CSc 553

Principles of Compilation

30 : Alias Analysis

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Aliasing – Definitions I

- Aliasing occurs when two variables refer to the same memory location.
- Aliasing occurs in languages with reference parameters, pointers, or arrays.
- There are two alias analysis problems. Let a and b be references to memory locations. At a program point p

  may-alias(p) is the set of pairs $\langle a, b \rangle$ such that there exists at least one execution path to p, where a and b refer to the same memory location.

  must-alias(p) is a set of pairs $\langle a, b \rangle$ such that on all execution paths to p, a and b refer to the same memory location.

Aliasing – Definitions II

- An alias analysis algorithm can be

  flow-sensitive
  : i.e. it takes the flow of control into account when computing aliases, or

  flow-insensitive
  : i.e. it ignores if-statements, loops, etc.

- There are intra-procedural and inter-procedural alias analysis algorithms.
- In the general case alias analysis is undecidable. However, there exist many conservative algorithms that perform well for actual programs written by humans.

Aliasing – Definitions III

- A conservative may-alias analysis algorithm may sometimes report that two variables p and q might refer to the same memory location, while, in fact, this could never happen. Equivalently, p **may-alias** q if we cannot prove that p is never an alias for q.

Where Does Aliasing Occur?

Formal–Formal Aliasing

```
VAR a : INTEGER;
PROCEDURE F (VAR b, c : INTEGER);
BEGIN
   b := c + 6; PRINT c;
END F;
BEGIN a := 5; F(a, a); END.
```

Generated Code

```
F:     load    R1, c^       # R1 holds c
       add     R2, R1, 6
       store   b^, R2
       PRINT   R1           # PRINT c
main:  storec  a, 5         # a := 5
       pusha   a
       pusha   a
       call    F            # F(&a,&a)
```

Formal–Global Aliasing

```
VAR a :  INTEGER;
PROCEDURE F (VAR b:  INTEGER);
   VAR x :  INTEGER;
BEGIN
   x := a; b := 6; PRINT a;
END F;
BEGIN a := 5; F(a); END.
```

Generated Code

```
F:     load     R1, a    # R1 holds a
       store    x, R1
       store    b^, 6
       PRINT    R1       # PRINT a
main:  storec   a, 5     # a := 5
       pusha    a
       call     F        # F(&a)
```

Pointer–Pointer Aliasing

```
TYPE Ptr = REF RECORD [N:Ptr; V:INTEGER];
VAR a,b :  Ptr; VAR X : INTEGER := 7;
BEGIN
   b := a := NEW Ptr;
   b^.V := X; a^.V := 5;
   PRINT b^.V;
END.
```

Generated Code

```
main: storec  X, 7        # X := 7
      new     a, 8        # a := NEW Ptr
      copy    b, a        # b := a
      load    R1, X       # R1 holds X
      store   b^+4, R1    # b^.V := X
      storec  a^+4, 5     # a^.V := 5
      PRINT   R1          # PRINT b^.X;
```

Array Element Aliasing

```
VAR A : ARRAY [0..100] OF INTEGER;
VAR i, j, X : INTEGER;
BEGIN
   i:=5; j:=2; X:=9; ···; j:=j+3;
   A[i] := X; A[j] := 8; PRINT A[i];
END.
```

Generated Code

```
main: storec  i, 5       # i := 5
      storec  j, 2       # j := 2
      storec  X, 9       # X := 9
      ...     ...
      add     j, 3       # j := j + 3
      load    R1, X      # R1 holds X
      store   A[i], R1   # A[i] := X
      store   A[j], 8    # A[j] := 8
      PRINT   R1         # PRINT A[i]
```

Classifying Aliasing

Flow-Sensitive vs. Flow-Insensitive

		Flow-Sensitive	Flow-Insensitive
S_1 :	p=&r;	{<*p,r>}	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}
	if (···)		
S_2 :	q=p	{<*p,r>,<*q,r>}	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}
	else		
S_3 :	q=&s	{<*p,r>,<*q,s>}	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}
S_4 :	···	{<*p,r>,<*q,s>	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}
		<*q,r>}	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}
S_5 :	q=&t	{<*p,r>,<*q,t>}	{<*p,r>,<*q,s>,<*q,r>,<*q,t>}

- <p,q> is a common notation for p **may-alias** q. Flow-insensitive algorithms are cheaper. Flow-sensitive algorithms are more precise.

