CSC D70: Compiler Optimization
Pointer Analysis

Prof. Gennady Pekhimenko
University of Toronto
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The content of this lecture is adapted from the lectures of Todd Mowry, Greg Steffan, and Phillip Gibbons
Outline

- Basics
- Design Options
- Pointer Analysis Algorithms
- Pointer Analysis Using BDDs
- Probabilistic Pointer Analysis
Pros and Cons of Pointers

• Many procedural languages have pointers
  – e.g., C or C++: int *p = &x;
• Pointers are powerful and convenient
  – can build arbitrary data structures
• Pointers can also hinder compiler optimization
  – hard to know where pointers are pointing
  – must be conservative in their presence
• Has inspired much research
  – analyses to decide where pointers are pointing
  – many options and trade-offs
  – open problem: a scalable accurate analysis
Pointer Analysis Basics: Aliases

• Two variables are **aliases** if:
  – they reference the same memory location

• More useful:
  – prove variables reference different location

```c
int x, y;
int *p = &x;
int *q = &y;
int *r = p;
int **s = &q;
```

**Alias Sets ?**
- `{x, *p, *r}
- `{y, *q, **s}
- `{q, *s}

p and q point to different locs

4
The Pointer Alias Analysis Problem

• Decide for every pair of pointers at every program point:
  – do they point to the same memory location?
• A difficult problem
  – shown to be undecidable by Landi, 1992
• Correctness:
  – report all pairs of pointers which do/may alias
• Ambiguous:
  – two pointers which may or may not alias
• Accuracy/Precision:
  – how few pairs of pointers are reported while remaining correct
  – i.e., reduce ambiguity to improve accuracy
Many Uses of Pointer Analysis

• **Basic compiler optimizations**
  – register allocation, CSE, dead code elimination, live variables, instruction scheduling, loop invariant code motion, redundant load/store elimination

• **Parallelization**
  – instruction-level parallelism
  – thread-level parallelism

• **Behavioral synthesis**
  – automatically converting C-code into gates

• **Error detection and program understanding**
  – memory leaks, wild pointers, security holes
Challenges for Pointer Analysis

• **Complexity**: huge in space and time
  – compare every pointer with every other pointer
  – at every program point
  – potentially considering all program paths to that point

• **Scalability vs. accuracy trade-off**
  – different analyses motivated for different purposes
  – many useful algorithms (adds to confusion)

• **Coding corner cases**
  – pointer arithmetic (*p++), casting, function pointers, long-jumps

• **Whole program?**
  – most algorithms require the entire program
  – library code? optimizing at link-time only?
Pointer Analysis: Design Options

- Representation
- Heap modeling
- Aggregate modeling
- Flow sensitivity
- Context sensitivity
Alias Representation

- **Track pointer aliases**
  - \(<*a, b>, <*a, e>, <b, e>\)
  - \(<**a, c>, <**a, d>, ...\)
  - More precise, less efficient

- **Track points-to info**
  - \(<a, b>, <b, c>, <b, d>, <e, c>, <e, d>\)
  - Less precise, more efficient
  - Why?

```c
a = &b;
b = &c;
b = &d;
e = b;
```
Heap Modeling Options

• Heap merged
  – i.e. “no heap modeling”

• Allocation site (any call to malloc/calloc)
  – Consider each to be a unique location
  – Doesn’t differentiate between multiple objects allocated by
    the same allocation site

• Shape analysis
  – Recognize linked lists, trees, DAGs, etc.
Aggregate Modeling Options

**Arrays**

Elements are treated as individual locations

or

Treat entire array as a single location

or

Treat first element separate from others

**Structures**

Elements are treated as individual locations ("field sensitive")

or

Treat entire structure as a single location

What are the tradeoffs?
Flow Sensitivity Options

• Flow insensitive
  – The order of statements doesn’t matter
    • Result of analysis is the same regardless of statement order
    – Uses a single global state to store results as they are computed
    – Not very accurate

• Flow sensitive
  – The order of the statements matter
  – Need a control flow graph
  – Must store results for each program point
  – Improves accuracy

