Interprocedural Analysis part 2; pointer analysis part 1

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15-819O: Program Analysis

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Context-sensitive analysis

- Analyze a function multiple times, differentiating by call site.
  - **Too bad we allow recursive functions!**
- Build a summary: map input to output info, and analyze each function once per context.
  - Different definitions of context give different tradeoffs.
  - Option 1: input dataflow information.
  - Option 2: call strings

Graph reachability: two sentence summary

- It is possible to encode a certain set of dataflow analysis problems in a way that lets you solve them interprocedurally in polynomial time.
- And the problem representation is compact!

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Meet over realizable paths

- Before, collecting dataflow facts that hold at a node by taking the **meet over all paths** (MOP)
- Instead, consider the **meet over all realizable paths** (MRP)
  - …Which is still sound, but more precise.
- This is good, because it means that many analyses can be treated as context-free language reachability problems over directed graphs.

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Interprocedural finite distributive subset (IFDS) problems

- Interprocedural dataflow analysis with:
  - Finite set of data flow facts
  - Distributive dataflow functions ($f(a \sqcap b) = f(a) \sqcap f(b)$)
- Can convert any IFDS problem as a CFL-graph reachability problem, and find the MRP solution with no loss of precision
  - May be some loss of precision phrasing problem as IFDS

Instance of an IFDS problem

- G* is a supergraph
- D is a finite set of dataflow facts
- $F \subseteq 2^D \rightarrow 2^D$ is a set of distributive functions
- $M : E^* \rightarrow F$ is a map from G^*'s edges to dataflow functions
- meet is either union or intersection (assume it's just join; trust me)

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Or…

- Interprocedural dataflow analysis with
  - Finite set of dataflow facts
  - Distributive dataflow functions ($f(a \sqcup b) = f(a) \sqcup f(b)$)
  - For example?
  - But not?

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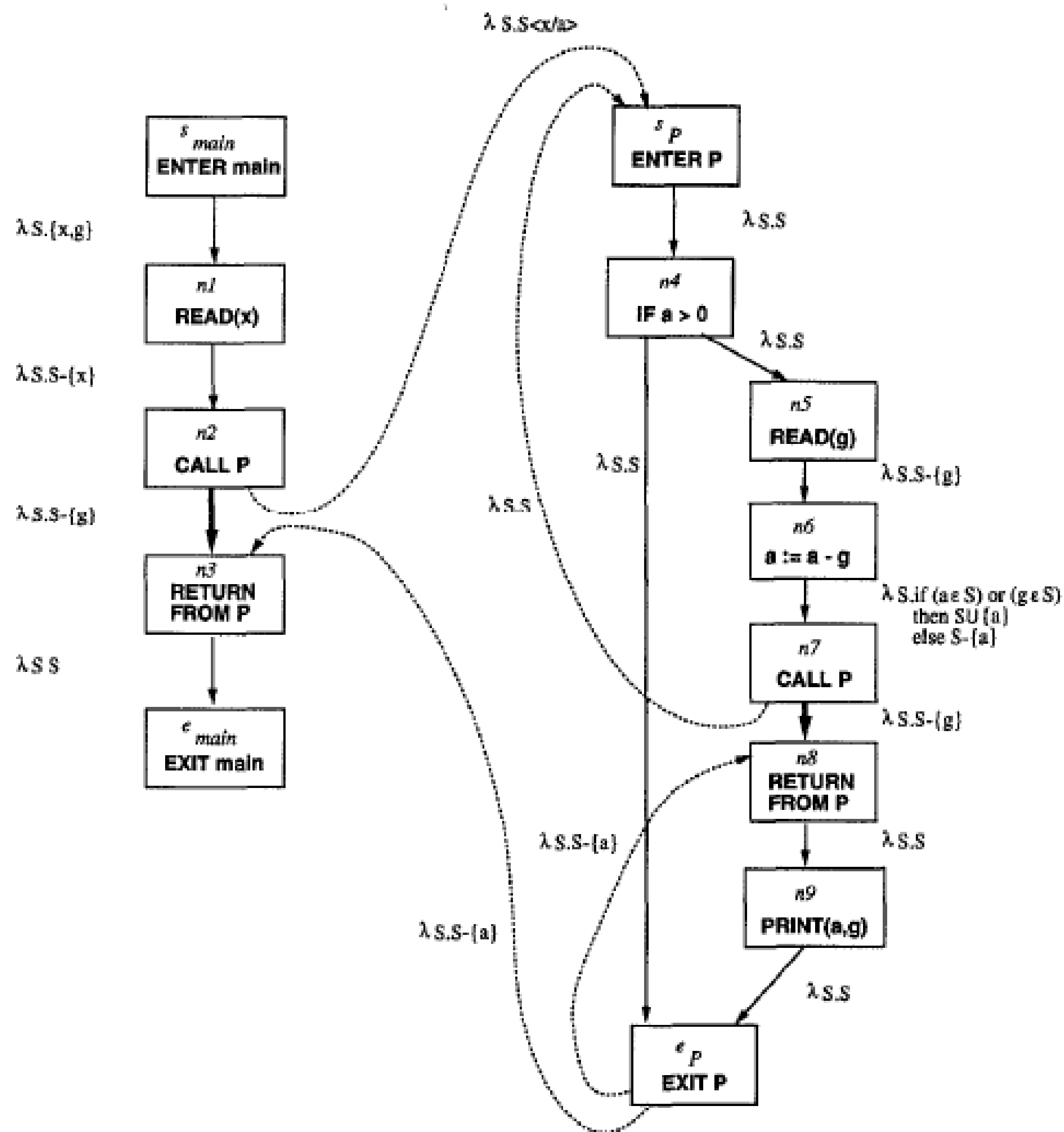
```
declare g: integer

program main
begin
  declare x: integer
  read(x)
  call P (x)
end


procedure P (value a : integer)
begin
  if (a > 0) then
    read(g)
    a := a − g
    call P (a)
    print(a, g)
  fi
end
```

