Points-To Analysis

Derek Rayside
MIT CSAIL 6.883, Prof Ernst

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1 Overview

Classic Research Challenge Getting precision for large program quickly.

Recently groups from McGill [2, 20] and Stanford [34, 35] have used *binary decision diagrams* (BDDs) to make precise analyses scale to large programs. Raman [28] has a brief overview of BDDs in this context.

New Research Challenges Incremental analyses. Incomplete programs. Demand-driven analyses (eg, [30]). Dynamic class loading (eg, [15, 24]).

Software Engineering Decision How to choose the right points-to analysis for the software engineering problem you're trying to solve. What costs are worth paying?

[13] [14] [23] [10]

Liang et al. [22] found Andersen-style (inclusion) analyses significantly more precise than Steensgaard-style (unification).

Lhoták and Hendren [21] found object-sensitivity Milanova et al. [25] gave the most bang for the buck for Java, vs approaches such as [34, 35].

Surveys Hind [12] Raman [28]

Dynamic Analysis Relatively little work done here. Gross [10], Mock et al. [26] show 100x improvement over static analyses, with 100x slowdown in program execution.

Context Sensitivity $\left\{ \begin{array}{l} fun \\ string \end{array} \right.$

1.1 Complexity

Abstract from Chakaravarthy [3]:

> Given a program and two variables p and q, the goal of points-to analysis is to check if p can point to q in some execution of the program. This well-studied problem plays a crucial role in compiler optimization. The problem is known to be undecidable when dynamic memory is allowed. But the result is known only when variables are allowed to be structures. We extend the result to show that, the problem remains undecidable, even when only scalar variables are allowed. Our second result deals with a version of points-to analysis called flow-insensitive analysis, where one ignores the control flow of the program and assumes that the statements can be executed in any order. The problem is known to be NP-Hard, even when dynamic memory is not allowed and variables are scalar. We show that when the variables are further restricted to have well-defined data types, the problem is in P. The corresponding flow-sensitive version, even with further restrictions, is known to be PSPACE-Complete. Thus, our result gives some theoretical evidence that flow-insensitive analysis is easier than flow-sensitive analysis. Moreover, while most variations of the points-to analysis are known to be computationally hard, our result gives a rare instance of a non-trivial points-to problem solvable in polynomial time.

Ramalingam [27]: Aliasing is undecidable

Landi [17]: PSPACE-complete even with no procedures or memory allocations

Landi and Ryder [18]

Figure 1 A Brief History of Pointer Analysis [33] — focus on scalability and precision

	Equality-based	**Subset-based**	**Flow-sensitive**
Context-insensitive	• Weihl [32] 1980: < 1 KLOC first paper on pointer analysis • Steensgaard [31] 1996: **1+ MLOC** first scalable pointer analysis	• Andersen [1] 1994: 5 KLOC • Fähndrich et al. [7] 1998: 60 KLOC • Heintze and Tardieu [11] 2001: **1 MLOC** • Berndl et al. [2] 2003: **500 KLOC** first to use BDDs	• Choi et al. [5] 1993: 30 KLOC
Context-sensitive	• Fähndrich et al. [8] 2000: **200K**	• Whaley and Lam [35] 2004: **600 KLOC** cloning-based BDDs	• Landi and Ryder [19] 1992: 3 KLOC • Wilson and Lam [37] 1995: 30 KLOC • Whaley and Rinard [36] 1999: 80 KLOC

Horwitz [16]: Even flow-insensitive problem is NP-hard

Chakaravarthy [3]: Cannot even get a good approximation (within a constant factor) unless P=NP

1.2 Axes of Precision

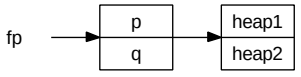
less precise	*more precise*
equivalence	subset/inclusion
flow-insensitive	flow-sensitive
context-insensitive	context-sensitive

Consider the following example [33]:

