Few is Just Enough!

Small Model Theorem { *Parameterized Verification* / *Shape Analysis*

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Abstract

This doctoral thesis considers the automatic verification of *parameterized systems*, i.e. systems with an arbitrary number of communicating components, such as mutual exclusion protocols, cache coherence protocols or heap manipulating programs. The components may be organized in various topologies such as words, multisets, rings, or trees.

The task is to show correctness regardless of the size of the system and we consider two methods to prove safety: (i) a backward reachability analysis, using the well-quasi ordered framework and monotonic abstraction, and (ii) a forward analysis which only needs to inspect a small number of components in order to show correctness of the whole system. The latter relies on an abstraction function that views the system from the perspective of a fixed number of components. The abstraction is used during the verification procedure in order to dynamically detect cut-off points beyond which the search of the state-space need not continue.

Our experimentation on a variety of benchmarks demonstrate that the method is highly efficient and that it works well even for classes of systems with undecidable property. It has been, for example, successfully applied to verify a fine-grained model of Szymanski's mutual exclusion protocol. Finally, we applied the methods to solve the complex problem of verifying highly concurrent data-structures, in a challenging setting: We do not a priori bound the number of threads, the size of the data-structure, the domain of the data to store nor do we require the presence of a garbage collector. We successfully verified the concurrent Treiber's stack and Michael&Scott's queue, in the aforementioned setting.

To the best of our knowledge, these verification problems have been considered challenging in the parameterized verification community and could not be carried out automatically by other existing methods.

Pour Papa, Maman, Franck *et* Alexandre

List of papers

This thesis is based on the following papers, which are referred in the text by their roman numerals.

I **All for the Price of Few** VMCAI'13
Parosh A. Abdulla, Frédéric Haziza, and Lukás Holík.
In *Verification, Model Checking, and Abstract Interpretation*, 2013.

II **An Integrated Specification and Verification Technique for Highly Concurrent Data Structures** TACAS'13
Parosh A. Abdulla, Frédéric Haziza, Lukás Holík, Bengt Jonsson, and Ahmed Rezine.
In *Tools and Algorithms for the Construction and Analysis of Systems*, 2013.
Best paper award at the Joint European Conferences on Theory and Practice of Software, ETAPS 2013.

III **Block Me If You Can! (Context-Sensitive Parameterized Verification)** SAS'14
Parosh A. Abdulla, Frédéric Haziza, and Lukás Holík.
In *Static Analysis Symposium*, 2014.

IV **Monotonic Abstraction for Programs with Dynamic Memory Heaps** CAV'08
Parosh A. Abdulla, Ahmed Bouajjani, Jonathan Cederberg, Frédéric Haziza, Ahmed Rezine.
In *Computer Aided Verification*, 2008.

V **Parameterized Tree Systems** FORTE'08
Parosh A. Abdulla, Noomene Ben Henda, Giorgio Delzanno, Frédéric Haziza, Ahmed Rezine.
In *Formal Techniques for Networked and Distributed Systems*, 2008.

VI **Model Checking Race-Freeness** SIGARCH'08
Parosh A. Abdulla, Frédéric Haziza, and Mats Kindahl.
In *SIGARCH Computer Architecture News*, 2008.

VII **Parameterized Systems through View Abstraction** STTT'15
Parosh A. Abdulla, Frédéric Haziza, and Lukás Holík.
In *International Journal on Software Tools for Technology Transfer*, 2015.

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Sammanfattning på Svenska

Du har säkerligen använt en dator och varit väldigt nöjd, och detta för att den förenklade många långa och svåra uppgifter. Ibland gör den dock inte som du vill: du klickar på knappen “Gör det”, men den följer inte ditt kommando. Eller ännu värre, datorn hänger upp sig och svarar inte på något kommando alls. Viktiga arbetstider har kanske gått till spillo. Du tar ett djupt andetag, startar om datorn, och allting fungerar igen som det ska. Felet verkar komma från *programvaran* som styr datorn, inte från själva maskinen. Du undrar varför detta fel inte redan korrigerats, och dessutom, varför det från början inte *försäkrades* om att felet inte kunde inträffa.

Termen *buggar* används generellt för att beskriva alla typer av fel, vare sig felet finns i dem elektriska delarna av maskinen eller i programmeringen. Med tanke på hur komplexa dagens datorer är, är det inte förvånande att de innehåller många buggar. De behöver ju hantera en stor mängd parametrar och egenskaper som kan generera många olika möjliga beteenden. Och vi nämner inte ens den mänskliga faktorn som inför fel under programmeringsfasen! Därför finns det en trend att bygga datorer med flera mindre enheter, som då gör datorn enklare att hantera. Men då ställs vi inför ett nytt problem: dessa enheter kan när som helst kommunicera med varandra. På grund av denna oförutsägbarhet blir det väldigt svårt att ta hänsyn till alla scenarier.

Företag som tillverkar programvara har inget intresse av att lämna buggar, eftersom ett fel någonstans kan orsaka en rad andra fel i efterhand. De inkluderar därför en viktig kvalitetskontroll under utvecklingsfasen: om det finns för många buggar blir det helt enkelt inte kostnadseffektivt eller ens möjligt att senare eliminera dem. En del buggar är dock enklare att lösa än andra. Det spelar faktiskt ingen större roll om man inte kan svara i telefonen när man får ett samtal, eller om texteditorn förlorar dem senaste dokumentsuppdateringarna. Detta är väldigt tråkigt, men ingen fara på taket! Vi klarar oss och väntar bara på programuppdateringen som löser buggen. Å andra sidan får inga fel inträffa för dem så-kallade *kritiska systemen*, vars säkerhet är viktig i allra högsta grad. Alla fel måste elimineras, antingen i programvaran eller i maskinvaran. Det är oacceptabelt, till exempel, att en pacemaker slutar fungera när ägaren passerar säkerhetskontrollen på flygplatsen, att krockkudden inte utlöses snabbt nog vid en trafikolycka om radion är på, eller om två tåg kolliderar på grund av att signalsystemet inte fungerat. Därför är det nödvändigt att utveckla metoder som upptäcker ett felaktigt beteende i sådana system.