(a) Example program



(b) Its supergraph G^*

Valid/Realizable paths

- Grammar that represents balanced calls/returns.
- matched ::= “” | e
  | matched matched
  | $(_i$ matched $)_i$
- Grammar of partially balanced parents is the same, without the second $)_i$

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Solution to IFDS problems

- MVP solution: meet-over-all-valid paths solution

$$MVP_n = \bigsqcap_{q \in \mathrm{IVP}(s_{main},\, n)} pf_q(\top) \qquad \text{for each } n \in N^*.$$

- Don't look at the formula – Intuitively it means "union of all solutions from initial state to node n"
- Example: Possibly uninitialized variables problem

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On the board!

FUNCTIONS AS RELATIONS

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Converting it into a graph reachability problem

- Represent functions as relations:

$$R_f =_{df} \{(\mathbf{0}, \mathbf{0})\} \cup \{(\mathbf{0}, y) \mid y \in f(\emptyset)\} \cup \{(x, y) \mid y \in f(\{x\}) \text{ and } y \notin f(\emptyset)\}.$$

Example. The following table shows three functions and their representation relations:

id: $2^{\{a,b\}} \to 2^{\{a,b\}}$ id = $\lambda S.S$	a: $2^{\{a,b\}} \to 2^{\{a,b\}}$ a = $\lambda S.\{a\}$	f: $2^{\{a,b,c\}} \to 2^{\{a,b,c\}}$ f = $\lambda S.(S - \{a\}) \cup \{b\}$
0 a b 0 a b	0 a b 0 a b	0 a b c 0 a b c

- Composition of two relations relates to the compositions of two functions

$$\text{For all } f, g \in 2^D \to 2^D, [\![R_f ; R_g]\!] = g \circ f.$$

- Using this property, we define exploded supergraph.

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Exploded supergraph

- Let G^* be supergraph (i.e., interprocedural CFP)
- For each node $n \in G^*$, there is node $\langle n,\Lambda\rangle \in G\#$
- For each node $n \in G^*$, and $d \in D$ there is node $\langle n,d\rangle \in G\#$
- For function f associated with edge $a \rightarrow b \in G^*$
  - Edge $\langle a,\Lambda\rangle \rightarrow \langle b,d\rangle$ for every $d \in f(\emptyset)$
  - Edge $\langle a, d1\rangle \rightarrow \langle b,d2\rangle$ for every $d2 \in f(\{d2\})$ - $f(\emptyset)$
  - Edge $\langle a,\Lambda\rangle \rightarrow \langle b, \Lambda\rangle$

