CS 526

Advanced
Compiler
Construction

http://misailo.cs.Illinois.edu/courses/cs526

POINTER ANALYSIS

The slides adapted from Vikram Adve

Course

So far:

- Dataflow analysis (examples and theory)
- Dependency analysis
- SSA (applied dataflow analysis)

Coming up next:

- Pointer analysis (generalize the dependence relationship)
- Abstract interpretation (generalize dataflow analysis)
- Interprocedural analysis (how to analyze function calls?)
- Fun topics (probabilistic, validation, …)

POINTER ANALYSIS

The slides adapted from Vikram Adve

Pointer Analysis

Pointer and Alias Analysis are fundamental to reasoning about heap manipulating programs (pretty much all programs today).

- **Pointer Analysis:**
  - What objects does each pointer points to?
  - Also called points-to analysis
- **Alias Analysis:**
  - Can two pointers point to the same location?
  - Client of pointer analysis

Example

```
X = 1
P = &X
*P = 2
return X

// What is the value of X?
```

Aliases

Consider references r1 or r2,

- may be of the form "x" or "*p" "**p", "(*p)->q->i"…
- We assume C notation for dereferencing pointers (*, ->)

Alias: r1 are r2 are aliased if the memory locations accessed by r1 and r2 overlap.

Alias Relation: A set of ordered pairs {(ri, rj)} denoting aliases that ***may hold*** at a particular point in a program.

- Sometimes called a ***may-alias*** relation.

May or Must: A kind of aliasing if it happens optionally or always

- May: e.g., depending on the control flow: `if (b) { p = &q; }`
- Must: determined that they always represents aliases

Aliases

We look at the language that extends the simple expressions with the additional pointer-like structures:

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

Consider references r1 or r2,

- may be of the form "x" or "*p" "**p", "(*p)->q->i"…
- We assume C notation for dereferencing pointers (*, ->)

Example

X = 1

P = &X

Q = P

*P = 2

Alias: r1 are r2 are aliased if the memory locations accessed by r1 and r2 overlap.

Example

Aliasing pairs

X = 1

P = &X

// (*P, X)

Q = P

// { (*P, X), (*Q, X) }

*P = 2

Points-To Facts

Points-to Pair: pair (r1, r2) denoting that one of the memory locations of r1 may hold the address of one of the memory locations of r2.

- Also written: r1 → r2, means "r1 points to r2".

Points-to Set: {(ri, rj)} : A set of points-to pairs that may hold at a particular point in a program.

Points-To Graph: A directed graph where

- ***Nodes*** represents one or more memory objects;
- Each *Edge* p → q means some object in the node p may hold a pointer to some object in the node q.

Points-to Pair: pair (r1, r2) denoting that one of the memory locations of r1 An ordered may hold the address of one of the memory locations of r2.

Example

Points-to pairs

```
X = 1
P = &X      // (P, X)
Q = P       // { (P, X), (Q, X) }
*P = 2
```

Challenges of Points-To Analysis

- **Pointers to pointers**, which can occur in many ways: take address of pointer; pointer to structure containing pointer; pass a pointer to a procedure by reference
- **Aggregate objects**: structures and arrays containing pointers
- **Recursive data structures** (lists, trees, graphs, etc.) closely related problem: anonymous heap locations
- **Control-flow:** analyzing different data paths
- **Interprocedural:** a location is often accessed from multiple functions; a common pattern (e.g., pass by reference)
- Compile-time cost
    - Number of variables, $|V|$, can be large
    - Number of alias pairs at a point can be $O(|V|^2)$

Common Simplifying Assumptions

Aggregate objects: arrays (and perhaps structures) containing pointers

Simple solution: Treat as a single big object!