Den vanligaste metoden är *testing*: man kör programmet med olika värden för varje variabel och kollar om funktionaliteten överensstämmer med det som förväntas. Dessa testscenarier är genomtänkta för att beskriva ett maximalt antal beteenden. När komplexiteten däremot ökar, kan programmet befinna sig i väldigt många olika tillstånd. Det börjar då bli svårt att *garantera* att metoden täcker alla möjliga programkörningar. Det är även rent av omöjligt om systemet innehåller en parameter vars värde exempelvis är en siffra. Metoden är ett effektivt sätt att upptäcka enkla buggar snabbt, men subtila buggar, såsom dem som kommer från en oförutsägbar tajming, kvarstår obemärkta. För dem kritiska systemen där säkerheten är ytterst viktig, är det otänkbart att använda en metod som eventuellt tar sig igenom alla tester, men fortfarande innehåller buggar.

För att visa att ett program verkligen uppfyller vissa egenskaper, måste vi först komma överens om vad det ska överensstämma med —vilket formellt heter en *specifikation*. Genom att lista programkonfigurationerna som borde undvikas, eller som önskas, alternativt båda, så beskriver man dem två kategorierna av specifikationer: *säkerhetsegenskaper* och *livlighetsegenskaper* (Safety och Liveness på engelska). Till exempel, "pacemakern stannar aldrig", "krockkudden måste öppnas inom mindre än x millisekonder", eller "ingen enstaka process blockerar övriga processer" är säkerhetsegenskaper. Vi måste se till att programmet aldrig befinner sig i en felaktig konfiguration. Till motsatsen, "brevbäraren levererar till rätt mottagare", "systemet gör framsteg", eller "servern hanterar en HTTP-förfråga" är livlighetsegenskaper, där man observerar rätta konfigurationer, förknippade med vissa sannolikheter. Det är upp till oss att definiera vad specifikationen ska innehålla, för att verifiera det som önskas. Om ett låsningsfritt bromssystem (ABS) beräknar hur hårt bilens bromsning ska vara men gör detta för sent, bör systemet betraktas som felaktigt. Denna avhandling fokuserar på säkerhetsegenskaper.

Säkerhet: *Givet en specifikation, kan systemet hamna i en fel konfiguration?*

Snarare än att testa programmet i specifika scenarier eller att analysera källkoden, fokuserar vi i denna avhandling på *formell verifiering*, som är ett matematiskt ramverk, för att *bevisa* att programmet uppfyller sina egenskaper. Dessutom vill vi bevisa det helt *automatiskt*, det vill säga utan tillsyn av användaren. Vi börjar genom att extrahera en modell som motsvarar det ursprungliga programmet. I samband med det borttar vi delarna som är irrelevanta för den egenskapen som verifieras. Men vad händer när programmet manipulerar obegränsade variabler? Vi talar då om system med ett oändligt antal tillstånd, och vi behöver framställa en approximation som är i linje med själva programmet. Målet är att utforma en metod som *garanterar* att inget fel kvarstår, och som även ger svar inom en rimlig tid.

Många system med ett oändligt antal tillstånd kan faktiskt karakteriseras av en familj som består av system med ett ändligt antal tillstånd, och en parameter

(eller flera) med värde från en obegränsad domän. För varje värde på parametern, innehåller systemet ett ändligt antal tillstånd. Parametern kan exempelvis vara antalet processer som är aktiva i en viss session av ett protokoll, antalet noder i ett nät, eller hur komponenterna av ett program kommunicerar med varandra. Hur som helst, system som innehåller en preliminärt okänd parameter bör ha ett korrekt beteende oavsett värdet på parametern. De betraktas därför som system med ett oändligt antal tillstånd och kallas för parametriserade system. I denna avhandling presenterar vi två metoder för att verifiera vissa säkerhetsegenskaper hos sådana parametriserade system.

Den första metoden körs baklänges. Den startar från dem felaktiga tillstånden, och beräknar vilka andra tillstånd som skulle kunna leda till ett fel. Med andra ord upptäcker metoden alla konfigurationer som direkt eller indirekt är felaktiga. Om initialtillstånden av programmet inte tillhör dem sistnämnda, anses programmet vara korrekt. Vi måste såklart först se till att approximationen av modellen motsvarar det ursprungliga programmet.

Den andra metoden startar från initialtillstånden. Den begränsar sig till små värden av parametern, och härleder ett tröskelvärde, efter vilket metoden inte behöver fortsätta: den har faktiskt all nödvändig information för att dra slutsatsen att det inte finns några felkonfigurationer för större värden på parametern över denna tröskel. För att förenkla, bryter metoden ner varje konfiguration i små bitar av en viss storlek, och rekombinerar bitarna på alla möjliga sätt, just för att skapa konfigurationer av större storlek (litegrann som Legobitar). Tanken är att samla alla dem små bitarna och se till att ingen rekombination matchar någon felaktig konfiguration. I så fall är tröskeln hittad. Annars börjar man om med lite större bitar.

Slutligen är det intressant att undra vilka av villkoren som behövs för att metodens beräkningar inte ska fortsätta för evigt. Problemet klassas som oavgörbart, det vill säga att det inte finns någon generell metod som kan lösa *alla* instanser av problemet. Däremot har dessa två metoder trots allt visat sig vara väldigt effektiva. Där andra metoder tog timmar, kunde dessa två metoder faktiskt verifiera vissa program inom sekunder, vilket var målet. I vissa fall kan man även ge garanti på att antalet beräkningar är begränsad.

Contents

How to read this thesis

This document is a comprehensive summary.