• Path sensitive
  – Each path in a control flow graph is considered
Flow Sensitivity Example

(assuming allocation-site heap modeling)

Flow Insensitive

\[ a_{S7} \rightarrow \{\text{heapS1, heapS2, heapS4, heapS6}\} \]

(order doesn抰 matter, union of all possibilities)

Flow Sensitive

\[ a_{S7} \rightarrow \{\text{heapS2, heapS4, heapS6}\} \]

(in-order, doesn抰 know s5 & s6 are exclusive)

Path Sensitive

\[ a_{S7} \rightarrow \{\text{heapS2, heapS6}\} \]

(in-order, knows s5 & s6 are exclusive)

\[ S1: a = \text{malloc}(\ldots); \]
\[ S2: b = \text{malloc}(\ldots); \]
\[ S3: a = b; \]
\[ S4: a = \text{malloc}(\ldots); \]
\[ S5: \text{if}(c) \]
\[ \quad a = b; \]
\[ S6: \text{if}(!c) \]
\[ \quad a = \text{malloc}(\ldots); \]
\[ S7: \ldots = *a; \]
Context Sensitivity Options

- **Context insensitive/sensitive**
  - whether to consider different calling contexts
  - e.g., what are the possibilities for `p` at `S6`?

```c
int a, b, *p;
int main()
{
  S1: f();
  S2: p = &a;
  S3: g();
}

int f()
{
  S4: p = &b;
  S5: g();
}

int g()
{
  S6: ... = *p;
}
```

**Context Insensitive:**

- `p_{S6} => {a,b}`

**Context Sensitive:**

- Called from `S5`: `p_{S6} => {b}`
- Called from `S3`: `p_{S6} => {a}`
Pointer Alias Analysis Algorithms

References:

• “Points-to analysis in almost linear time”, Steensgaard, POPL 1996
• “Program Analysis and Specialization for the C Programming Language”, Andersen, Technical Report, 1994
• “Context-sensitive interprocedural points-to analysis in the presence of function pointers”, Emami et al., PLDI 1994
• “Pointer analysis: haven't we solved this problem yet?”, Hind, PASTE 2001
• “Which pointer analysis should I use?”, Hind et al., ISSTA 2000
• ...

• “Introspective analysis: context-sensitivity, across the board”, Smaragdakiset al., PLDI 2014
• “Sparse flow-sensitive pointer analysis for multithreaded programs”, Sui et al., CGO 2016
• “Symbolic range analysis of pointers”, Paisanteet al., CGO 2016
Address Taken

• Basic, fast, ultra-conservative algorithm
  – flow-insensitive, context-insensitive
  – often used in production compilers

• Algorithm:
  – Generate the set of all variables whose addresses are assigned to another variable.
  – Assume that any pointer can potentially point to any variable in that set.

• Complexity: $O(n)$ - linear in size of program

• Accuracy: very imprecise
Address Taken Example

T *p, *q, *r;

int main() {
    S1: p = alloc(T);
    f();
    g(&p);
    S4: p = alloc(T);
    S5: ... = *p;
}

void f() {
    S6: q = alloc(T);
    g(&q);
    S8: r = alloc(T);
}

g(T **fp) {
    T local;
    if(...) {
        S9: p = &local;
    }
}

\[ P_{S5} = \{ \text{heap}_S1, p, \text{heap}_S4, \text{heap}_S6, q, \text{heap}_S8, \text{local} \} \]
Andersen’s Algorithm

- Flow-insensitive, context-insensitive, iterative
- Representation:
  - one points-to graph for entire program
  - each node represents exactly one location
- For each statement, build the points-to graph:

<table>
<thead>
<tr>
<th>Statement</th>
<th>Points-to Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y = &amp; x )</td>
<td>( y ) points-to ( x )</td>
</tr>
<tr>
<td>( y = x )</td>
<td>if ( x ) points-to ( w ) then ( y ) points-to ( w )</td>
</tr>
<tr>
<td>( *y = x )</td>
<td>if ( y ) points-to ( z ) and ( x ) points-to ( w ) then ( z ) points-to ( w )</td>
</tr>
<tr>
<td>( y = *x )</td>
<td>if ( x ) points-to ( z ) and ( z ) points-to ( w ) then ( y ) points-to ( w )</td>
</tr>
</tbody>
</table>

