizable array with the listed functions:

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], [23], there is defined another extension with *spoilers*, which considering contextual information of function calls.

2.3.2 Contracts with Parameters

```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]

Example 2.3.2. Consider the following example from [11], [23], 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`.

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], [23] 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 $\texttt{o}_1/\texttt{o}_2/\texttt{o}_3$ 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

Proposal of Static Analyser for Detecting Atomicity Violations

Chapter 4

Implementation of the Analyser in Facebook Infer

Chapter 5

Experimental Verification and Evaluation of the Analyser

Chapter 6

Conclusion

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Appendix A

Contents of Attached Memory Media

Appendix B

Installation and User Manual