Alias Analysis

Last time

- Alias analysis I (pointer analysis)
  - Address Taken
  - FIAlias, which is equivalent to Steensgaard

Today

- Alias analysis II (pointer analysis)
  - Anderson
  - Emami

Next time

- Midterm review

Properties of Alias Analysis

Scope: Intraprocedural (per procedure) or Interprocedural (whole program)

Representation

- Alias pairs - pairs of memory references that may access the same location
- Points-to sets - relations of the form (a->b) such that location a contains the address of location b
- Equivalence sets - all memory references in the same set may alias

Flow sensitivity: Sensitive versus insensitive

Context sensitivity: Sensitive versus insensitive

Definiteness: May versus must as well

Heap Modeling - How are dynamically allocated locations modeled?

Aggregate Modeling - are fields in structs or records modeled separately?

Address Taken

Algorithm overview

- Assume that nothing *must* alias
- Assume that all pointer dereferences *may* alias each other
- Assume that variables whose addresses are taken (and globals) *may* alias all pointer dereferences

Characterization of Address Taken

- Per procedure
- Flow-insensitive
- Context-insensitive
- May analysis
- Alias representation: equivalence sets
- Heap modeling: none
- Aggregate modeling: none

```
int **a, *b, c, *d, e;
1: a = &b;
2: b = &c;
3: d = &e;
4: a = &d;
```

```
two equivalence sets

a

**a, *a, *b, *d, b, c, e, d
```


Steensgaard 96 equivalent to FIAlias [Ryder et. al. 2001]

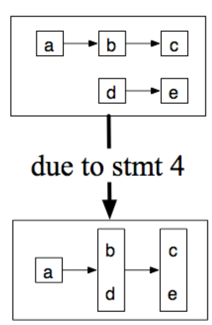
Overview

- Uses unification constraints, for pointer assignments, p = q, Pts-to(p) = Pts-to(q). The union is done recursively for multiple-level pointers
- Almost linear in terms of program size, O(n)
- Uses fast union-find algorithm
- Imprecision stems from merging points-to sets

Characterization of Steensgaard

- Whole program
- Flow-insensitive
- Context-insensitive
- May analysis
- Alias representation: points-to
- Heap modeling: none
- Aggregate modeling: possibly

```
int **a, *b, c, *d, e;
1: a = &b;
2: b = &c;
3: d = &e;
4: a = &d;
```



source: Barbara Ryder's Reference Analysis slides

Unification Constraints

Conceptual Outline

– Add a constraint for each statement
– Solve the set of constraints

Steensgaard Constraints for C

– s: **`p = &x;`**
  $x \in$ Pts-to(p)
– s: **`p = q;`**
  Pts-to(p) = Pts-to(q)
– s: **`p = *q;`**
  $\forall a \in$ Pts-to(q), Pts-to(p) = Pts-to(a)
– s: **`*p = q;`**
  $\forall b \in$ Pts-to(p), Pts-to(b) = Pts-to(q)

Andersen 94

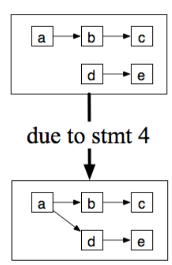
Overview

– Uses inclusion constraints, for pointer assignments, p = q, Pts-to(q) $\subseteq$ Pts-to(p)
– Cubic complexity in program size, $O(n^3)$

Characterization of Andersen

– Whole program
– Flow-insensitive
– Context-insensitive
– May analysis
– Alias representation: points-to
– Heap modeling?
– Aggregate modeling: fields

```
int **a, *b, c, *d, e;
1: a = &b;
2: b = &c;
3: d = &e;
4: a = &d;
```



source: Barbara Ryder's Reference Analysis slides

Outline of Andersen's Algorithm

Find all pointer assignments in the program

For each pointer assignment

- For p = q, all outgoing points-to edges from q are copied to be outgoing from p
- If new outgoing edges are added to q during the algorithm they must also be copied to p