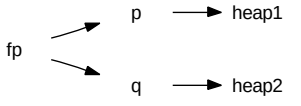
```
p = malloc();
q = malloc();
fp = &p;
fp = &q;
... = *fp;
```

What does the points-to graph look like at the end of the snippet? Depends on what analysis you do:

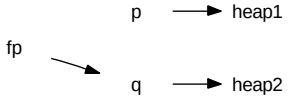
flow-insensitive, equality-based, eg Steensgaard [31]



flow-insensitive, subset-based, eg Andersen [1]

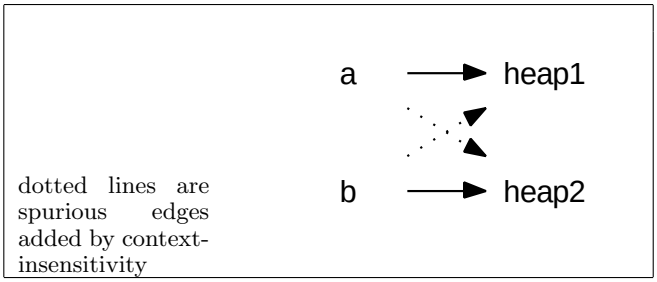


flow-sensitive



Another example, for context-sensitivity [33]:

```
id (x) { return x; }
foo() {
    a = malloc();
    a = id(a);
}
bar() {
    b = malloc();
    b = id(b);
}
```



2 Steensgaard [31] Example

Consider the following program:

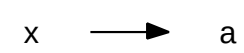
1. `x = &a;`
2. `y = &b;`
3. `p = &x;`
4. `p = &y;`

2.1 Intuitive formulation [29]

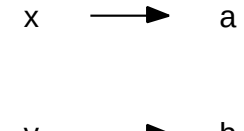
Now we'll construct the points-to graph for this program using the Steensgaard approach as formulated by Ryder [29].

First three statements are easy:

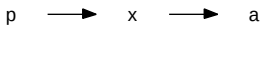
`x = &a;`



`y = &b;`

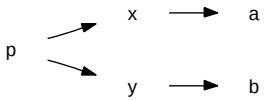


`p = &x;`

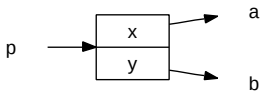


Last statement takes more effort to process:

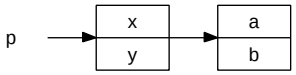
`p = &y;`



add edge

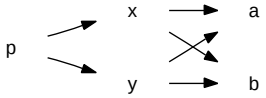


collapse x and y



collapse a and b

Resulting points-to graph over-approximates:



points-to graph

Why do we have to do this collapsing? It seems that the analysis would be linear in the size of the program if we didn't do collapsing. The issues is statements like `a=b;` see the example of Andersen's analysis below for why these introduce more complexity.

2.2 Type-based formulation [6]

First we assign each variable its own type:

- `x` : t_1
- `y` : t_2
- `a` : t_3
- `b` : t_4
- `p` : t_5

Then we construct the initial constraints:

1. `x = &a;` $t_1 = \mathsf{ref}(t_3 \times \_)$
2. `y = &b;` $t_2 = \mathsf{ref}(t_4 \times \_)$
3. `p = &x;` $t_5 = \mathsf{ref}(t_1 \times \_)$
4. `p = &y;` $t_5 = \mathsf{ref}(t_2 \times \_)$

Now we solve/unify the constraints. First we see:

$$t_5 = \mathsf{ref}(t_1 \times \_) = \mathsf{ref}(t_2 \times \_)$$

So we merge t_1 and t_2 into t_1. The world looks like this:

- `x` : t_1
- `y` : t_1
- `a` : t_3
- `b` : t_4
- `p` : t_5
- $t_1 = \mathsf{ref}(t_3 \times \_)$
- $t_1 = \mathsf{ref}(t_4 \times \_)$
- $t_5 = \mathsf{ref}(t_1 \times \_)$