- Iterate until graph no longer changes
- Worst case complexity: \( O(n^3) \), where \( n = \) program size
Andersen Example

```c
T *p, *q, *r;
int main() {
    S1: p = alloc(T);
        f();
        g(&p);
    S4: p = alloc(T);
    S5: ... = *p;
}

void f() {
    S6: q = alloc(T);
        g(&q);
    S8: r = alloc(T);
}

g(T **fp) {
    T local;
    if(...) s9: p = &local;
}
```

\[ \mathcal{P}_{S5} = \{ \text{heap}_S1, \text{heap}_S4, \text{local} \} \]
Steensgaard’s Algorithm

- Flow-insensitive, context-insensitive
- **Representation:**
  - a compact points-to graph for entire program
    - each node can represent multiple locations
    - but can only point to one other node
      - i.e. every node has a fan-out of 1 or 0
- **union-find** data structure implements fan-out
  - “unioning” while finding eliminates need to iterate
- **Worst case complexity:** $O(n)$
- **Precision:** less precise than Andersen’s
Steensgaard Example

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

int main() {
    S1: p = alloc(T);
        f();
        g(&p);
    S4: p = alloc(T);
    S5: ... = *p;
}

void f() {
    S6: q = alloc(T);
        g(&q);
    S8: r = alloc(T);
}

g(T **fp) {
    T local;
    if (...) 
        S9: p = &local;
}
```

\[ P_{S5} = \{ \text{heap}_S1, \text{heap}_S4, \text{heap}_S6, \text{local} \} \]
Example with Flow Sensitivity

T *p, *q, *r;

int main() {
    S1: p = alloc(T);
        f();
        g(&p);
    S4: p = alloc(T);
    S5: ... = *p;
}

void f() {
    S6: q = alloc(T);
        g(&q);
    S8: r = alloc(T);
}

g(T **fp) {
    T local;
        if(...) 
    s9:   p = &local;
}
Pointer Analysis Using BDDs

References:

• “Cloning-based context-sensitive pointer alias analysis using binary decision diagrams”, Whaley and Lam, PLDI 2004

• “Symbolic pointer analysis revisited”, Zhu and Calman, PDLI 2004

• “Points-to analysis using BDDs”, Berndl et al, PDLI 2003
Binary Decision Diagram (BDD)

Binary Decision Tree

Truth Table

<table>
<thead>
<tr>
<th>x1</th>
<th>x2</th>
<th>x3</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
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</tbody>
</table>

BDD
BDD-Based Pointer Analysis

• Use a BDD to represent transfer functions
  – encode procedure as a function of its calling context
  – compact and efficient representation
• Perform context-sensitive, inter-procedural analysis
  – similar to dataflow analysis
  – but across the procedure call graph
• Gives accurate results
  – and scales up to large programs
Probabilistic Pointer Analysis

References:
• “A Probabilistic Pointer Analysis for Speculative Optimizations”, DaSilva and Steffan, ASPLOS 2006
• “Compiler support for speculative multithreading architecture with probabilistic points-to analysis”, Shen et al., PPoPP 2003
• “Speculative Alias Analysis for Executable Code”, Fernandez and Espasa, PACT 2002
• “A General Compiler Framework for Speculative Optimizations Using Data Speculative Code Motion”, Dai et al., CGO 2005
• “Speculative register promotion using Advanced Load Address Table (ALAT)”, Lin et al., CGO 2003
Do pointers a and b point to the same location?
   – Repeat for every pair of pointers at every program point

How can we optimize the “maybe” cases?
Let’s Speculate

- Implement a potentially unsafe optimization
  - Verify and Recover if necessary

```c
int *a, x;
...
while(…)
{
    x = *a;
    ...
}
```

- `a` is probably loop invariant