We first describe the domain of formal verification, where this thesis belongs, and approach the problem in a top down fashion.

We present two techniques in Chapter **??** and **??** to prove safety properties for a wide range of programs (listed in Chapter **??**). Finally, we dedicate Chapter **??** to the problem of shape analysis. It deals with a class of programs that manipulate memory heaps concurrently. To finish, we give some conclusions and potential directions for future research topics.

1. Introduction

Computers have been used for variety of applications in business, science, education, engineering and so on. They help to solve real world problems that would otherwise be slow, impossible or extremely difficult to achieve without computers. However, sometime they do not behave exactly as we expect them to do. In some cases, the consequence could be very serious such as errors in banking systems and airplanes. The error is obviously not caused by the machine itself, but it seems to originate from the program that controls the machine. The error is normally called bugs. The probability of existing bugs in complex software systems is not low, in particular concurrent systems. They usually have complicated input and involve many features, they have to handle many concurrent operations which makes them difficult to design and make them perfect by human effort. Detecting and fixing software bugs are important tasks in software process in software industry. Leave bugs undetected in any project might in fact lead to subsequent bugs and other problems. It will become too costly to solve them or too daunting to attempt to. Therefore, the quality phase takes a substantial amount of resources, both in terms of time and manpower.

Some bugs are less serious than others. We can still use software programs with these bugs. For example, bugs appearing in computer games and online news. However, in the case of critical systems such as banking or software systems in airplanes, safety is the most important aspect and we have to ensure that there no bugs in either the software nor the hardware. The predominant method to improve software quality is *testing*. It is a dynamic analysis where a program is run under specific conditions, so-called test cases, and checking whether the result with a given input matches the expected output. The test cases are carefully designed to cover all possible cases of program executions. Similarly, we can check for correctness of a program by using a *model* of the program. The model can be extracted by removing all parts that are irrelevant for the tests, and can be used to *simulate* the executions. However, there is no guarantee to cover all possible executions. Therefore, we have to find the way to achieve a full coverage of program executions. When the domain of the input parameters is large or if the program is complex, the method will suffer from the state-space explosion problem.

The topic of this thesis is design methods guaranteeing that no error is undetected and that do not suffer from state-space explosion.

Formal Verification: Computer programs are written based on human intuition, which is probably leads to programming errors. Current practice is

to test programs on various sample inputs in the hope of finding any possibility of incorrect program behavior. There exist many approaches like testing, simulation, static analysis and simple debugging techniques, such as inserting assertions and print statements in the source code, which show the presence of software errors. Formal verification uses mathematical methods to prove that a program is correct. Formally, formal verification is the process of checking whether a software satisfies its predefined properties. There is a wide variety of properties to be checked for software programs, these properties can be either safety or liveness properties. Liveness properties state that program execution eventually reaches several desirable states at some point of execution, for example liveness properties can be "the postman delivers the letter to the recipient", "A sent message is eventually received". In order to specify liveness properties, it is needed to describe traces of events by using temporal logics, statistics, and probabilities. Checking aliveness property is done by repeatedly checking reachability of good situations in program executions. In contract, verifying safety property of a program is satisfied is reduced to checking that something bad will never happen in the execution of the program [48]. There are three state-of-the-art approaches for formal verification namely model checking, theorem proving and equivalence checking. The first approach model checking exhaustively explorer all possible states of the model which can be finite or infinite models where infinite sets of states can be represented finitely by using abstraction techniques). Equivalence checking method decides whether system is equivalent to its specification with respect to some notation of behavioral equivalence. Theorem proving is a technique where both the system and its desired properties are expressed in mathematical logic. Then, theorem proving will try to prove these properties. In this thesis though, we consider programs where the specification describes the bad behaviors. We concentrate on safety properties and try to design abstraction techniques to verify that a program including both sequential and concurrent program respects its specifications.

2. Research Challenges

In this thesis, we consider two challenges in software verification, the first challenge is to automate its application to sequential programs that manipulate complex dynamic linked data structures. The problem becomes even more challenging when program correctness depends on relationships between data values that are stored in the dynamically allocated structures. Such ordering relations on data are central for the operation of many data structures such as search trees, priority queues (based, e.g., on skip lists), key-value stores, or for the correctness of programs that perform sorting and searching, etc. The challenge for automated verification of such programs is to handle both

Ⓐ infinite sets of reachable heap configurations and

Ⓑ relationships between data values embedded in such graphs,

e.g., to establish sortedness properties, there exist many automated verification techniques, based on different kinds of logics, automata, graphs, or grammars, that handle these pointer structures. Most of these approaches abstract from properties of data stored in dynamically allocated memory cells. The few approaches that can automatically reason about data properties are often limited to specific classes of structures, mostly singly-linked lists (SLLs), and/or are not fully automated.

We present a general framework for verifying programs with complex dynamic linked data structures whose correctness depends on relations between the stored data values. Our framework is based on the notion of forest automata (FA) which has previously been developed for representing sets of reachable configurations of programs with complex dynamic linked data structures [?]

The second challenge is to verify concurrent algorithms with an unbounded number of threads that concurrently access and manipulate a dynamically allocated shared heap where data stored in each heap cell can be in unbound domain. Such programs and algorithms are difficult to get correct and verify, since their shapes are complicated to represent and they typically employ fine-grained synchronization, replacing locks by atomic operations such as compare-and-swap, and are therefore notoriously difficult to get correct, witnessed, e.g., by a number of bugs in published algorithms [?,?]. It is therefore important to develop efficient techniques for automatically verifying their correctness. This requires overcoming several challenges. This thesis presents simple and efficient techniques to verify that a concurrent implementation of a

common data type abstraction, namely queue, stack, set, conforms to a simple abstract specification of its (sequential) functionality. The data structures we consider for these programs can be singly-linked lists, sets of linked lists or skip-lists. In order to deal with this problem, we have to deal with several combined challenges as follow.