- Commonplace for arrays.
- Not a good choice for structures?
    - *See Intel Paper (Ghiya, Lavery & Sehr, PLDI 2001)*
- Pointer arithmetic is only legal for traversing an array:

q = p ± i and q = &p[i] are handled the same as q = p

Common Simplifying Assumptions

Recursive data structures (lists, trees, graphs, …)

Solution: Compute aliases, not "shape"

- Don't prove something is a linked-list or a binary tree (leave that for ***shape analysis***)
- ***k-limiting:*** only track k or fewer levels of dereferencing
- Use simplified naming schemes for heap objects (later slide)

Common Simplifying Assumptions

Control-flow: analyzing different data paths blows up the analysis time/space

Solution(?): Could ignore the issue and compute a single common result for any path!

No consensus on this issue! (Will discuss later)

Naming Schemes for Heap Objects

The Naming Problem: Example 1

```
int main() {
   // Two distinct objects
   T* p = create(n);
   T* q = create(m);
}

T* create(int num) {
   // Many objects allocated here
   return new T(num);
}
```

Q. Should we try to distinguish the objects created in main()?

Naming Schemes for Heap Objects

The Naming Problem: Example 2

```
T* makelist(int len) {
  T* newObj = new T; // Many distinct objects
                     // allocated here
  newObj->next = (--len == 0)? NULL :
                               makelist(len);
}
```

Q. Can we distinguish the objects created in makelist()?

Possible Naming Abstractions

H_0 : One name for the entire heap

H_T : One name per type T (for type-safe languages)

H_L : One name per heap allocation site L (line number)

H_C : One name per (acyclic) call path C ("*cloning*")

H_F : One name per immediate caller F or call-site ("*one-level cloning*")

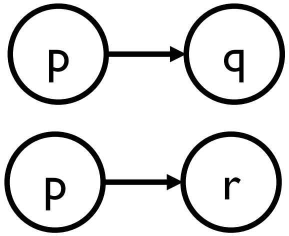
Flow-sensitivity of Analysis

Def. A *flow-sensitive analysis* is one that computes a distinct result for each program point. A *flow-insensitive analysis* generally computes a single result for an entire procedure or an entire program.

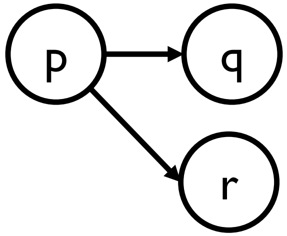
A flow-insensitive algorithm effectively <u>ignores</u> the order of statements!

```
int f(T q, T r){
  T* p;
  …
  p = &q;
  …
  p = &r;
}
```

Flow Sensitive



Flow Insensitive



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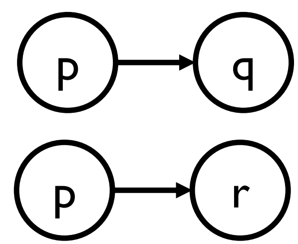
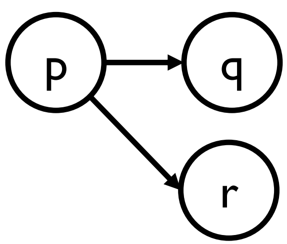
```
int f(T q, T r){
  T* p;
  if (...)
     p = &q;
  else
     p = &r;
}
```

Flow Sensitive



Flow Insensitive



Flow-Sensitivity of Analysis

Pointer Analysis

- **Flow-sensitive** : At program point n, compute alias pairs <a, b> that may hold at n for some path from program entry to n.
- **Flow-insensitive** : Compute all alias pairs <a, b> such that a may be aliased to b at *some* point in a program (or function).

Important special cases

- Local scalar variables: SSA form gives flow-sensitivity
- Malloc or new: Allocates "fresh" memory, i.e., no aliases
- Read-only fields: e.g., array length

Realizable Paths

Definition: Realizable Path

A program path is realizable iff every procedure call on the path returns control to the point where it was called (or to a legal exception handler or program exit)

Whole-program Control Flow Graph?