Using May-Alias Analysis

- Let `z` and `v` be pointers in the following program fragment:

```
(1)    x := y + z^
(2)    v^ := 5
(3)    PRINT y + z^
```

- If we were performing an Available Expressions data flow analysis in order to find common sub-expressions, we would have to assume that the value computed for `y + z^` on line `(1)` was killed by the assignment on line `(2)`.
- However, if alias analysis could determine that `may-alias(z,v)=false` then we could be sure that replacing `y + z^` by `x` on line `(3)` would be safe.

A Type-Based Algorithm

Type-Based Algorithms

- In strongly typed languages (Java, Modula-3) we can use a type-based alias analysis algorithm.
- Idea: if *p* and *q* are pointers that point to different types of objects, then they cannot possibly be aliases.
- Below, `p` **may-alias** `r`; but `p` and `q` cannot possibly be aliases.
- This is an example of a *flow-insensitive* algorithm; we don't detect that `p` and `r` actually point to different objects.

```
TYPE T1 :  POINTER TO CHAR;
TYPE T2 :  POINTER TO REAL;
VAR p,r :  T1; VAR q :  T2;
BEGIN
   p := NEW T1; r := NEW T1; q := NEW T2;
END;
```

A Flow-Sensitive Algorithm

A Flow-Sensitive Algorithm I

- Assume the following language (p and q are pointers):

`p := new` $\mathcal{T}$	create a new object of type $\mathcal{T}$.
`p := &a`	p now points only to a.
`p := q`	p now points only to what q points to.
`p := nil`	p now points to nothing.

- The language also has the standard control structures.
- May-alias analysis is a forward-flow data-flow analysis problem.

A Flow-Sensitive Algorithm II

- We'll be manipulating sets of alias pairs `<p,q>`. `p` and `q` are *access paths*, either:
  1. l-value'd expressions (such as `a[i].v^[k].w`) or
  2. program locations $S_1, S_2, \cdots$.

  Program locations are used when new dynamic data is created using **new**.
- `in[B]` and `out[B]` are sets of `<p,q>`-pairs.
- $< \mathtt{p}, \mathtt{q} > \in \mathtt{in}[\mathtt{B}]$ if `p` and `q` could refer to the same memory location at the beginning of `B`.

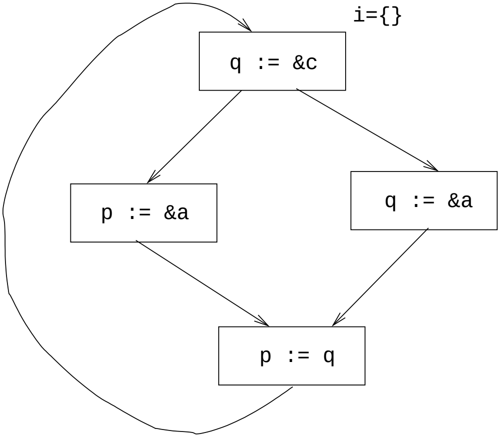
$$
\begin{aligned}
\mathtt{out}[B] &= \mathtt{trans}_B(\mathtt{in}[B]) \\
\mathtt{in}[B] &= \bigcup_{\substack{\mathtt{predecessors} \\ P \text{ of } B}} \mathtt{out}[P]
\end{aligned}
$$

A Flow-Sensitive Algorithm III

- $\texttt{trans}_B(S)$ is a *transfer* function. If S is the alias pairs defined at the beginning of B, then $\texttt{trans}_B(S)$ is the set of pairs defined at the exit of B.