Ⓐ The abstract specification is infinite-state, because the implemented data structure may contain an unbounded number of data values from an infinite domain.

Ⓑ The program is infinite-state in several dimensions:
- it consists of an unbounded number of concurrent threads,
- it uses unbounded dynamically allocated memory, and
- the domain of data values is unbounded.
- it consists of unbounded number of pointers

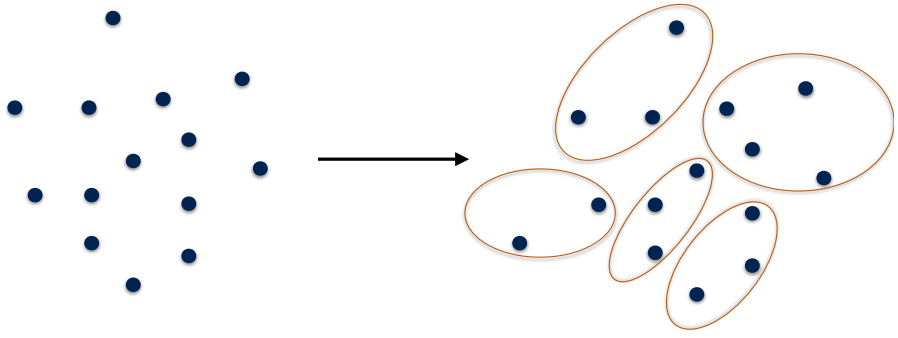
Ⓒ Linearization points are not fixed, they depend on future executions of programst

We present, in the first section of this chapter, the type of programs we consider. In the following sections, we introduce in a stepwise manner how we cope with each of the above challenges. In the last section, we combine the different techniques and present the verification method.

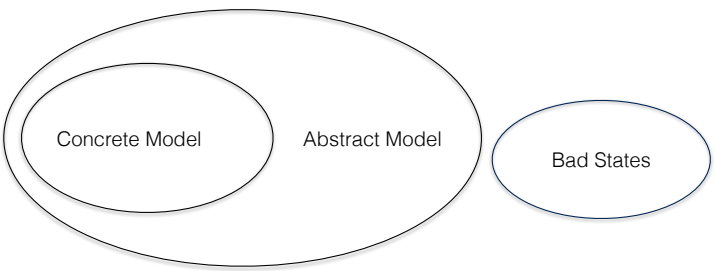
3. Technical Background

3.1 Model Checking

The approach that we focus on this thesis is *model-checking*. This method will try to verify whether a model of the program satisfies its specification. This approach was introduced by Emerson and Clarke [30] and by Queille and Sifakis [75]. The method requires a program and a property as input and then it extracts a model from the program. The method then computes and returns either "correct" when the specification is satisfied by the program, or "incorrect" when the program does not satisfy its specification. In the case of incorrect answer, the method can explain the reason by giving a counter-example. A state in the model contains relevant information about the program. Alongside all the states of the system, the model depicts the transitions, i.e. how to move from one state to another state. Every behaviour of the system is represented as a succession of transitions, starting from some initial states. States and transitions together describe the *operational semantics*, that is, how every step of the system takes place in the model. The number of states and transitions can be finite or infinite Model-checking aims to explore the state-space entirely from some initial states. However, when the state-space is of large size. It grows in-fact exponentially with the number of parameters or the size of their domain. Therefore, there have been several methods to deal with the state-space explosion problem. The choice of which transition to pick during the exploration can be crucial for the efficiency of the procedure. In some cases, exploring all orderings of events is not necessary because some states can be re-visited. *Partial order* techniques aim at detecting and avoiding redundant situations, while retaining important dependencies among actions. They however do not reduce the state-space. The main approach called *symbolic representation* to solve the state-space explosion problem is to avoid representing concretely all states of the system. the approach group several states together form sets of states and represent them by single states. The grouping process is performed by



by *dropping* irrelevant details (as opposed to disregarding them) based on properties that we want to verify. It is sound to prove safety of the abstract model in order to imply safety for the original system, since all the behaviours of the latter are represented in the former. The challenge is to find over-approximations that do not introduce behaviours that could turn out to be bad. Indeed, the method would return that the property is not satisfied and we would not know whether it comes from the approximation or from the concrete system itself.



To palliate to the imprecision caused by a too coarse over-approximation, it is possible to analyze the returned counter-example and find the origin of the problem. If it turns out to be a real concrete example, the method has in fact found a bug, and the property is surely not satisfied. Otherwise, the counter-example comes from the approximation, that is, there is a step in the sequence of events leading to that counter-example which is not performed by the original system but only by the abstract model. The approximation is be refined by discarding this step and the method should be run anew.

Nevertheless, finding suitable over-approximations is a challenge on its own. This thesis now revolves around the following problem statement.

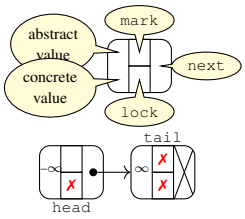


Figure 3.1. A cell and the initial heap in the `Lazy Set` Algorithm.

3.2 Concurrent Heap Programs

We consider systems consisting of an arbitrary number of concurrently executing threads. Each thread may at any time invoke one of a finite set of methods. Each method corresponding to one operation on the data structure. Each method declares local variables and a method body. We assume that the local variables include the program counter `pc` and also potentially include an input parameter of the method. The body is built in the standard way from atomic commands using standard control flow constructs (sequential composition, selection, and loop constructs). Each run of the program consists of an arbitrary (but finite) number of concurrently executing threads. Each thread invokes one of the methods. Thread execution is terminated by executing a `return` command, which may return a value. The shared variables can be accessed by all threads, whereas local variables can be accessed only by the thread which is invoking the corresponding method. We assume that the global variables and the heap are initialized by an initialization thread, which is executed once at the beginning of program execution. Furthermore, we assume that the local variables have arbitrary initial values. In this thesis, we assume that variables are either pointer variables (to heap cells) or data variables. The data variables assume values from an unbounded or infinite (ordered) domain, or from some finite set $\mathbb{F}$. We assume w.l.o.g. that the infinite set is given by the set $\mathbb{Z}$ of integers.

