A Framework For Efficient Modular Heap Analysis

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Contents

Abstract

Modular heap analysis techniques analyze a program by computing summaries for every procedure in the program that describes its effects on an input heap, using pre-computed summaries for the called procedures. In this article, we focus on a family of modular heap analyses that summarize a procedure's heap effects using a context-independent, shape-graph-like summary that is agnostic to the aliasing in the input heap. The analyses proposed by Whaley, Salcianu and Rinard, Buss *et al.*, Lattner *et al.* and Cheng *et al.* belong to this family. These analyses are very efficient. But their complexity and the absence of a theoretical formalization and correctness proofs makes it hard to produce correct extensions and modifications of these algorithms (whether to improve precision or scalability or to compute more information). We present a modular heap analysis framework that generalizes these four analyses. We formalize our framework as an abstract interpretation and establish the correctness and termination guarantees. We formalize the four analyses as instances of the framework. The formalization explains the basic principle behind such modular analyses and simplifies the task of producing extensions and variations of such analyses.

We empirically evaluate our framework using several real-world $C^\sharp$ applications, under six different configurations for the parameters, and using three client analyses. The results show that the framework offers a wide range of analyses having different precision and scalability.

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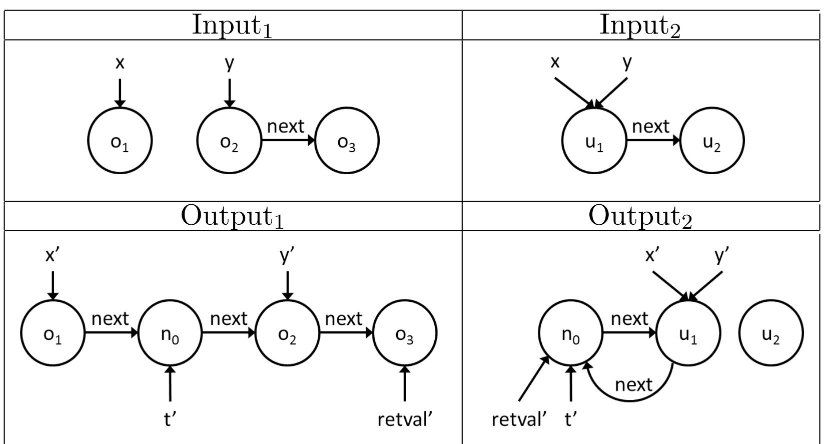
Introduction

Compositional or modular analysis [Cousot and Cousot, 2002] is a key technique for scaling static analysis to large programs. Our interest is in techniques that analyze a procedure in isolation, using pre-computed summaries for called procedures, computing a summary for the analyzed procedure. Such analyses are widely used and have been found to scale well. However, computing such summaries for a heap analysis (or points-to analysis) is challenging because of the aliasing in the input heap. For example, consider the procedure `P` shown in Fig. 1.2(a). Its behaviour on two different input heaps is shown in Fig. 1.2(b) and Fig. 1.2(c). (The heaps are depicted as shape graphs. The input heap is shown at the top and the corresponding output heap at the bottom). It can be seen that the behaviour of `P` varies significantly depending on the aliasing between the variables `x` and `y` in the input heap. A sound summary for `P` should be able to approximate the behaviour of `P` in both these scenarios.

Existing modular heap analyses can be broadly classified into the following categories. (The following classification is not exhaustive. There are modular analyses such as [Nystrom et al., 2004] that cannot be easily classified into any of the categories mentioned. It is also pos-

```
   P (x, y) {
     t = new ();
     x.next = t;
     t.next = y;
     retval = y.next;
   }
```

Figure 1.1: A procedure `P` whose behaviour depends on the aliasing in the input heap.



(a) (b)

Figure 1.2: (a) Output of `P` when `x` and `y` are not aliases in the input heap. (b) Output of `P` when `x` and `y` are aliases in the input heap.

sible to design analyses that belong to more than one of the categories though we aren't aware of any.) (a) Analyses such as [Calcagno et al., 2009] compute *conditional summaries* that are applicable only in the contexts that satisfy certain conditions (e.g., aliasing or non-aliasing conditions). (b) Some analyses such as [Chatterjee et al., 1999], [Dillig et al., 2011], [Jeannet et al., 2010] enumerate all relevant configurations of the input heap belonging to a fixed abstract domain and generate summaries for each configuration. A major challenge with this approach is reducing the number of configurations that are enumerated, which can quickly become intractable, and finding efficient ways of representing them. (c) A few analyses, namely, [Whaley and Rinard, 1999], [Cheng and Hwu, 2000], [Liang and Harrold, 2001], [Lattner et al., 2007], [Buss et al., 2008] compute context-independent summaries that are agnostic to the aliasing in the input heap *without* enumerating the possible configurations of the input heap. To our knowledge, these are the only existing analyses having this property.

The analysis proposed by Whaley and Rinard [Whaley and Rinard, 1999] was later on refined and improved by Salcianu and Rinard [Salcianu and Rinard, 2005]. We will refer to this analysis as the WSR analysis. Adopting the terminology of [Lattner et al., 2007], we will refer to the analysis proposed by Lattner *et al.* as Data Structure Analysis (DSA).