Conceptually extend CFG to span whole program:

- split a call node in CFG into two nodes: CALL and RETURN
- add edge from CALL to ENTRY node of each callee
- add edge from EXIT node of each callee to RETURN

Problem: This produces many unrealizable paths

Focusing only on realizable paths requires context-sensitive analysis

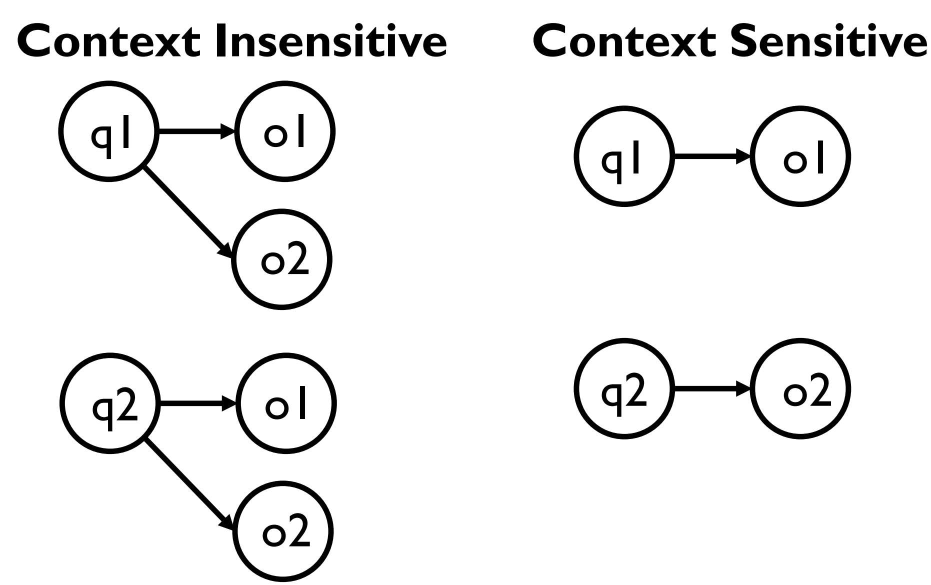
Context-Sensitivity of Analysis

Def. A context-sensitive interprocedural analysis computes results that may hold only for realizable paths through the program. Otherwise, the analysis is context-insensitive.

```
T* identity(T* p) {
  return p;
}

void f1() {
  T* p1 = new T; // Object o1
  T* q1 = identity(p1);
}

void f2() {
  T* p2 = new T; // Object o2
  T* q2 = identity(p2);
}
```



Context-Sensitivity of Analysis

Pointer Analysis

Apply the definitions directly using points-to pairs <a, b>.

But important variations exist:

- Heap cloning vs. no cloning: Cloning gives greater context-sensitivity
- Bottom-up vs. top-down: Does final result for a procedure include only "realizable" behavior from all contexts?
- Handling of recursive functions: Does analysis retain context-sensitivity within SCCs in the call graph?

Object Sensitivity: Context represents each allocation site. Typically offers quite precise context analysis

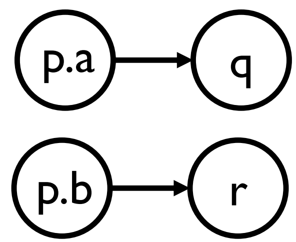
[Parameterized Object Sensitivity for Points-to and Side-Effect Analyses for Java; Milanova et al. ISSTA 2002]

Field-Sensitivity of Analysis

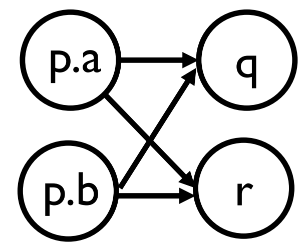
Def. A field-sensitive analysis is one that tracks distinct behavior for individual fields of a record type. Otherwise, it is field-insensitive

```
int f(T q, T r) {
  p.a = &q;
  p.b = &r;
}
```

Field Sensitive



Field Insensitive



Challenges

- Complexity: For certain analysis techniques, converts linear representation to worse (perhaps even exponential)
- Non-type-safe programs: May have to track behavior at every byte offset within the structure (not just each field)

Flow Insensitive Algorithms

3 popular algorithms

- Any address
- Andersen, 1994
- Steensgard, 1996

Acceptable precision in practice for compiler optimization, however perhaps insufficient for static analysis approaches for security, reliability, or bug finding

Any Address Analysis

- ***Single points-to set***: contains all variables whose address is taken, passed by reference, etc.