A parameter of a method may be instantiated by any value in $\mathbb{Z}$. Heap cells can have a number of data fields that contain data either from $\mathbb{Z}$ or $\mathbb{F}$. A cell has only one pointer field, denoted `next`. Atomic commands include assignments between data variables, pointer variables, or fields of cells pointed to by a pointer variable. The command `new Node()` allocates a new structure of type `Node` on the heap, and returns a reference to it. The compare-and-swap command `CAS(&a,b,c)` atomically compares the values of `a` and `b`. If equal, it assigns the value of `c` to `a` and returns `true`, otherwise, it leaves `a` unchanged and returns `false`. We assume that each statement in a method has a unique label.

As an example, Fig. 3.3 depicts a program `Lazy Set` [50] that implements a concurrent set containing elements from $\mathbb{I}$. The set is implemented as an ordered singly linked list. The program contains three methods, namely `add`, `rmv`, and `ctn`, corresponding to operations that respectively add, remove, and

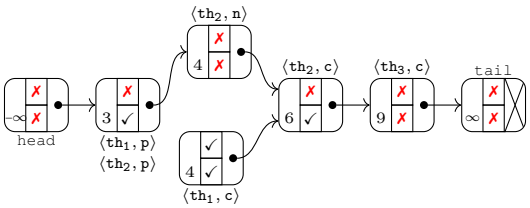


Figure 3.2. A heap configuration of the `Lazy Set` Algorithm. The abstract data values, and the dotted arrows represent performing data abstraction. There are three active threads $\mathtt{th}_1$, $\mathtt{th}_2$, and $\mathtt{th}_3$, running the methods $\mathtt{rmv}(4)$, $\mathtt{add}(4)$, and $\mathtt{ctn}(9)$ respectively. The symbols ✓ and ✗represent the Boolean values `true` and `false`.

```
struct Node( bool lock; int val; Node *next; bool mark);
```

```
0  locate(e):
1    local p, c
2     while (true)
3      p := head;
4      c := p.next;
5      while (c.val < e)
6       p := c;
7       c := c.next
8      lock(p); lock(c);
9      if (!p.mark && !c.mark && p.next=c)
10      return(p,c);
11     else
12      unlock(p);
13      unlock(c);
```

```
10 ctn(e):
11  local c
12   c := Head;
13   while (c.val < e)
14     c := c.next; b := c.mark
15     if (! b && c.val = e)
16       return true;
17     else return false;
```

```
10 add(e):
11 local p, c, n, r
12  (p,c) := locate(e);
13  if (c.val <> e)
14    n := new Node(0,e,c,false);
15    p.next := n;
16    r := true;
17  else r := false;
18  unlock(p);
19  unlock(c);
20  return r;
```

```
10 rmv(e):
11  local p, c, n, r
12   (p,c) := locate(e);
13   if (c.val = e)
14     c.mark := true;
15     n := c.next;
16     p.next := n;
17     r := true;
18   else r := false;
19   unlock(p);unlock(c);
20   return r;
```

Figure 3.3. Lazy set.

check the existence of an element in the set. Each method takes an argument which is the value of the element, and returns a value which indicates whether the operation has been successful or not. For instance, the operation `add`(e) returns the value *true* if e is not already a member of the set. In such a case a new cell with data value e is added to its appropriate position in the list. If e is already present, then the list is not changed and the value `false` is returned. The program also contains the subroutine `locate` that is called by the three methods. A cell in the list has three fields `mark`, `lock`, and `val`. The `rmv` method first logically removes the node from the list by setting the `mark` field, before physically removing the node. The `ctn` method is wait-free and traverses the list ignoring the locks inside the cells. Fig. 3.1 depicts a cell in the heap together with the initial configuration of the heap. The `val` field is represented both by a concrete value and an abstract value. Fig 3.2 depicts a typical configuration of the heap. The algorithm uses two global pointers, `head` that points to the first cell of the heap, and `tail` that points to the last cell. These two cells contain two values that are smaller and larger respectively than all keys that may be inserted in the set.

3.3 Specification for a Concurrent Data Structure

In a concurrent program, the methods of the different executing threads can overlap in time. Therefore, the order in which they take effect is ambiguous. The program statements in each method are totally ordered. Whereas, statements from different methods in different executing threads might form a partial order. This partial order raise the difficult of reasoning about program execution. One of the main correctness criterion of a concurrent program is linearizability, which defines consistency for the history of call and response events generated by an execution of the program at hand [51]. Intuitively, linearizability requires every method to take effect at some point (*linearization point*) between it's call and return events. A linearization point is often a moment where the effect of the method becomes visible to other threads. A (concurrent) history is linearizable if and only if there is some order for the effects of the actions that corresponds to a valid sequential history. The valid sequence history can be generated by an execution of the sequential specification object. A concurrent object is linearizable iff each of its histories is linearizable.

The Figure 3.4 provides a examples of trace of methods of concurrent program implementing sets. In the trace, each method takes effect instantaneously at its (called the *linearization point*) between call and return events [51]. When we order methods according to its linearization point, we get a total ordered sequence that respect the behavior of the set. A linearization point normally stays inside the code of the method. However, in some cases, it it is located in the code of another method depending on the execution path.

