Alias and Points-to Analysis

Alan Mycroft

Computer Laboratory, Cambridge University

`http://www.cl.cam.ac.uk/teaching/current/OptComp`

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Points-to analysis, parallelisation etc.

Consider an MP3 player containing code:

```
for (channel = 0; channel < 2; channel++)
  process_audio(channel);
```

or even

```
process_audio_left();
process_audio_right();
```

Can we run these two calls in parallel?

Points-to analysis, parallelisation etc. (2)

Multi-core CPU: *probably* want to run these two calls in parallel:

```
#pragma omp parallel for         // OpenMP
for (channel = 0; channel < 2; channel++)
  process_audio(channel);
```

or

```
spawn process_audio_left();      // e.g. Cilk, X10
process_audio_right();
sync;
```

or

```
par { process_audio_left()       // language primitives
  ||| process_audio_right()
    }
```

Question: when is this transformation *safe*?

Can we know what locations are read/written?

Basic parallelisation criterion: parallelise only if neither call writes to a memory location read or written by the other.

So, we want to know (at compile time) what locations a procedure might write to at run time. Sounds hard!

Can we know what locations are read/written?

Non-address-taken variables are easy, but consider:

```
for (i = 0; i < n; i++) v[i]->field++;
```

Can this be parallelised? Depends on knowing that each cell of `v[]` points to a distinct object (i.e. there is no *aliasing*).

So, given a pointer value, we are interested in finding a *finite description* of what locations it *might* point to – or, given a procedure, a description of what locations it might read from or write to.

If two such descriptions have empty intersection then we can parallelise.

Can we know what locations are read/written?

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For simple variables, even including address-taken variables, this is moderately easy (we have done similar things in "ambiguous *ref*" in LVA and "ambiguous *kill*" in Avail). Multi-level pointers, e.g.

```
int a, *b, **c;
b=&a;
c=&b;
```

make the problem more complicated here.

What about `new`, especially in a loop?

Coarse solution: treat all allocations done at a single program point as being aliased (as if they all return a pointer to a single piece of memory).

Andersen's points-to analysis

An $O(n^3)$ analysis – underlying problem same as 0-CFA.
We'll only look at the intra-procedural case.

First assume program has been re-written so that all *pointer-typed* operations are of the form

$x := \texttt{new}_\ell$	ℓ is a program point (label)
$x := \texttt{null}$	optional, can see as variant of `new`
$x := \&y$	only in C-like languages, also like `new` variant
$x := y$	copy
$x := *y$	field access of object
$*x := y$	field access of object

Note: no pointer arithmetic (or pointer-returning functions here).
Also fields conflated (but 'field-sensitive' is possible too).

Andersen's points-to analysis (2)

Get set of abstract values $V = \mathit{Var} \cup \{\mathtt{new}_\ell \mid \ell \in \mathit{Prog}\} \cup \{\mathtt{null}\}$.

Note that this means that all `new` allocations at program point ℓ are conflated – makes things finite but loses precision.

The *points-to* relation is seen as a function $pt : V \to \mathcal{P}(V)$. While we might imagine having a different pt at each program point (like liveness) Andersen keeps one per function.

Have type-like constraints (one per source-level assignment)

$$\frac{}{\vdash x := \&y : y \in pt(x)} \qquad \frac{}{\vdash x := y : pt(y) \subseteq pt(x)}$$

$$\frac{z \in pt(y)}{\vdash x := *y : pt(z) \subseteq pt(x)} \qquad \frac{z \in pt(x)}{\vdash *x := y : pt(y) \subseteq pt(z)}$$

$x := \mathtt{new}_\ell$ and $x := \mathtt{null}$ are treated identically to $x := \&y$.

Andersen's points-to analysis (3)

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Alternatively, the same formulae presented in the style of 0-CFA (this is only stylistic, it's the same constraint system, but there are no obvious deep connections between 0-CFA and Andersen's points-to):

- for command $x := \&y$ emit constraint $pt(x) \supseteq \{y\}$
- for command $x := y$ emit constraint $pt(x) \supseteq pt(y)$
- for command $x := *y$ emit constraint implication $pt(y) \supseteq \{z\} \Longrightarrow pt(x) \supseteq pt(z)$
- for command $*x := y$ emit constraint implication $pt(x) \supseteq \{z\} \Longrightarrow pt(z) \supseteq pt(y)$

Andersen's points-to analysis (4)

Flow-insensitive – we only look at the assignments, not in which order they occur. Faster but less precise – syntax-directed rules all use the same set-like combination of constraints ($\cup$ here).

Flow-insensitive means property inference rules are essentially of the form:

$$(\text{ASS})\frac{}{\vdash x := e : \ldots} \qquad (\text{SEQ})\frac{\vdash C : S \quad \vdash C' : S'}{\vdash C; C' : S \cup S'}$$

$$(\text{COND})\frac{\vdash C : S \qquad \vdash C' : S'}{\vdash \texttt{if}\ e\ \texttt{then}\ C\ \texttt{else}\ C' : S \cup S'}$$

$$(\text{WHILE})\frac{\vdash C : S}{\vdash \texttt{while}\ e\ \texttt{do}\ C : S}$$

Andersen: example

[Example taken from notes by Michelle Mills Strout of Colorado State University]

command	constraint	solution
$a = \&b;$	$pt(a) \supseteq \{b\}$	$pt(a) = \{b, d\}$
$c = a;$	$pt(c) \supseteq pt(a)$	$pt(c) = \{b, d\}$
$a = \&d;$	$pt(a) \supseteq \{d\}$	$pt(b) = pt(d) = \{\}$
$e = a;$	$pt(e) \supseteq pt(a)$	$pt(e) = \{b, d\}$

Note that a flow-sensitive algorithm would instead give $pt(c) = \{b\}$ and $pt(e) = \{d\}$ (assuming the statements appear in the above order in a single basic block).

Andersen: example (2)

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command	constraint	solution
$a = \&b;$	$pt(a) \supseteq \{b\}$	$pt(a) = \{b, d\}$
$c = \&d;$	$pt(c) \supseteq \{d\}$	$pt(c) = \{d\}$
$e = \&a;$	$pt(e) \supseteq \{a\}$	$pt(e) = \{a\}$
$f = a;$	$pt(f) \supseteq pt(a)$	$pt(f) = \{b, d\}$
$*e = c;$	$pt(e) \supseteq \{z\} \Longrightarrow pt(z) \supseteq pt(c)$	
(generates)	$pt(a) \supseteq pt(c)$	

Points-to analysis – some other approaches

- Steensgaard's algorithm: treat $e := e'$ and $e' := e$ identically. Less accurate than Andersen's algorithm but runs in almost-linear time.
- shape analysis (Sagiv, Wilhelm, Reps) – a program analysis with elements being abstract heap nodes (representing a family of real-world heap notes) and edges between them being *must* or *may* point-to. Nodes are labelled with variables and fields which may point to them. More accurate but abstract heaps can become very large.

Coarse techniques can give poor results (especially inter-procedurally), while more sophisticated techniques can become very expensive for large programs.

Points-to and alias analysis

"Alias analysis is undecidable in theory and intractable in practice."

It's also very discontinuous: small changes in program can produce global changes in analysis of aliasing. Potentially bad during program development.

So what can we do?

Possible answer: languages with type-like restrictions on where pointers can point to.

- Dijkstra said (effectively): spaghetti *code* is bad; so use structured programming.
- I argue elsewhere that spaghetti *data* is bad; so need language primitives to control aliasing ("structured data").