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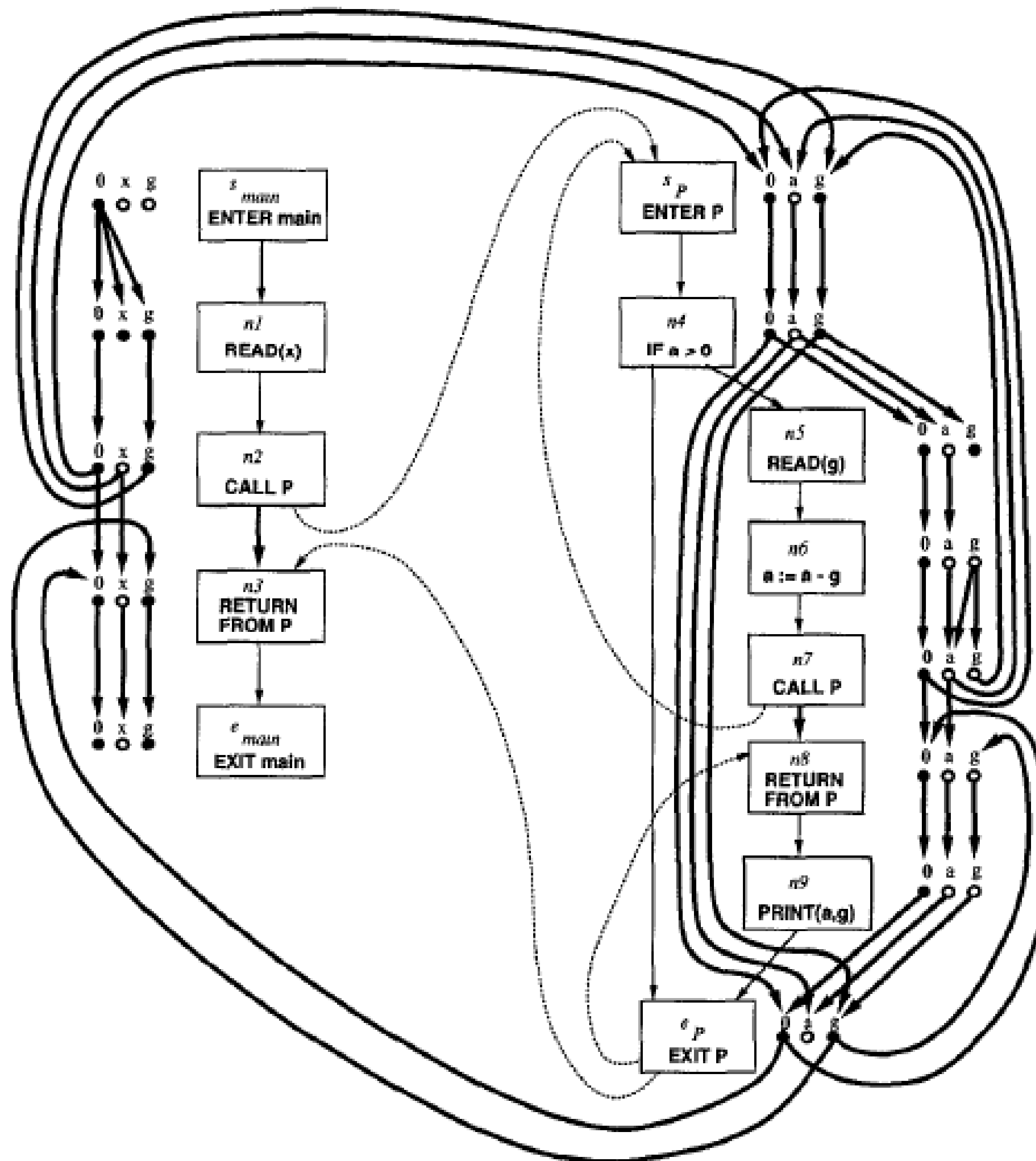

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CFL

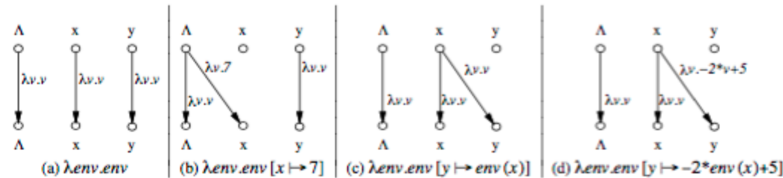
- If L is a CF language over an alphabet, and G a graph with edges from that alphabet.
- Each path in G is a word over the alphabet
- A path is an L-path if it its word is in L
- Reachability problems:
  - All-pairs L-path problem: all pairs of nodes such that there is an L path between them
  - Single-source/target L-path problem: all nodes n_2 such that there is an L-path from a given node n_1 to n_2 (or vice versa).
  - Single source single-target: is there an L-path between two given nodes?
- Why? All CFL reachability problems can be solved in time cubic in the nodes of the graph.