Using flow-insensitive, points-to

- s: **`p = &x;`**
  $x \in$ Pts-to(p)
- s: **`p = q;`**
  Pts-to(q) $\subseteq$ Pts-to(p)
- s: **`p = *q;`**
  $\forall a \in$ Pts-to(q), Pts-to(a) $\subseteq$ Pts-to(p)
- s: **`*p = q;`**
  $\forall b \in$ Pts-to(p), Pts-to(q) $\subseteq$ Pts-to(b)

source: Barbara Ryder slides and Maks Orlovich Slides

Flow-sensitive May Points-To Analysis

Analogous flow functions

- $\sqcap$ is $\cup$
- s: **`p = &x;`**
  out[s] = $\{(\mathbf{p}\rightarrow\mathbf{x})\} \cup (\text{in}[s] - \{(\mathbf{p}\rightarrow\mathbf{y})\ \forall \mathbf{y}\})$
- s: **`p = q;`**
  out[s] = $\{(\mathbf{p}\rightarrow\mathbf{t}) \mid (\mathbf{q}\rightarrow\mathbf{t}) \in \text{in}[s]\} \cup (\text{in}[s] - \{(\mathbf{p}\rightarrow\mathbf{y})\ \forall \mathbf{y}\})$
- s: **`p = *q;`**
  out[s] = $\{(\mathbf{p}\rightarrow\mathbf{t}) \mid (\mathbf{q}\rightarrow\mathbf{r}) \in \text{in}[s]\ \&\ (\mathbf{r}\rightarrow\mathbf{t}) \in \text{in}[s]\} \cup$
  $(\text{in}[s] - \{(\mathbf{p}\rightarrow\mathbf{x})\ \forall \mathbf{x}\})$
- s: **`*p = q;`**
  out[s] = $\{(\mathbf{r}\rightarrow\mathbf{t}) \mid (\mathbf{p}\rightarrow\mathbf{r}) \in \text{in}[s]\ \&\ (\mathbf{q}\rightarrow\mathbf{t}) \in \text{in}[s]\} \cup$
  $(\text{in}[s] - \{(\mathbf{r}\rightarrow\mathbf{x})\ \forall \mathbf{x} \mid (\mathbf{p}\rightarrow\mathbf{r}) \in \text{in}_{must}[s]\})$

Flow-sensitive May Alias-Pairs Analysis

In the below data-flow equations, M and N represent any memory reference expression and + represents a specific number of dereferences. Meet function is ∪

- s: `p = &x;`
  out[s] = {(`*p`,`x`)} ∪ (in[s] – {(`*p`→`y`) ∀`y`})
  ∪ {(*M,x) | (M,p) ∈ in[s]} ∪ {(**+M,N) | (M,p) ∈ in[s] & (+x,N) ∈ in[s]}
- s: `p = q;`
  out[s] = {(`*p`,`t`) | (`*q`,`t`) ∈ in[s]} ∪ (in[s] – {(`*p`,`y`) ∀`y`})
  ∪ {(*M,t) | (M,p) ∈ in[s] & (`*q`,`t`) ∈ in[s] }
  ∪ {(**+M,N) | (M,p) ∈ in[s] & (`*q`,`t`) ∈ in[s] & (+t,N) ∈ in[s]}
- s: `p = *q;`
  out[s] = {(`*p`,`t`) | (`*q`,`r`) ∈ in[s] & (`*r`,`t`) ∈ in[s]} ∪ (in[s] –{(`*p`,`x`) ∀`x`})
  ∪ {(*M,t) | (M,p) ∈ in[s] & (`*q`,`r`) ∈ in[s] & (`*r`,`t`) ∈ in[s] }
  ∪ {(**+M,N) | (M,p) ∈ in[s] & (`*q`,`r`) ∈ in[s] & (`*r`,`t`) ∈ in[s]} & (+t,N) ∈ in[s]}
- s: `*p = q;`
  out[s] = {(`*r`,`t`) | (`*p`,`r`) ∈ in[s] & (`*q`,`t`) ∈ in[s]}
  ∪ (in[s] – {(`*r`,`x`) ∀`x` | (`*p`,`r`) ∈ in_{must}[s]})
  ∪ {(*M,t) | (M,r) ∈ in[s] & (`*p`,`r`) ∈ in[s] & (`*q`,`t`) ∈ in[s]}
  ∪ {(**+M,N) | (M,r)∈in[s] & (`*p`,`r`)∈in[s] & (`*q`,`t`)∈in[s]&(+t,N)∈in[s]}