- ***Any pointer*** **may point** to ***any variable*** in this set

- Simple, fast, linear-time algorithm

- Common choice for function pointers, and for global variables, e.g., for initial call graph

Example 1

```
void main() {
    T *p, *q, *r;
    T t;

o1:p = new T;           // {p} -> {o1}
    q = &t;             // {p,q} -> {o1, t}
    r = q;              // {p,q,r} -> {o1, t}
}
```

Example 2 (Interprocedural)

```
T *p, *q, *r;

void main() {
   p = new T;
   g(&p);
   f();
   p = new T;
   . . . = *p;
}
```

```
void f() {
   q = new T;
   g(&q);
   r = new T;
}

void g(T** fp) {
   T* local = new T;
   if (. . .)
      *fp = local;
   . . .
}
```

Model argument passing and returns with assignment:

g(&p):
   fp = &p
   p = *fp

Andersen's Algorithm

- Generally the most precise flow- and context-insensitive algorithm
- Compute a single points-to graph for entire program
- Refinement by Burke: Separate points-to graph for each function
- Cost is $O(n^3)$ for program with n assignments
    - McAlister, On the complexity analysis of static analyses (SAS'99)
    - Sridharan and Fink, The Complexity of Andersen's Analysis in Practice (SAS'09)

Andersen's Algorithm: Conceptual

Initialize: Points-to graph with a separate node per variable

Iterate until convergence:

At each statement, evaluate the appropriate rule:

Form	**Action**
p = &x	Add $p \to x$
p = q	$\forall x$: if $q \to x$, add $p \to x$
*p = q	$\forall x, r$: if $q \to x$ and $p \to r$, add $r \to x$
p = *q	$\forall x, r$: if $q \to x$ and $x \to r$, add $p \to r$

Andersen's Algorithm: Actual

1. Build initial "inclusion constraint graph" and initial points-to sets
2. Iterate until converged:
   - Update constraint graph for new points-to pairs
   - Update the points-to sets according to new constraints

Inclusion Constraint Graph: Add constraint for pointer assignments (pts is points-to set):

Name	**Form**	**Constraint**	**Action**
Points-to pair	p = &x	$p \supseteq \{x\}$	pts(p) U= {x}
Direct constraint	p = q	$p \supseteq q$	pts(p) U= pts(q)
Indirect constraint	*p = q	$*p \supseteq q$	$\forall v \in pts(p)$. pts(v) U= pts(q)
Indirect constraint	p = *q	$p \supseteq *q$	$\forall v \in pts(q)$. pts(p) U= pts(v)

Andersen’s Algorithm: Cycles

Cycle in constraint graph:

$\mathrm{pts}(p) \supseteq \mathrm{pts}(q) \supseteq \mathrm{pts}(r) \supseteq \mathrm{pts}(p)$

$\Rightarrow \mathrm{pts}(p) = \mathrm{pts}(q) = \mathrm{pts}(r) = \mathrm{pts}(p)$

$\Rightarrow$ No need to propagate points-to pairs around such cycles!

Offline cycle elimination:

- Find cycles due to direct pointer copies (direct constraints)
- Collapse each cycle into a single node, reduces size of constraint graph
- But many more cycles can be induced by indirect constraint edges: we need cycle elimination during transitive closure ("*online*“)

“Off-line Variable Substitution for Scaling Points-To Analysis,” Rountev and Chandra, PLDI’00.