High points of algorithm

- Worklist algorithm.
- Computes summary edges that capture the partial effects of functions on datflow information.
- Tabulation algorithm in paper is a dynamic programming approach.

Interprocedural Distributive Environment (IDE) problems

- Interprocedural dataflow analysis with:
  - Dataflow info at program point represented as a finite **environment** (i.e., mapping from variables/locations to finite height domain of values)
  - Transfer function distributive "environment transformer":



- E.g., copy constant propagation
  - interprets assignment statements such as x=7 and y=x
- E.g. linear constant propagation
  - also interprets assignment statements such as y = 5*z + 9

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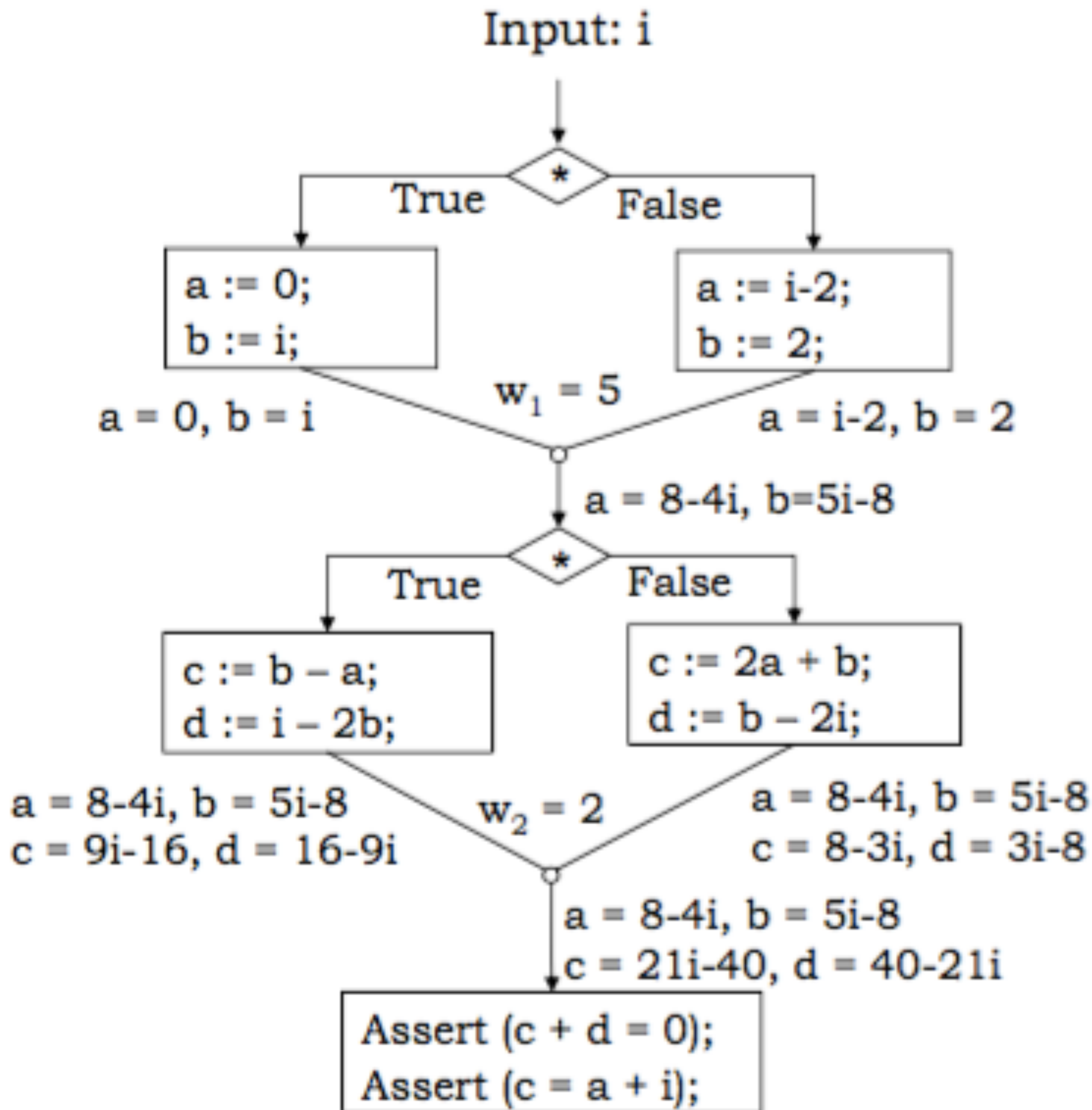
Solving