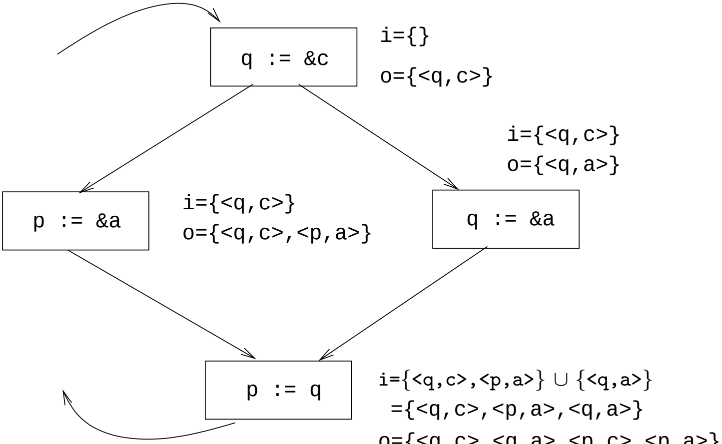
B	$\texttt{trans}_B(S)$
d: `p := ` **new** $\mathcal{T}$	$(S - \{< \mathrm{p}, b > \mid \text{any } b\}) \cup \{< \mathrm{p}, d >\}$
`p := &a`	$(S - \{< \mathrm{p}, b > \mid \text{any } b\}) \cup \{< \mathrm{p}, a >\}$
`p := q`	$(S - \{< \mathrm{p}, b > \mid \text{any } b\}) \cup \{< \mathrm{p}, b > \mid < \mathrm{q}, b > \text{ in } S\}$
`p := nil`	$S - \{< \mathrm{p}, b > \mid \text{any } b\}$

Example I/A – Initial State

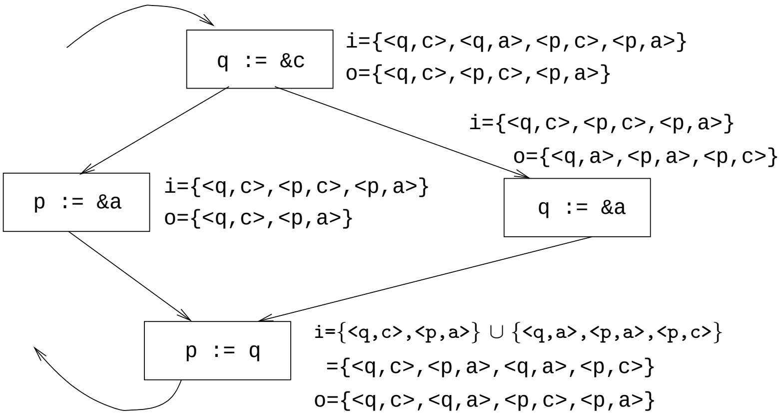



```
repeat
   q := &c;
   if (...)
      p := &a
   else
      q := &a
   p := q
until ...;
```

Example I/B – After First Iteration

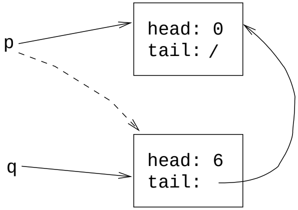


Example I/C – After Second Iteration



Example II/A

```
TYPE T =
  REF RECORD[head:INTEGER;tail:T];
VAR p,q :  T;
BEGIN
  S1: p := NEW T;
  S2: p^.head := 0;
  S3: p^.tail := NIL;
  S4: q := NEW T;
  S5: q^.head := 6;
  S6: q^.tail := p;
      IF a=0 THEN
        S7:  p := q;
      ENDIF;
  S8:  p^.head := 4;
END;
```



Example II/B

S_1: `p:= new T`	$\text{in}[S_1] = \{\}$ $\text{out}[S_1] = \{< \mathrm{p}, S_1 >\}$
S_2: `p^.head := 0`	$\text{in}[S_2] = \text{out}[S_1] = \{< \mathrm{p}, S_1 >\}$ $\text{out}[S_2] = \{< \mathrm{p}, S_1 >\}$
S_3: `p^.tail := nil`	$\text{in}[S_3] = \text{out}[S_2] = \{< \mathrm{p}, S_1 >\}$ $\text{out}[S_3] = \{< \mathrm{p}, S_1 >\}$
S_4: `q:= new T`	$\text{in}[S_4] = \text{out}[S_3] = \{< \mathrm{p}, S_1 >\}$ $\text{out}[S_4] = (\text{in}[S_4] - \{\}) \cup \{< \mathrm{q}, S_4 >\}$ $= \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >\}$

