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

\[ X = 1 \]
\[ P = &X \]
\[ *P = 2 \]
\[ \text{return } X \]

// 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 \((r_1, r_2)\) denoting that one of the memory locations of \(r_1\) may hold the address of one of the memory locations of \(r_2\).

- Also written: \(r_1 \rightarrow r_2\), means “\(r_1\) points to \(r_2\)”.

**Points-to Set:** \(\{(r_i, r_j)\}\) : 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*: \(p \rightarrow q\) 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:
  \[ q = p \pm i \text{ and } q = \&p[i] \text{ are handled the same as } q = p \]
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

```c
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!**

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

![Flow Sensitive Diagram](image)

![Flow Insensitive Diagram](image)
**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!**

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

![Flow Sensitive Diagram](image1)

![Flow Insensitive Diagram](image2)
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.

```cpp
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);
}
```

![Diagram showing context-sensitive and context-insensitive analysis](image-url)
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.

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

**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;
    . . .
}
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:

<table>
<thead>
<tr>
<th>Form</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p = &amp;x$</td>
<td>Add $p \rightarrow x$</td>
</tr>
<tr>
<td>$p = q$</td>
<td>$\forall x :$ if $q \rightarrow x$, add $p \rightarrow x$</td>
</tr>
<tr>
<td>$*p = q$</td>
<td>$\forall x, r :$ if $q \rightarrow x$ and $p \rightarrow r$, add $r \rightarrow x$</td>
</tr>
<tr>
<td>$p = *q$</td>
<td>$\forall x, r :$ if $q \rightarrow x$ and $x \rightarrow r$, add $p \rightarrow r$</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Name</th>
<th>Form</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points-to pair</td>
<td>p = &amp;x</td>
<td>p ⊇ {x}</td>
</tr>
<tr>
<td>Direct constraint</td>
<td>p = q</td>
<td>p ⊇ q</td>
</tr>
<tr>
<td>Indirect constraint</td>
<td>*p = q</td>
<td>*p ⊇ q</td>
</tr>
<tr>
<td>Indirect constraint</td>
<td>p = *q</td>
<td>p ⊇ *q</td>
</tr>
</tbody>
</table>
Andersen's Algorithm: Cycles

Cycle in constraint graph:
\[ \text{pts}(p) \supseteq \text{pts}(q) \supseteq \text{pts}(r) \supseteq \text{pts}(p) \]
\[ \Rightarrow \text{pts}(p) = \text{pts}(q) = \text{pts}(r) = \text{pts}(p) \]
\[ \Rightarrow \text{No need to propagate points-to pairs around such cycles!} \]

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
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 \( \text{pointer-analysis}(p) \cap \text{pointer-analysis}(q) \neq \emptyset \)
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

<table>
<thead>
<tr>
<th>Context-insensitive</th>
<th>Equality-based</th>
<th>Subset-based</th>
<th>Flow-sensitive</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1980: &lt; 1 KLOC</td>
<td>1994: 5 KLOC</td>
<td>1993: 30 KLOC</td>
</tr>
<tr>
<td></td>
<td>first paper on pointer analysis</td>
<td>1998: 60 KLOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Steensgaard [31]</td>
<td>• Fähndrich et al. [7]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1996: 1+ MLOC</td>
<td>1998: 60 KLOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>first scalable pointer analysis</td>
<td>2001: 1 MLOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Heintze and Tardieu [11]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2001: 1 MLOC</td>
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<tr>
<td></td>
<td></td>
<td>• Berndl et al. [2]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>2003: 500 KLOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>first to use BDDs</td>
<td></td>
</tr>
<tr>
<td>Context-sensitive</td>
<td>• Fähndrich et al. [8]</td>
<td>• Whaley and Lam [35]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000: 200K</td>
<td>2004: 600 KLOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>cloning-based BDDs</td>
<td></td>
</tr>
</tbody>
</table>

Derek Rayside, Points-To Analysis (Summary), 2005

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**