Online cycle elimination:

- Fähndrich, Foster, Aiken and Su (PLDI ’98): Cycle elimination is essential for scalability.
- Heintze and Tardieu (PLDI 2001): "A million lines of code per second."
- Hardekopf and Lin (PLDI 2007)

Steensgard's Algorithm

Unification:

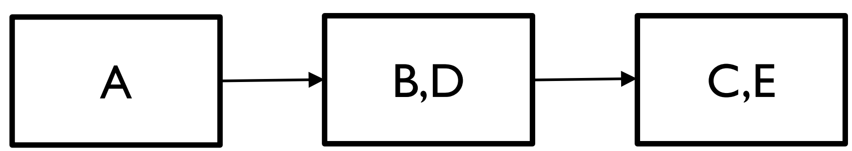
- Conceptually: restrict every node to only one outgoing edge (on the fly)
- If p $\rightarrow$ x and p $\rightarrow$ y, merge x and y ("unify")
- All objects "pointed to" by p comprise a single equivalence class

A = &B

B = &C

A = &D

D = &E



Steensgard's Algorithm

Unification: Conceptually: restrict ***every node to only one outgoing edge*** (on the fly)

- If $p \rightarrow x$ and $p \rightarrow y$, merge x and y ("unify")
- All objects "pointed to" by p comprise a single equivalence class

Algorithm

1. For each statement, merge points-to sets:
   p = q: Merge two equivalence classes (targets of p and of q)
   Instead of computing points-to iterations – less expensive
   This may cause other nodes to collapse!
2. Use Tarjan's "union-find" data structure to record equivalence classes (addition and merge of sets in near constant time, i.e. $\alpha(n, n)$)

Non-iterative algorithm, almost-linear running time: $O(n\alpha(n, n))$
Like Anderson, single solution for entire program

Steensgard vs. Anderson

Consider assignment p = q, i.e., only p is modified, not q

Subset-based Algorithms (Anderson's algorithm is an example)

- Add a constraint: Targets of q must be subset of targets of p
- Graph of such constraints is also called "inclusion constraint graphs"
- Enforces unidirectional flow from q to p

Unification-based Algorithms (Steensgard is an example)

- Merge equivalence classes: targets of p and q must be identical
- Assumes bidirectional flow from q to p and vice-versa

In-between solutions:

- Unification-based Pointer Analysis with Directional Assignment, Das, PLDI 2000 – exploits the semantics of C; uses Andersen for top pointers, Steensgard elsewhere

Alias Analysis

- Alias analysis is a common client of pointer (points-to) analysis
  - **Pointer Analysis:** What objects does each pointer points to?
  - **Alias Analysis:** Can two pointers point to the same location?
- Once we have performed the pointer analysis, it is trivial to compute alias analysis (but not vice versa)

- **Two pointers p and q may alias if points-to(p) $\cap$ points-to(q) $\neq \emptyset$**

Which Pointer Analysis To Use?

Hind & Pioli, ISSTA, Aug. 2000

Compared 5 algorithms (4 flow-insensitive, 1 flow-sensitive):

- Any address
- Steensgard
- Anderson
- Burke (like Anderson, but separate solution per procedure)
- Choi et al. (flow-sensitive)

Metrics

1. Precision: number of alias pairs
2. Precision of important optimizations: MOD/REF, REACH, LIVE, flow dependences, constant prop.
3. Efficiency: analysis time/memory, optimization time/memory

Benchmarks: 23 C programs, including some from SPEC benchmarks

Which Pointer Analysis To Use?

1. **Precision:** (Table 2)
   - Steensgard much better than Any-Address (6x on average)
   - Anderson/Burke significantly better than Steensgard (about 2x)
   - Choi negligibly better than Anderson/Burke
2. **MOD/REF precision:** (Table 2)
   - Steensgard much better than Any-Address (2.5x on average)
   - Anderson/Burke significantly better than Steensgard (15%)
   - Choi very slightly better than Anderson/Burke (1%)
3. **Analysis cost:** (Table 5)
   - Any-Address, Steensgard extremely fast
   - Anderson/Burke about 30x slower
   - Choi about 2.5x slower than Anderson/Burke
4. **Total cost of analysis + optimizations:** (Table 5)
   - Steensgard, Burke are 15% faster than Any-Address!
   - Anderson is as fast as Any-Address!
   - Choi only about 9% slower