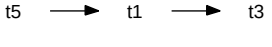
Next we see:

$$t_1 = \mathsf{ref}(t_3 \times \_) = \mathsf{ref}(t_4 \times \_)$$

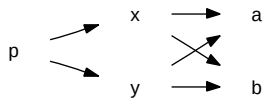
So we merge t_3 and t_4 into t_3. The world looks like this:

- `x` : t_1
- `y` : t_1
- `a` : t_3
- `b` : t_3
- `p` : t_5
- $t_1 = \mathsf{ref}(t_3 \times \_)$
- $t_5 = \mathsf{ref}(t_1 \times \_)$

We're done solving. The storage shape graph is:



If we expand that to a points-to graph we get:

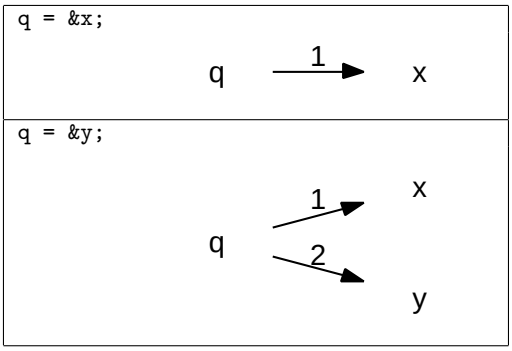


3 Andersen [1] Example [29]

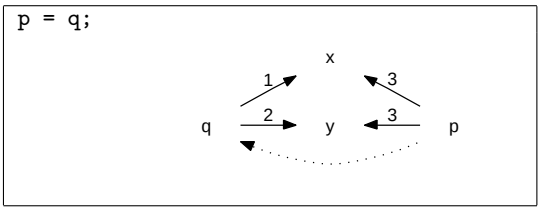
Consider the following program:

1. `q = &x;`
2. `q = &y;`
3. `p = q;`
3. `q = &z;`

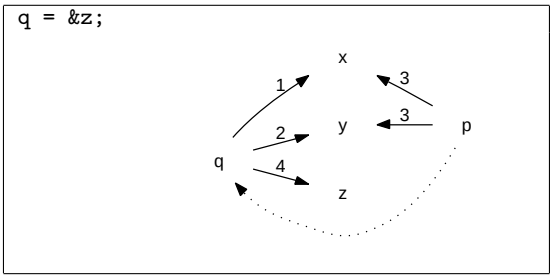
First two statements are easy:



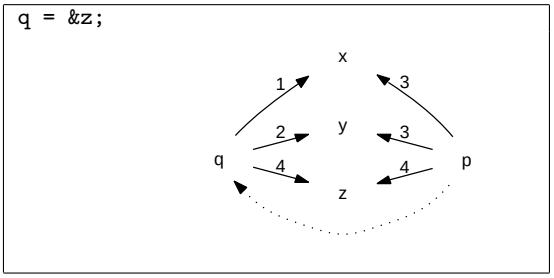
Third statement. See all the things `q` points to, and make `p` point to them as well. Add in dotted line, to remind us $\mathsf{pts(q)} \subseteq \mathsf{pts(p)}$.



Fourth statement. Add in $q \rightarrow z$ edge.



But dotted line reminds us that $\mathsf{pts(q)} \subseteq \mathsf{pts(p)}$. So we need to add $p \rightarrow z$ edge as well. This is the extra work that makes Andersen's analysis more expensive. In a Steensgaard style analysis we would have collapsed x and y at the second statement, and then we wouldn't have to worry about this extra work (although we would lose precision).



Andersen is $O(n^3)$.

Steensgaard is said to be equality-based, eg: $\mathsf{pts(q)} = \mathsf{pts(p)}$.

Acknowledgements

Thanks to Greg Dennis and Rob Seater for discussions. Thanks to John Whaley for sending me his slides [33]. Thanks to Michael Ernst for sending me to Dagstuhl where I saw Barbara Ryder's talk [29].

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