Other Issues (Modeling the Heap)

Issue

- Each allocation creates a new piece of storage
  e.g., `p = new T`

Proposal?

- Generate (at compile-time) a new "variable" to stand for new storage
- **`newvar`**: Creates a new variable

Flow function

- s: `p = new T;`
  out[s] = {(**p→newvar**)} ∪ (in[s] – {(**p→x**) ∀**x**})

Problem

- Domain is unbounded!
- Iterative data-flow analysis may not converge

Modeling the Heap (cont)

Simple solution

- Create a summary "variable" (node) for each allocation statement
- Domain: $2^{(\text{Var} \cup \text{Stmt}) \times (\text{Var} \cup \text{Stmt})}$ rather than $2^{\text{Var} \times \text{Var}}$
- *Monotonic* flow function
  s: **`p = new T;`**
  out[s] = {(**p→stmt$_s$**)} ∪ (in[s] – {(**p→x**) ∀**x**})
- Less precise (but finite)

Alternatives

- Summary node for entire heap
- Summary node for each type
- K-limited summary
  - Maintain distinct nodes up to k links removed from root variables

Other issues: Function Calls

Question

- How do function calls affect our points-to sets?
  e.g.,

```
p1 = &x;
p2 = &p1;
...
foo();
```

{(**p1→x**), (**p2→p1**)}

???

Be conservative

- Assume that any reachable pointer may be changed
- Pointers can be "reached" via globals and parameters
  - May pass through objects in the heap
- Can be changed to anything reachable or something else
- Can we prune aliases using types?

Problem

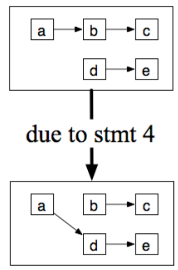
- Lose a lot of information

Emami 1994

Overview

- Compute L and R locations to implement flow-sensitive data-flow analysis
- Uses invocation graph for context-sensitivity
- Can be exponential in program size
- Handles function pointers

```
int **a, *b, c, *d, e;
1: a = &b;
2: b = &c;
3: d = &e;
4: a = &d;
```



Characterization of Steensgaard

- Whole program
- Flow-sensitive
- Context-sensitive
- May and must analysis
- Alias representation: points-to
- Heap modeling: one heap variable
- Aggregate modeling: fields and first array element

Using Alias Information

Example: reaching definitions

- Compute at each point in the program a set of (s,v) pairs, indicating that statement s may define variable v

Flow functions

- s: `*p = x;`
  $out_{reach}[s] = \{(s,\mathbf{z}) \mid (\mathbf{p}\rightarrow\mathbf{z}) \in in_{may\text{-}pt}[s]\} \cup$
  $(in_{reach}[s] - \{(t,\mathbf{y})\ \forall t \mid (\mathbf{p}\rightarrow\mathbf{y}) \in in_{must\text{-}pt}[s]\}$
- s: `x = *p;`
  $out_{reach}[s] = \{(s,\mathbf{x})\} \cup (in_{reach}[s] - \{(t,\mathbf{x})\ \forall t\}$
- . . .

Concepts

Properties of alias analyses

Alias/Pointer Analysis algorithms
- Address Taken
- Steensgaard or FIAlias
- Andersen
- Emami

Flow-insensitive alias algorithms can be specified with constraint equations

Flow-sensitive alias algorithms can be specified with data-flow equations

Function calls degrade alias information
- Context-sensitive interprocedural analysis

Next Time

Assignments
- HW2 due

Lecture
- Midterm review