Electronic Notes in Theoretical Computer Science 131 (2005) 75–84 

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Abstract Interpretation and Object-oriented Programming: Quo Vadis?

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Abstract

The aim of this position paper is to draw a quick overview of the main contributions in abstract interpretation of object-oriented programs, and to draw possible lines of research in this field.

*Keywords:* Abstract interpretation, Object-oriented programming, static analysis

# Introduction

Abstract Interpretation is a theory for static analysis of software systems that formalizes the notion of approximation and abstraction in a mathematical setting, and which is independent of particular languages and applications. Nevertheless, when looking at the literature produced in the last two decades

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3 Partially supported by MIUR FIRB grant n.RBAU018RCZ and by MIUR PRIN’04 grant n.2004013015

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doi:10.1016/j.entcs.2005.01.024

(see the electronic version with extended bibliography of [[14](#_bookmark10)]), the amazingly rich suite of problems and solutions that fit in the abstract interpretation setting is often dependent both on the specific programming language and on the given property to be analyzed (that might also be language dependent). Since abstract interpretation has a very semantic-based character, it is not surprising that language paradigms with strong semantic foundations, e.g. functional and logic programming, have been in the past a very fertile test bed for the development of sophisticated abstract domains and specialized fix- point algorithms. On the other hand, when looking at the contributions in the area of object-oriented programming, the picture is somehow still fragmented, and this may overshadow the great potentialities of abstract interpretation on the mainstream programming platforms where the OO paradigm is getting a leader position.

This paper is aimed at providing a general survey of existing literature on abstract interpretation for object-oriented languages, and draw a few hints on how the research in this field may get further advances.

# What has been done...

First, let us try to revisit a few interesting contributions (no claim of being complete!) in the static analysis of object-oriented languages. They are mainly focused on optimization issues.

* 1. *Class Analysis*

A class analysis computes, for each program point PP and for each variable xPP a set of classes CxPP such that if in an execution of the program x, at program point PP, has a runtime type C, then C ∈ CxPP . Class analysis is useful (i) for optimization of object-oriented programs, so to statically resolve virtual calls, and (ii) for the static construction of the control-flow graph of a program, so to provide the first step for a further analysis. In fact, if class analysis infers that a given program point, corresponding to a method invocation, CxPP is a singleton, then there is no need for a look-up procedure in the class hierarchy to determine the method to be invoked at runtime.

Several class analyses have been proposed in the literature, which consider different values for the ratio precision/cost. For instance, the seminal work by Palsberg and Schwartzbach, [[37](#_bookmark37)], presents a very precise, but also expen- sive, analysis for untyped object-oriented languages. These results have been improved by the same authors, [[36](#_bookmark36)], as well as by others, [[4](#_bookmark4),[18](#_bookmark18),[15](#_bookmark15),[45](#_bookmark43)], which consider fast, but also imprecise, class analyses for the removal of virtual func- tion calls in C++.

Another approach for reducing the cost of the analysis is by modularizing it: Besson and Jensen introduced a modular class analysis based on DAT- ALOG, [[5](#_bookmark5)], and Probst described an analysis to incrementally construct the control-flow graph of Java programs, [[39](#_bookmark39)].

Spoto and Jensen, [[44](#_bookmark44),[24](#_bookmark24)], provided a uniform, abstract interpretation- based, view of such analyses. The authors define a concrete trace semantics, and they proved how existing analyses are an abstraction of such a semantics. Given an execution trace *σ*0*σ*1*σ*2 *... σn* and a function *typeOf* which returns the runtime type of an object, the analysis of Palsberg and Schwartzbach is obtained by considering an abstraction function such that

*αPS*(*σ*0*σ*1*σ*2 *... σn*)= *λ*PP*. λ*x*.* {*typeOf* (*σi*(x)) | *i* ∈ [0 *... n*]*, σi*(*pp*)= PP}*.* The fast type analysis of Bacon and Sweeney is obtained by considering a fur- ther abstraction which collects together the types of a given variable through

all the program points:

*αBS*(*σ*0*σ*1*σ*2 *... σn*)= *λ*x*.*  *αPS*(*σ*0*σ*1*σ*2 *... σn*)(*pp*)(x)*.*

*pp*∈Program

As a corollary of their formalization, Spoto and Jensen formally relate the relative precision of the analyses, by considering the relative precision of the corresponding abstract domains.