Example II/C

S_5: `q^.head:=6`	$\mathrm{in}[S_5]$	$= \mathtt{out}[S_4] = \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >\}$
	$\mathrm{out}[S_5]$	$= \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >\}$
S_6: `q^.tail:=p`	$\mathrm{in}[S_6]$	$= \mathtt{out}[S_5] = \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >\}$
	$\mathrm{out}[S_6]$	$= (\mathtt{in}[S_6] - \{\}) \cup \{< \mathrm{q}.\mathtt{tail}, S_1 >\}$
		$= \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >, < \mathrm{q}.\mathtt{tail}, S_1 >\}$
S_7: `p:=q`	$\mathrm{in}[S_7]$	$= \mathtt{out}[S_6] =$
		$= \{< \mathrm{p}, S_1 >, < \mathrm{q}, S_4 >, < \mathrm{q}.\mathtt{tail}, S_1 >\}$
	$\mathrm{out}[S_7]$	$= (\mathtt{in}[S_6] - \{< \mathrm{p}, S_1 >\}) \cup \{< \mathrm{p}, S_4 >\}$
		$= \{< \mathrm{p}, S_4 >, < \mathrm{q}, S_4 >, < \mathrm{q}.\mathtt{tail}, S_1 >\}$

Example II/D

S_8: `p^.head := 4`

$$\text{in}[S_8] = \texttt{out}[S_6] \cup \texttt{out}[S_7] =$$
$$= \{< \texttt{p}, S_1 >, < \texttt{p}, S_4 >,$$
$$< \texttt{q}, S_4 >, < \texttt{q.tail}, S_1 >\}$$
$$\text{out}[S_8] = \texttt{in}[S_8] =$$
$$= \{< \texttt{p}, S_1 >, < \texttt{p}, S_4 >,$$
$$< \texttt{q}, S_4 >, < \texttt{q.tail}, S_1 >\}$$

Summary

Complexity Results

- Inter-procedural case is no more difficult than intra-procedural (wrt $\mathcal{P}$ vs. $\mathcal{NP}$).
- 1-level of indirection $\Rightarrow \mathcal{P}$; $\geq$ 2-levels of indirection $\Rightarrow \mathcal{NP}$.

Banning'79 Reference formals, no pointers, no structures $\Rightarrow \mathcal{P}$.

Horwitz'97 Flow-insensitive, may-alias, arbitrary levels of pointers, arbitrary pointer dereferencing $\Rightarrow \mathcal{NP} - \text{hard}$.

Landi&Ryder'91 Flow-sensitive, may-alias, multi-level pointers, intra-procedural $\Rightarrow \mathcal{NP} - \text{hard}$.

Landi'92 Flow-sensitive, must-alias, multi-level pointers, intra-procedural, dynamic memory allocation $\Rightarrow$ Undecidable.

Shape Analysis I

- It is often useful to determine what kinds of dynamic structures a program constructs.
- For example, we might want to find out what a pointer `p` points to at a particular point in the program. Is it a linked list? A tree structure? A DAG?
- If we know that
  1. `p` points to a (binary) tree structure, and
  2. the program contains a call `Q(p)`, and
  3. `Q` doesn't alter `p`

  then we can parallelize the call to `Q`, running (say) `Q(p^.left)` and `Q(p^.right)` on different processors. If `p` instead turns out to point to a general graph structure, then this parallelization will not work.

Shape Analysis II

- Shape analysis requires alias analysis. Hence, all algorithms are approximate.

Ghiya'96a	Accurate for programs that build simple data structures (trees, arrays of trees). Cannot handle major structural changes to the data structure.
Chase'90	Problems with destructive updates. Handles *list append*, but not *in-place list reversal*.
Hendren'90	Cannot handle cyclic structures.
various	Only handle recursive structures no more than k levels deep.
Deutsch'94	Powerful, but large (8000 lines of ML) and slow (30 seconds to analyze a 50 line program).

Readings and References

- Appel, "Modern Compiler Implementation in {Java,C,ML}", pp. 402–407.
- The Dragon Book: pp. 648–652.
- Further readings:
  - Shape analysis: Rakesh Ghiya, "Practical Techniques for Interprocedural Heap Analysis", PhD Thesis, McGill Univ, Jan 1996.
  - Complexity Results: Bill Landi, "Interprocedural Aliasing in the Presence of Pointers", PhD Thesis, Rutgers, Jan 1992.

Summary

- We should track aliases across procedure calls. This is *inter-procedural alias analysis*. See the Dragon book, pp. 655–660.
- Why is aliasing difficult? A program that has recursive data structures can have an infinite number of objects which can alias each other. Any aliasing algorithm must use a finite representation of all possible objects.
- Many (all?) static analysis techniques require alias analysis. Much use in software engineering, e.g. in the analysis of legacy programs.
- Pure functional languages don't need alias analysis!