In this article, we consider analyses belonging to the final category. They are interesting for several reasons. (a) They have a number of applications, discussed shortly. (b) The analyses are very efficient. DSA scales to the entire Linux kernel comprising 3 million lines of code in 3 seconds. An optimized version of WSR analysis discussed in [Madhavan et al., 2011] scales to $C^\sharp$ libraries with 250 thousand lines of code. (c) Being modular, they can analyze open programs, libraries, and, in fact, any arbitrary chunk of code without requiring any knowledge of the environment. Moreover, the summaries computed are such that they be refined incrementally when more knowledge about the environment becomes available.

These analyses have been used in a number of applications. Salcianu and Rinard present an application of their analysis to compute the *side-effects* of a procedure, which are the effects of the procedure on the pre-existing state, and use it to classify procedures as *pure* (having no side-effects) or *impure* [Salcianu and Rinard, 2005]. This analysis, referred to as purity analysis, itself has a number of applications.

Whaley and Rinard applied their analysis to identify objects that can be safely allocated in the stack instead of the heap [Whaley and Rinard, 1999]. We use an extension of the WSR analysis to statically verify the correctness of the use of speculative parallelism [Prabhu et al., 2010]. Lattner *et al.* use their analysis to perform *pool allocation* in which different instances of data structures are allocated to distinct memory pools, which enables certain compiler optimizations [Lattner and Adve, 2005b].

However, the complexity of the analyses makes the task of extending and modifying these analyses challenging and time consuming. Questions such as the following often arise while designing new applications based on the analyses and there is no easy way of answering them. Can the scalability of the WSR analysis be improved at the expense of precision? Can DSA be extended to yield more precise results when more time and resources are available? Is it possible to integrate a modular static analysis that requires heap information (such as an *information flow analysis*) with these analyses as typically done in top-down whole program analyses? A sound theoretical formulation of the analyses will greatly aid in answering such questions.

Upon investigating the theoretical basis of these analyses, we realized that, in spite of the apparent dissimilarity between the analyses and the differences in the precision, scalability, and functionality, there are some fundamental ideas common to all of these analyses. This motivated us to develop a parametric framework for designing efficient modular heap analyses. The analyses listed earlier become specific instances of our framework.

We formulate our framework as a parametric abstract interpretation and establish the correctness and termination of the semantics. We present several transformations and optimizations (collectively called as specializations) of our framework and establish their correctness using the standard theory of abstraction interpretation. Our framework with its parametric domains, parametric semantics and several correctness preserving transformations provides a convenient mechanism for obtaining modular heap analyses with different levels of precision and scalability.

We formally establish that the four analyses: [Whaley and Rinard, 1999], [Cheng and Hwu, 2000] [Lattner et al., 2007] (except for the handling of indirect calls), [Buss et al., 2008] are specific instances of our framework. We exclude the analysis proposed in [Liang and Harrold, 2001] (called as *MoPPA*) as it is very similar to [Lattner et al., 2007]. Nevertheless, it can also be expressed as an instance of our framework.

Formulating the analyses as instances of the framework has several advantages. It provides an immediate proof of correctness and termination for the analyses. It also helps understand the abstractions performed by the analyses and identify opportunities for making them more precise or scalable. In fact, we were able to identify several corner cases that were not handled by some of the algorithms and were able to fix them. Since we were unable to find complete formalization of some of the analyses, it is not clear to us if the problems we identified are bugs in the algorithm or gaps in the informal descriptions.

We implemented the framework in our open source heap analysis tool *Seal* (`seal.codeplex.com`). *Seal* is a fairly robust tool which has been used in several program analysis applications. We empirically studied the different configurations of the framework using *Seal*. We present a summary of the results in Chapter 8. The results throw light on the importance of the parameters of the framework by measuring their impact on the precision and scalability of three client analyses.

The framework presented in this article has some limitations. Most importantly, it does not support strong updates on heap locations and path-sensitivity. To our knowledge, all existing modular heap analysis approaches (such as [Dillig et al., 2011], [Jeannet et al., 2010]) that perform strong updates on heap locations enumerate the possible configurations of the input heap. Nevertheless, we believe that both these challenges can be addressed without resorting to enumeration of the input heap configurations. We briefly outline a potential approach in the Future Works section (see Chapter 9).

The following are the main contributions of this article:

- We propose a modular heap analysis framework that is a generalization of a family of existing modular heap analyses. To our knowledge, this is the first attempt to connect and develop a common theory for the different modular heap analyses proposed in the past.
- We formulate our framework as an abstract interpretation and prove the correctness and termination properties.
- We present several correctness preserving transformations that are applicable to all instances of the framework.
- We formalize four existing modular heap analyses as abstractions of instances of our framework, thereby provide a proof of correctness and termination for the analyses. The formalization exposes the relationships between the analyses and provides ways of improving and modifying them.
- We present an empirical evaluation of the framework by analyzing ten open source $C^\sharp$ applications with six different configurations of the framework. We used three client analyses, namely, *Purity and Side Effects Analysis*, *Escape Analysis* and *Call-graph Analysis* to measure the precision and scalability of each of the six configurations.

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