CS 526

Advanced
Compiler
Construction

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

POINTER ANALYSIS

The slides adapted from Vikram Adve

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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"…

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

Points-To Facts

Points-to Pair: An ordered 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 each *Node* represents one or more memory objects; an *Edge*: p → q means some object in node p may hold a pointer to some object in node q.

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:

$q = p \pm i$ 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*")

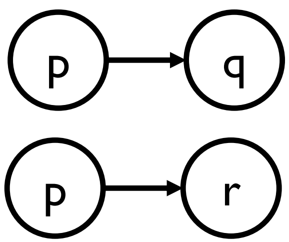
Flow-sensitivity of Analysis

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.

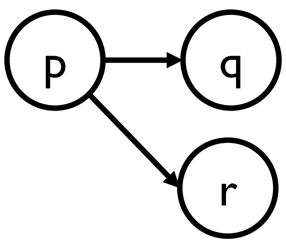
A flow-insensitive algorithm effectively ignores the order of statements!

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

Flow Sensitive



Flow Insensitive



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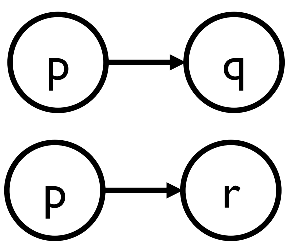
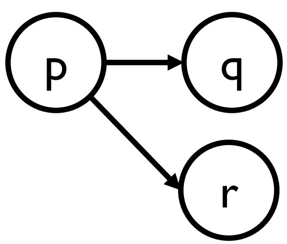
```
int f(T q, T r){
  T* p;
  if (...)
     p = &q;
  else
     p = &r;
}
```

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

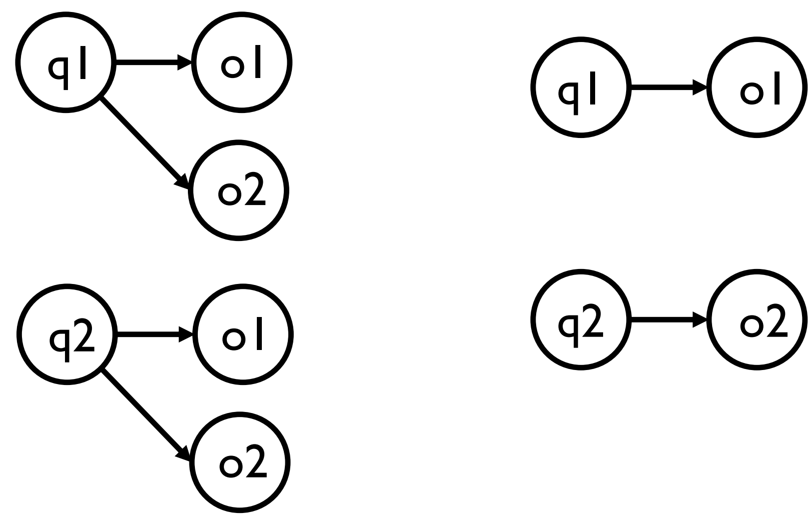
Def. A context-sensitive interprocedural analysis computes results that may hold only for realizable paths through a program. Otherwise, the analysis is context-insensitive.

```
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 Insensitive **Context Sensitive**



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

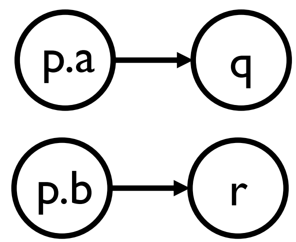
[Parameterized Object Sensitivity for Points-to and Side-Effect Analyses for Java; Milanova et al. ISSTA 2002]

Field-Sensitivity of Analysis

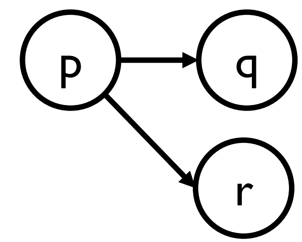
Def. A field-sensitive analysis is one that tracks distinct behavior for individual fields of a record type. Otherwise, it is field-insensitive

```
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 a 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: 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

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

void main() {
   p = new T;
   f();
   g(&p);
   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

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 $p \rightarrow x$
p = q	$\forall x$: if $q \rightarrow x$, add $p \rightarrow x$
*p = q	$\forall x, r$: if $q \rightarrow x$ and $p \rightarrow r$, add $r \rightarrow x$
p = *q	$\forall x, r$: if $q \rightarrow x$ and $x \rightarrow r$, add $p \rightarrow r$

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:

Name	**Form**	**Constraint**
Points-to pair	p = &x	$p \supseteq \{x\}$
Direct constraint	p = q	$p \supseteq q$
Indirect constraint	*p = q	$*p \supseteq q$
Indirect constraint	p = *q	$p \supseteq *q$

Andersen's Algorithm: Cycles

Cycle in constraint graph:

$\quad pts(p) \supseteq pts(q) \supseteq pts(r) \supseteq pts(p)$

$\Rightarrow pts(p) = pts(q) = pts(r) = pts(p)$

$\Rightarrow$ 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, significantly 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,"
Atanas Rountev and Satish Chandra, PLDI 2000.

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 are a single equivalence class

Algorithm

1. For each statement, merge points-to sets:
    - e.g., p = q: Merge two equivalence classes (targets of p and of q)
    - This may cause other nodes to collapse!
2. Use Tarjan's "union-find" data structure to record equivalence classes

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

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 pointer-analysis(p) ∩ pointer-analysis(q) ≠ ∅**

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

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

- Abstract Interpretation Formulation