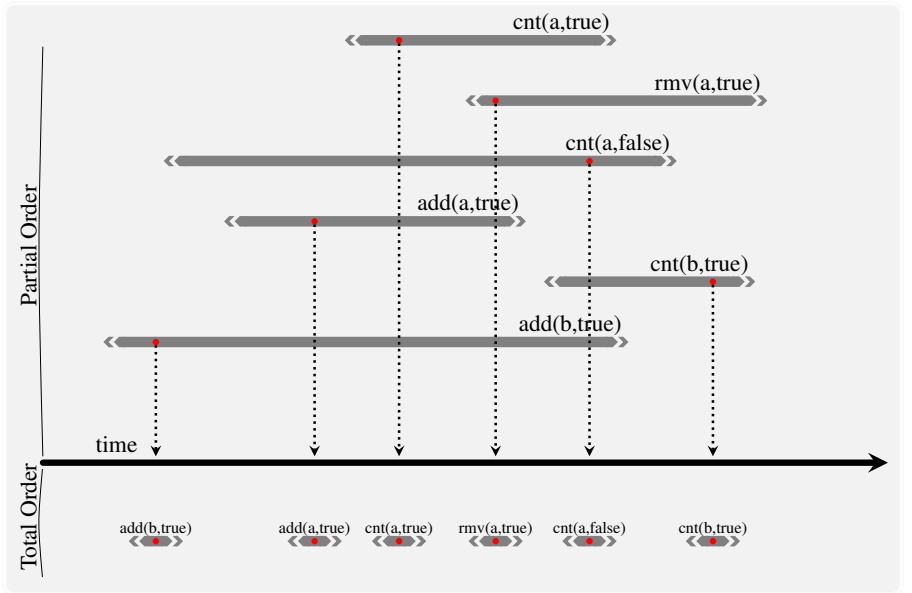


Figure 3.4. Linearizability, where the commit points are marked with .

In order to derive the totally ordered execution from a concurrent execution, each method is instrumented to generate a so-called abstract event whenever a linearization point is passed.

Right after the program pass the linearization point, the abstract event is communicated to an external *observer*, which records the sequences of abstract events from the code execution. In the next section, we introduce the notion of observer, which essentially separates good traces of events from bad ones. Several observers shall be used to specify the safety property.

3.4 Observers

We specify the serial semantics of data structures by observers, as introduced in [2]. Observers are finite automata extended with a finite set of observer registers that assume values in $\mathbb{Z}$. At initialization, the registers are nondeterministically assigned arbitrary values, which never change during a run of the observer. Transitions are labeled by linearization events that may be parameterized on registers. Observers are used as acceptors of sequences of linearization events. The observer processes such sequences one event at a time. If there is a transition, whose label, after replacing registers by their values, matches the event, such a transition is performed. If there is no such transition, the observer remains in its current state. The observer accepts a sequence if it can be processed in such a way that an accepting state is reached. We use observers to give exact specifications of the behaviors of data structures such as sets, queues,

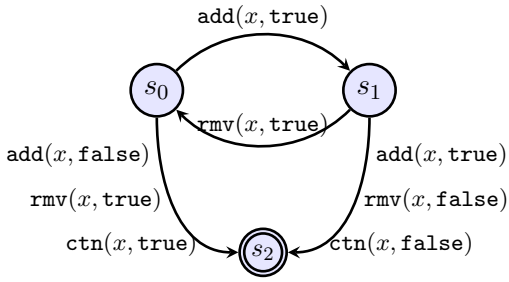


Figure 3.5. A stack observer

and stacks. The observer is defined in such a way that it accepts precisely those sequences of abstract events that are not allowed by the semantics of the data structure. This is best illustrated by an example. Fig. 3 depicts an observer that accepts the set of method invocations that are not allowed by behavior of a set

3.5 Linearization Policies

To prove linearizability, the most intuitive approach is to find a linearization point (LP) in the code of the implementation, and show that it is the single point where the effect of the operation takes place. However, for a large class of linearizable implementations, the LPs are not fixed in the code of their methods, but depend on actions of other threads in each particular execution. This happens, e.g., for algorithms that employ various forms of helping mechanisms, in which the execution of a particular statement in one thread defines the LP for one or several other threads. For example, in the the `Lazy Set` algorithm, the linearization point of unsuccessful `ctn` method is not fixed in the code of the method. It stays in the code of the `add` method. There have been several previous works dealing with the problems of non-fixed linearization points [96, 33, 32, 81, 37, 80, 89, 27]. However, they are either manual approaches without tool implementation or not strong enough to cover various types of concurrent programs. In this thesis we handle non-fixed linearization points by providing semantic for specifying linearization policies. The linearization point of a thread may be defined in two ways: (i) The thread may define its own linearization point, and in that case may also help other threads define their own linearization points. (ii) The thread may be helped by other threads. The helping mechanism may contain complicated patterns. For instance, the helping thread may broadcast a message to the other threads (e.g., the `Lazy Set` algorithm). Both the helping and the helped threads will then interact with the observer to communicate their parameters and return values. In such a case, the helping thread may be able to help an unbounded number of threads (all those who can be helped in the current configuration). In other cases, the

helping thread may explicitly linearize for the helped thread, which means that the helped thread itself need not communicate with the observer. Furthermore, a given algorithm may use several of these patterns to define its linearization points. To specify the linearization patterns, we equip each method with a *controller* whose behavior is defined by a set of rules which are described detail in paper II. The controller is occasionally activated by the thread, and helps organize the interaction of the thread with other threads as well as with the observer. More precisely, some statements in a method are declared to be *triggering*. If a triggering statement is executed then the controller of the thread will also be executed simultaneously.

In the `Lazy Set` algorithm, the linearization point of the `add` operation is defined statically in the code of the method (lines `2` and `4`). There are two possible linearization points corresponding to whether the operation is *unsuccessful* (the element to be added is already in the list), or *successful* (the element is not in the list.) In the first case, the thread reaches the triggering statement at line `2` and the condition "`c.val = e`" holds, i.e., we have found the element `e` in the list. Thereafter, it informs the observer that an `add` operation with argument `e` has been performed, and that the outcome of the operation is `false` (the operation was unsuccessful.) A successful `add` operation is communicated to the observer in a similar manner. However, in this case, the controller will also help other threads by to linearize. This is done by *broadcasting* a message to the other threads which is executing `ctn`. These threads will inform the observer that the element e is not in the list before the helping thread communicate to the observer. The detail of controller is described in paper II.