Analysis Scalability

	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

Derek Rayside, Points-To Analysis (Summary), 2005
https://www.cs.utexas.edu/~pingali/CS395T/2012sp/lectures/points-to.pdf

More recent: Flow-Sensitive Pointer Analysis for Millions of Lines of Code
Hardekopf and Lin (CGO'11)

Advanced Techniques

- **Shape Analysis**: discovers and reasons about dynamically allocated data structures (e.g., lists, trees, heaps)

- **Escape Analysis:** computes which program locations can access a pointer (across function boundaries)

- **Datalog:** Declarative, constraint-based approach to specify analysis, offers pretty good scalability

  Pointer Analysis; Yannis Smaragdakis; George Balatsouras, Now Publishing, 2015

Datalog

Datalog: declarative language with Prolog-like notation

Elements: ***atoms*** of the form p(X1, X2, … Xn)

- p is a predicate
- X1, X2, … Xn are variables or constants

Ground atoms: predicate with only constant arguments

- Its value is either true or false

Rules: H :- B1 & B2 & … & Bn

- H is an ***atom***, B1…Bn are ***atoms*** or ***negations*** of atoms
- :- is "if" --- so H is valid if all B1…Bn are valid

Datalog program is a collection of rules. The program is applied to a set of ground atoms. The result is the set of ground atoms inferred by applying the rules until fixpoint

Datalog Example

Simple Datalog program (from Dragon book):

path(X,Y) :- edge (X,Y)

path(X,Y) :- path (X,Z) & path (Z,Y)

The meaning of the program: A single edge is a path; a path also exist if there is a path between the start point and some other point, and that other point and the end point.

Consider this example:

- True ground atoms: edge(1,2), edge(2,3), edge(3,4)
- Infer path(1,2), path(2,3), path(3,4) using rule #1
- Infer composite paths using successive application of rule #2

Flow-Insensitive Pointer Analysis

(Dragonbook) Compute:

- **Pts**(V, H) – the variable V can point to heap object H
- **Hpts**(H, F, G) – field F of heap object H points to heap object G

Rules constructed by traversing the program:

1. **Pts(V, H) :- "H: V = malloc"**

   V points to heap loc H if it is allocated at H (say we use line number calling)

2. **Pts(V, H) :- "V = W" & Pts (W, H)**

   V points to H if V points to W and W points to H

3. **Hpts(H,F,G) :- "V.F = W" & Pts(W, G) & Pts(V,H)**

   In stmt V.F=W, field F of object H points to object G if ptr W points to G and ptr V points to H

4. **Pts(V, H) :- "V = W.F" & Pts(W, G) & Hpts(G, F, H)**

   In stmt V=W.F, V points to H if W points to G and field F of G points to H

Context-Sensitive Pointer Analysis

First compute:

- **Pts**(V, C, H) – the variable V in context C can point to heap object H
- **Hpts**(H, F, G) – field F of heap object H points to heap object G
- **CSinvokes**(S, C, M, D) – the calls site S in context C calls the D context of M

Rules constructed by traversing the program:

1. **Pts(V, C, H) :- "H: V = malloc" & CSinvokes(H, C, _, _)**
2. **Pts(V, C, H) :- "V = W" & Pts (W, C, H)**
3. **Hpts(H,F,G) :- "V.F = W" & Pts(W, C, G) & Pts(V,C,H)**
4. **Pts(V, C, H) :- "V = W.F" & Pts(W, G) & Hpts(G, F, H)**
5. **Pts(V, D, H) :- CSinvokes(H, C, _, _) & formal(M,I,V) & actual(S,I,W) & pts(W,C,H)**

   If the call site S in context C calls method M of context D, then the formal parameters in method M of context D can point to the objects pointed to by the actual params in C