* 1. *Pointer Analysis*

A pointer analysis computes, for each program point PP, and for each variable x a set AxPP of heap objects, such that if in an execution of the program, at program point PP, x points to an heap object *h*, then *h* ∈ AxPP .

A precise and scalable pointer analysis is a basic requirement for an effec-

tive static analysis of object-oriented programs. In fact, in real-world object- oriented languages, objects are heap-allocated and they are unequivocally identified by their heap address. As a consequence, a precise determination of the addresses a variable may point to allows one to have a precise infor- mation on the objects a program is made of. Furthermore, pointer analysis implies class analysis. In fact, given a result AxPP of a pointer analysis, the

set of classes x can evaluate to at program point PP is given by an abstraction

function *αL*, which collects the types of the heap objects whom address is in

AxPP :

*αL*(AxPP )= {*typeOf* (heap(*h*)) | *h* ∈ AxPP } = CxPP *.*

The first attempts for an effective pointer analysis of object-oriented language focused on modifications/adaptations of existing pointer analyses for C. For instance, Rountev, Milanova, and Ryder proposed a pointer analysis for Java,

[[41](#_bookmark41),[34](#_bookmark34)], that adapts the Anderesen’s pointer analysis for C [[3](#_bookmark3)]; and Rama- lingam *et al.* presented an analysis for inferring the local heap structure of Java containers, [[40](#_bookmark40)], which uses TVLA [[25](#_bookmark25)]. More recently, Pollet, Le Char- lier, and Cortesi introduced two abstract domains to express type, structural, and sharing information about dynamically created objects, [[38](#_bookmark38)]; and Chang and Leino presented an algebra of abstract domains that is essentially the reduced product of a precise alias analysis for heap-allocated objects and a generic abstract domain (parameter of the algebra), [[9](#_bookmark9)].

* 1. *Escape Analysis*

Escape analysis determines whether the lifetime of an object oversteps its static scope. If PP is the exit point of a method, then an escape analysis computes the set EPP of the heap-allocated objects at PP. Escape analysis is useful for program optimization, and in particular for (i) stack-allocating

objects and (ii) removing synchronization. Escape analysis is strictly related to pointer analysis. In fact, if A is the information computed by a pointer analysis, for all the program points and variables, then

*αB*(A)=

x∈*Vars*

APPx = EPP*.*

Gay and Steensgaard apply a very fast, but imprecise, escape analysis to the stack allocation in Java, [[21](#_bookmark21)]; Bogda and H¨oltz addressed the problem of syn- chronization elimination in concurrent Java programs, through the use of a more precise analysis [[8](#_bookmark8)]; Blanchet developed an escape analysis for the full Java whom soundness proof relies on a pointer analysis [[7](#_bookmark7),[6](#_bookmark6)]. The analysis of Blanchet is precise and efficient enough to be applied to boost stack alloca- tion and synchronize removal tasks. Several others escape analyses have been developed, with different values of the precision/cost ration. We recall the Whaley-Rinard and Viven-Rinard analyses, based on points-to escape graphs, [[47](#_bookmark45),[46](#_bookmark46)]; the Choi *et. al* analysis, based on connection graphs, [[10](#_bookmark11)]; the Ruf analysis, which exploits static fields, [[42](#_bookmark42)].

* 1. *Inference of Class Invariants*

Class invariants represent the basis of good software engineering of object- oriented programs, [[33](#_bookmark33)]. A class invariant is a property of a class valid before and after the execution of any method of the class. It can be characterized as an abstraction of the trace semantics, where just the states corresponding to the entry points and exit points of method invocations of instances of a class are retained, [[30](#_bookmark26),[29](#_bookmark27)].

Abstract Interpretation Class Hierarchies

Abstract Domains

Classes

Approximation Order (±)

Subclassing Relation (≤)

Most Abstract Domain(TD )

Object

Reduced Product

Multiple Inheritance

Domain Refinement

Class Extension

Fig. 1. The parallel between abstract domains and class hierarchies.

Automatic-inferred class invariants are useful for modular software ver- ification of classes, for optimization, for code documentation and for com- piler designing. Ghemawat, Randall, and Scales [[22](#_bookmark22)] and subsequently Ag- garwal and Randall [[1](#_bookmark1)] presented a static analysis for the removal of checks on array bounds, that essentially computes a class invariant in the form of

a == null ∨ 0 ≤ b ≤ a*.*length*.* Detlefs was interested in inferring correct explicit deallocation of elements of long-lived data structures [[16](#_bookmark16)]. Flanagan and Leino developed Houdini, a tool based on ESC/Java, for the inference of

invariants, [[20](#_bookmark20)]. Ernst designed Daikon, a tool for the inference of pseudo-class invariants, [[19](#_bookmark19)]. Logozzo introduced a generic framework for the inference of class invariants, which takes into account inheritance, polymorphism, mutu- ally recursive classes, [[32](#_bookmark32),[28](#_bookmark28),[26](#_bookmark29),[27](#_bookmark30)].