3.6 Heap Abstraction

A difficult challenge in verifying heap manipulation programs is to handle infinite sets of reachable heap configurations. The area of verifying programs with dynamic linked data structures has been a subject of intense research for quite some time. Currently, there are several competing approaches for symbolic heap abstraction. The first approach is based on the use of logics to present heap configurations. The logics can be separation logic [76, 64, 19, 94, 38, 28, 60, ?, 41], 3-valued logic [78], monadic second- order logic [69, 55, 63] or other [77, 95]. Another approach is based on the use of automata. In this approach, elements of languages of the automata describe configurations of the heap [26, 25]. The last approach that we will mention is based on graph grammars describing heap graphs [49, 48]. The presented approaches differ in their degree of specialisation for a particular class of data structures, their efficiency, and their level of dependence on user assistance (such as definition of loop invariants or inductive predicates for the considered data structures).

Among the works based on separation logic, the work, such as [19, 94, 60] proposed more efficient approaches. The reason for that is that their approaches effectively decomposes the heap into disjoint components and process them independently). However, most of the techniques based on separation logic are either specialised for some particular data structure, or they need to be provided inductive definitions of the data structures. In addition, their entailment checking procedures are either for specific class of data structures or based on folding/unfolding inductive predicates in the formulae and trying to obtain a syntactic proof of the entailment.

This issue can be fixed by automata techniques using the generality of the automata-based representation such as techniques using tree automata. Finite tree automata, for instance, have been shown to provide a good balance between efficiency and expressiveness. In particular, the so-called abstract regular tree model checking (ARTMC) of heap-manipulating programs [BHRV12] uses a finite tree automaton to describe a set of heaps positioned on a tree backbone (non-tree edges of the heap are represented using regular "routing" expressions describing how the target can be reached from the source using tree edges). Manipulation with the heap is represented using a finite tree transducer and the set of reachable configurations is computed by iteratively applying the transducer on the initial configuration, until a fixpoint is reached. At each step, the obtained symbolic configuration is safely over-approximated using abstraction—which collapses certain states of the automaton—and a fixpoint is detected by standard automata language inclusion testing. The abstraction used is derived automatically during the run of the analysis, using the so-called counterexample-guided abstraction refinement (CEGAR) technique. This formalism is able to fully automatically verify even as complex data structures as binary trees with linked leaves, however, it suffers from the inefficiency of the monolithic encoding of the sets of heaps and the transition relation

In this thesis, we proposed three approaches for heap abstractions. In paper I, we proposed a novel approach of representing sets of heaps via tree automata (TA). In our representation, a heap is split in a canonical way into several tree components whose roots are the so-called cut-points. Cut-points are nodes pointed to by program variables or having several incoming edges. The tree components can refer to the roots of each other, and hence they are "separated" much like heaps described by formulae joined by the separating conjunction in separation logic [15]. Using this decomposition, sets of heaps with a bounded number of cut-points are then represented by the so called forest automata (FA) that are basically tuples of TA accepting tuples of trees whose leaves can refer back to the roots of the trees. Moreover, we allow alphabets of FA to contain nested FA, leading to a hierarchical encoding of heaps, allowing us to represent even sets of heaps with an unbounded number of cut-points (e.g., sets of DLL, skiplist). In addition, we express relationships between data elements associated with nodes of the heap graph by two classes of constraints. Local data constraints are associated with transitions of TA and capture relationships

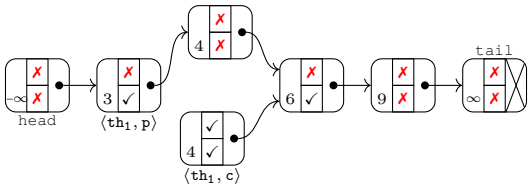


Figure 3.6. A heap configuration of the `Lazy Set` Algorithm in the view of thread $\mathtt{th}_1$.

between data of neighboring nodes in a heap graph; they can be used, e.g., to represent ordering internal to some structure such as a binary search tree. Global data constraints are associated with states of TA and capture relationships between data in distant parts of the heap. This approach was applied to verification of sequential heap manipulation programs. This approach is general and fully automatic, it can handle many types of sequential programs without any manual step. However, due to the complexity of tree automata operations, this approach is not suitable to handle concurrent programs where a large number of states and computation are needed. In paper II, we provide a symbolic encoding of the heap structure that is precise enough to allow the verification of the concurrent algorithms, and efficient enough to make the verification procedure feasible in practice. The main idea of the abstraction is to have a more precise description of the parts of the heap that are visible (reachable) from the shared pointers, and to make a succinct representation of the parts that are lo cal to the threads (see Fig. 5.) More concretely, we will extract a set of heap segments, where the end points of a segment are pointed to by shared pointers. For each segment, we will store a summary of the content of the heap along the segment. This summary contains different pieces of information, including the values of the cell variables if they have finite values, and the ordering among them if they are integer variables. It also includes information ab out paths along the heap that connects the lo cal pointers of the threads to the current segment. For each given program, the set of possible abstract shapes insight and hence the verification procedure is guaranteed to terminate. This approach is very efficient but it is not optimal for complicated concurrent data structures like trees, lists of lists or skiplists. Therefore in paper III, we present an approach which can handle concurrent programs implemented from

simple to complex data structures. I n our fragment abstraction, we represent the part of the heap that is accessible to a thread by a set of fragments. A fragment represents a pair of heap cells (accessible to `th`) that are connected by a pointer field, under the applied data abstraction. The fragment contains both (i) *local* information about the cell's fields and variables that point to it, as well as (ii) *global* information, representing how each cell in the pair can reach to and be reached from (by following a chain of pointers) a small set of globally significant heap cells. A set of fragments represents the set of heap