- First pass computes **jump functions** and **summary functions**
  - Summaries of paths within a procedure and of procedure calls, respectively
- Second pass uses these functions to compute environments at program points
- More details in “Precise Interprocedural Dataflow Analysis with Applications to Constant Propagation” by Sagiv, Reps, and Horwitz, 1996.

RANDOM INTERPRETATION?



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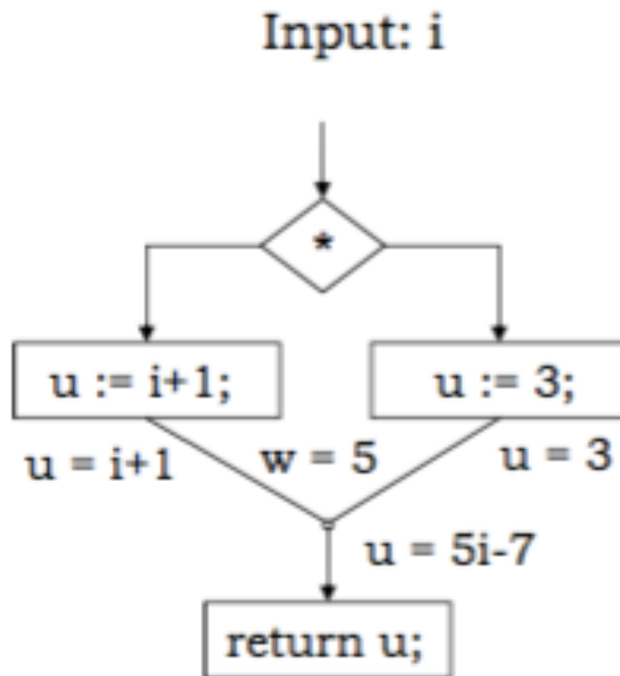

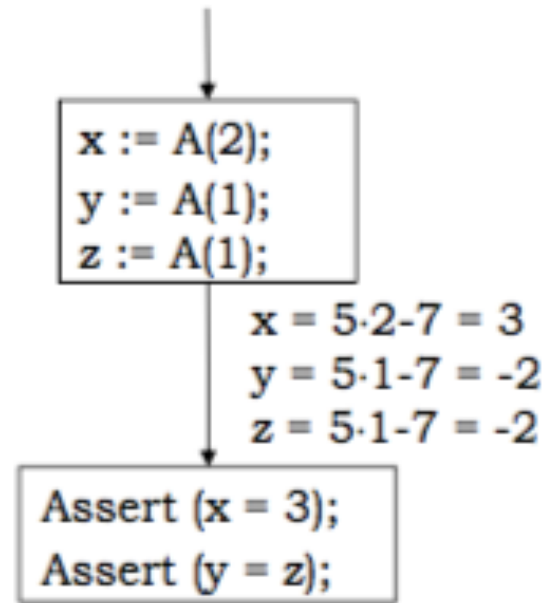

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Pointer (or points-to) analysis

```
I ::= ...
    | p := & x
    | p := q
    | *p := q
    | p := *q
```


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What memory locations can a pointer expression refer to?

- Alias analysis: When do two pointer expressions refer to the same storage location?
  1. int x;
  2. p = &x;
  3. q = p;
- *p and *q alias, as do x and *p, and x and *q

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Why do we want to know?

- Pointer analysis tells us what memory locations code uses or modifies, and is useful in many other analyses:
  - Available expressions: *p = a + b; y = a + b;
    - If *p aliases a or b, then second computation of a +b is not redundant
  - Constant propagation: x = 3; *p = 4; y = x;
    - Is y constant?
      - If *p and x do not alias each other, then yes.
      - If *p and x always alias each other, then yes.
      - If *p and x sometimes alias each other, then no.