* 1. *Other Analyses*

Among the other analyses that have been designed for object oriented lan- guages, we recall the one of Christensen, Møller, and Schwartzbach, that ap- proximates the result of string expressions, [[11](#_bookmark12)]; the one of Distefano, Katoen and Rensik, who present a temporal logic for object-oriented programs and the corresponding model-checking algorithm, [[17](#_bookmark17)]; the one of Owen and Watson, who present an analysis to remove unnecessary box/unboxing operations, [[35](#_bookmark35)]; the one of Zee and Rinard, which allows one to remove write barriers, [[48](#_bookmark48)]; the one of Alur, Cerny, Madhusudan, and Nam, which synthesises interface specifications for Java classes, [[2](#_bookmark2)]; and the one of Salcianu and Rinard, which checks if a Java method is pure or not, [[43](#_bookmark47)].

# ... and what could be done

In the previous survey we have seen how abstract interpretation is an effective technology for the analysis, the verification and the optimization of object- oriented languages. We think that it can be used *also* for the formalization and the description of object-oriented systems.

In fact, there are similarities between abstract interpretation theory and class hierarchies. A basic result in abstract interpretation theory is that, if the concrete domain is a complete lattice, then the set of all its abstractions is a complete lattice too, [[13](#_bookmark13)].

Let Ð be a lattice of abstractions, and let 7 a class hierarchy. The order on Ð is the relative precision of the abstract domains, i.e., D1 ± D2 iff D1 is an abstraction of D2. Intuitively, this means that D1 captures at least all the information of D2, i.e., D2 is a refinement of D1, [[23](#_bookmark23)]. On the other hand, the order on 7 is the subclass relation, i.e., C1 ≤ C2 iff C1 is a subclass of C2. Intuitively, it means that the class C1 is a specialization, or a refinement, of the class C2. Stated differently, C2 is a class more abstract than C1. As a consequence, (i) TD, the greatest element of Ð, is the the most abstract domain; and (ii) Object, the common superclass to all the classes in 7, is the most abstract class of the hierarchy.

Exploiting such a parallel between the two concepts, lattices of abstract domains and class hierarchies, we can say that the 7-counterpart for the meet operation on Ð is multiple inheritance. In fact, the meet operation of two abstract domains D1 and D2 is the reduced product, i.e., the most abstract domain D3, which contains all the information of D1 and D2, [[13](#_bookmark13)]. On the other hand, if C3 is a subclass of both C1 and C2, then it contains all the fields of, and it may behave as, its superclasses. Furthermore, abstract domain refinement and the extension of classes are related concepts, too. In fact, the refinement of

a given abstract domain is a domain that captures all the properties captured by the refined domain *plus* some others (specific to the refinement). On the other hand, the extension of a given base class is a class that inherits all the behaviors of the ancestor, *plus* some others (consider, e.g., the classical 2DPoints and 3DPoints classes, [[12](#_bookmark14)]).

We think that the analogies between the two concepts, that are summa- rized in Figure 1, deserve to be further studied, thus yielding to a cross-porting of results. For instance, which are the counterpart (i) in class hierarchies for the reduce cardinal power; and (ii) in abstract domains for interfaces and for polymorphism? We have begun a study in which we apply abstraction interpretation techniques to the definition and the manipulation of class hier- archies, [[31](#_bookmark31)], and the first results are very encouraging.

Future research in Abstract Interpretation for OO languages might con- sider the issue of validating the whole Object-oriented software engineering process: analysis (OOA), design (OOD) and implementation (OOI). Namely, it might be interesting to investigate how abstract interpretation can provide an alternative formal approach to requirement specifications (which are just abstractions of the behavior of the desired system), as well as a guideline for the software design (by exploiting class invariants), its implementation (by exploiting object invariants), and system integration (by a suitable abstract representation of non functional requirements).

# Conclusions

In this position we drew a quick overview of the main contributes in abstract interpretation of object-oriented languages, and we sketched some analogies between two core concepts of the two fields, respectively abstract domains and class hierarchies.

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