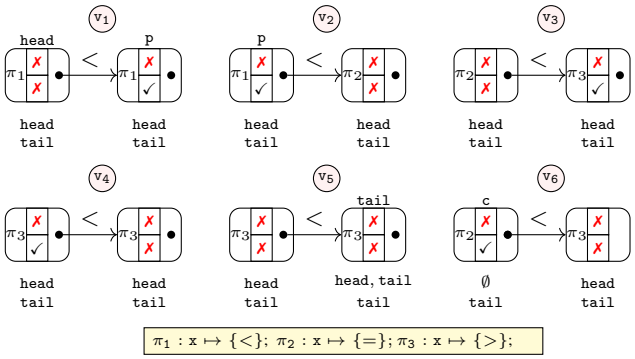


Figure 3.7. Fragment abstraction of `lazy set` algorithm

structures in which each pair of pointer-connected nodes is represented by some fragment in the set. Put differently, a set of fragments describes the set of heaps that can be formed by "piecing together" pairs of pointer-connected nodes that are represented by some fragment in the set. This "piecing together" must be both locally consistent (appending only fragments that agree on their common node), and globally consistent (respecting the global reachability information).

Let us illustrate how pairs of heap nodes can be represented by fragments. As a first example, in the view of thread $\mathtt{th}_1$ in Figure 3.6, the two left-most cells are represented by the $\mathtt{v}_1$ in Figure 3.6. Here, the mapping π_1 represents the data abstraction of the `key` field, here saying that it is smaller than the value 4 of the observer register. In each fragment, the abstraction of non-pointer fields are shown represented inside each tag of the fragment. The ordering between two keys of two nodes is shown as a label on the arrow between two tags. Above each tag is pointer variables. The first row under each tag is `reachfrom` information, whereas the second row is `reachto` information.

Figure 3.6 shows a set of fragments that is sufficient to represents the part of the heap that is accessible to $\mathtt{th}_1$ in the configuration in Figure 3.6. There are 6 fragments, named $\mathtt{v}_1$, …, $\mathtt{v}_6$. All other fragments consist of a pair of pointer-connected tags. The `private` field of the input tag of $\mathtt{v}_6$ is `true`, whereas the `private` field of other tags of other fragments are `false`.

To verify linearizability of the algorithm in Figure 3.3, we must represent several key invariants of the heap. These include (among others)

1. The list is strictly sorted in `key` order, two unmarked nodes cannot have the same `key`.
2. All nodes which are unreachable from the head of the list are marked.
3. The variable `p` points to a cells whose `key` field is never larger than the input parameter of its `add`,`rmv` and `cnt` methods.

Let us illustrate how such invariants are captured by our fragment abstraction. 1) All fragments are strictly sorted, implying that the list is strictly sorted. 2)

This is verified by inspecting each tag: $\mathtt{v}_6$ contains the only unreachable tag, and it is also marked. 3) The fragments express this property in the case where the value of `key` is the same as the value of the observer register `x`. Since the invariant holds for any value of `x`, this property is sufficiently represented for purposes of verification.

Summaries of Papers

My Contributions

?? I designed the method with Lukáš Holík. I am the sole implementer of the prototype and responsible for the experimentation. I participated in all parts of the writing, equally as my co-authors.

?? I designed the method with Lukáš Holík and Ahmed Rezine. I am the sole implementer of the prototype and responsible for the experimentation. I participated in all parts of the writing, equally as my co-authors.

III I designed the method with Lukáš Holík. I am the sole implementer of the prototype and responsible for the experimentation. I participated in all parts of the writing, equally as my co-authors.

Conclusion and Future Work

We have presented, in this thesis, approaches to verify the complex problem of both sequential and concurrent heap manipulating programs.Such programs induce an infinite-state space in several dimensions: they (i) consist of an unbounded number of concurrent threads, (ii) use unbounded dynamically allocated memory, and (iii) the domain of data values is unbounded. (iv) consist of un unbounded number of pointers. In addition, the linearization points of some programs are not fixed. They are depended on the future executions of these programs. In this thesis, we focus on proving both safety properties, and linearization properties for the system, regardless of the value of this parameter. In order to prove safety properties, we defines an abstract model of the program, and we employ approximation techniques to that ignore irrelevant information so that we can reduce the problem into a finite-state model. In fact, we use an over-approximation, such that the abstract model cover all the behaviors of the original system. However, it might cover other behaviors which are not in the original system. If the bad states are not reached during the computation of reachable states of the abstract model, then the abstract model is considered safe, and so is the original system is also safe. If the bad state is reachble, we have to refine the abstraction. In order to verity linearization properties of a program, we add a specification which expresses its a data structure, using the technique of observers. In our approaches, the user have to provide linearization policies which specify how the program is linearized. We use a technique call `controller` to specify linearization policies. We then verify that in any concurrent execution of a collection of method calls, the sequence of announced operations satisfies the semantics of the data structure. This check is performed by an observer, which monitors the sequence of announced operations. This reduces the problem of checking linearizability to the problem of checking that in this cross-product, the observer cannot reach a state where the semantics of the set data structure has been violated. To verify that that the observer cannot reach a state where a violation is reported, we compute a symbolic representation of an invariant that is satisfied by all reachable configuration of the cross-product of a program and an observer.

There are two main possible lines of future work we would like to work on from this thesis. The first line is to extend the type programs we consider, by allowing more complicated data structures such as trees and design methods that allow the automatic synthesis of the controllers. Another possible line of work is to extend the view abstraction to multi-threaded programs running on machines with different memory models. Such hardware systems employ

store buffers and cache systems that could be modeled using views. This is an interesting challenge since it would help programmers to write their code under a given memory model that is simpler to reason around, and verify that the behaviour of the program is the same under another less-restricted memory model.

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