Aliasing can arise due to

- Pointers, e.g., int *p, i; p = &i;
- Call-by-reference

  void m(Object a, Object b) { … }

  m(x,x); // a and b alias in body of m

  m(x,y); // y and b alias in body of m
- Array indexing:

  int i,j,a[100];

  i = j; // a[i] and a[j] alias

Many approaches to this

- Pointer/alias analysis had a major boom in research interest.
- Two “big names”/approaches to know: Andersen and Steensgaard.

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Dimensions of pointer analysis

- Intraprocedural / interprocedural
- Flow-sensitive / flow-insensitive
- Context-sensitive / context-insensitive
- Definiteness
- May versus must
- Heap modeling
- Representation

Flow-sensitive vs flow-insensitive

- Flow-sensitive: computes for each program point what memory locations pointer expressions may refer to.
  - Traditionally too expensive to perform for whole program.
- Flow-insensitive: computes what memory locations pointer expressions may refer to, at any time in program execution.
  - Typically used for whole program analyses.

Flow sensitive analysis is *hard*

Alias Mechanism	Intraprocedural May Alias	Intraprocedural Must Alias	Interprocedural May Alias	Interprocedural Must Alias
Reference Formals, No Pointers, No Structures	–	–	Polynomial[1, 5]	Polynomial[1, 5]
Single level pointers, No Reference Formals, No Structures	Polynomial	Polynomial	Polynomial	Polynomial
Single level pointers, Reference Formals, No Pointer Reference Formals, No Structures	–	–	Polynomial	Polynomial
Multiple level pointers, No Reference Formals, No Structures	$\mathcal{NP}$-hard	Complement is $\mathcal{NP}$-hard	$\mathcal{NP}$-hard	Complement is $\mathcal{NP}$-hard
Single level pointers, Pointer Reference Formals, No Structures	–	–	$\mathcal{NP}$-hard	Complement is $\mathcal{NP}$-hard
Single level pointers, Structures, No Reference Formals	$\mathcal{NP}$-hard[14]	Complement is $\mathcal{NP}$-hard	$\mathcal{NP}$-hard[14]	Complement is $\mathcal{NP}$-hard

Table 1: Alias problem decomposition and classification

Pointer-inducing aliasing: A Problem Classification, Landi and Ryder, POPL 1990

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Context sensitivity

- Also difficult, but success in scaling up to hundreds of thousands LOC
- BDDs, see Whaley and Lam PLDI 2004
  Doop, Bravenboer and Smaragdakis OOPSLA 2009

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Definiteness

- *May* analysis: aliasing that may occur during execution
  - (cf. must-not alias, although often has different representation)
- *Must* analysis: aliasing that must occur during execution
- Sometimes both are useful: consider liveness analysis for *p = *q + 4;
  - If *p must alias x, then x in kill set for statement
  - If *q may alias y, then y in gen set for statement

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May vs must analysis

```
1. z := 1
2. if cond
3.       p := y
4. else
5.       p = &z;
6. *p := 2
7. print z
```


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Possible representations

- Points-to pairs: first element points to the second
  - e.g., (p → b), (q → b)
  - *p and b alias, as do *q and b, as do *p and *q
- Pairs that refer to the same memory
  - e.g., (*p,b), (*q,b), (*p,*q), (**r, b)
  - General, may be less concise than points-to pairs
- Equivalence sets: sets that are aliases
  - e.g., {*p,*q,b}

Problem statement

- Consider flow-insensitive may pointer analysis
- Assume pointers $p,q \in P$ and address-taken variables $a,b \in A$ are disjoint
  - Can transform program to make this true: For any variable v for which this isn't true, add statement pv = &av, replace v with *pv
- Want to compute relation $pts : P \cup A \rightarrow 2^A$
  - Essentially *points to* pairs

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Andersen-style pointer analysis

- View pointer assignments as *subset constraints*
- Use constraints to propagate points-to information, solve them:

- p = &a;
- q = p;
- p = &b;
- r = p;

- $p \supseteq \{a\}$
- $q \supseteq p$
- $p \supseteq \{b\}$
- $r \supseteq p$

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