```c
int *a, x, tmp;
...
tmp = *a;
while(…)
{
    x = tmp;
    ...
}
```

<verify, recover?>
Data Speculative Optimizations

• EPIC Instruction sets
  – Support for speculative load/store instructions (e.g., Itanium)

• Speculative compiler optimizations
  – Dead store elimination, redundancy elimination, copy
    propagation, strength reduction, register promotion

• Thread-level speculation (TLS)
  – Hardware and compiler support for speculative parallel threads

• Transactional programming
  – Hardware and software support for speculative parallel
    transactions

Heavy reliance on detailed profile feedback
Can We Quantify “Maybe”?  

- Estimate the potential benefit for speculating:

  - Recovery penalty (if unsuccessful)
  - Expected speedup (if successful)
  - Overhead for verify
  - Probability of success
  - Maybe

Ideally “maybe” should be a probability.
Conventional Pointer Analysis

- Do pointers \( a \) and \( b \) point to the same location?
  - Repeat for every pair of pointers at every program point
Probabilistic Pointer Analysis

• Potential advantage of Probabilistic Pointer Analysis:
  – it doesn’t need to be safe
PPA Research Objectives

• Accurate points-to probability information
  – at every static pointer dereference
• Scalable analysis
  – Goal: entire SPEC integer benchmark suite
• Understand scalability/accuracy tradeoff
  – through flexible static memory model

*Improve our understanding of programs*
Algorithm Design Choices

**Fixed:**
- Bottom Up / Top Down Approach
- Linear transfer functions (for scalability)
- One-level context and flow sensitive

**Flexible:**
- Edge profiling (or static prediction)
- Safe (or unsafe)
- Field sensitive (or field insensitive)
Traditional Points-To Graph

```c
int x, y, z, *b = &x;
void foo(int *a) {
    if(...) b = &y;
    if(...) a = &z;
    else(...) a = b;
    while(...) {
        x = *a;
        ...
    }
}
```

- **\( \bigcirc \)** = pointer
- **\( \bigbox \)** = pointed at

\[ \text{Definitely} \]
\[ \text{Maybe} \]

Results are inconclusive
int x, y, z, *b = &x;
void foo(int *a) {
    if(...) 
        \textcolor{red}{\Rightarrow 0.1 \text{ taken (edge profile)}}
        b = &y;
    if(...) 
        \textcolor{red}{\Rightarrow 0.2 \text{ taken (edge profile)}}
        a = &z;
    else
        a = b;
    while(...) {
        x = *a;
        ...
    }
}
Probabilistic Pointer Analysis Results

Summary

• Matrix-based, transfer function approach
  – SUIF/Matlab implementation
• Scales to the SPECint 95/2000 benchmarks
  – One-level context and flow sensitive
• As accurate as the most precise algorithms
• Interesting result:
  – ~90% of pointers tend to point to only one thing
Pointer Analysis Summary

• **Pointers are hard to understand at compile time!**
  – accurate analyses are large and complex

• **Many different options:**
  – Representation, heap modeling, aggregate modeling, flow sensitivity, context sensitivity

• **Many algorithms:**
  – Address-taken, Steensgarde, Andersen, Emami
  – BDD-based, probabilistic

• **Many trade-offs:**
  – space, time, accuracy, safety

• **Choose the right type of analysis given how the information will be used**
CSC D70: Compiler Optimization
Memory Optimizations (Intro)

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Caches: A Quick Review

• How do they work?

• Why do we care about them?

• What are typical configurations today?

• What are some important cache parameters that will affect performance?
Optimizing Cache Performance

- Things to enhance:
  - temporal locality
  - spatial locality

- Things to minimize:
  - conflicts (i.e. bad replacement decisions)

What can the compiler do to help?
Two Things We Can Manipulate

• **Time:**
  – When is an object accessed?

• **Space:**
  – Where does an object exist in the address space?

*How do we exploit these two levers?*
Time: Reordering Computation

• What makes it difficult to know *when* an object is accessed?

• How can we predict a *better time* to access it?
  – What information is needed?

• How do we know that this would be *safe*?
Space: Changing Data Layout

• What do we know about an object’s location?
  – scalars, structures, pointer-based data structures, arrays, code, etc.

• How can we tell what a better layout would be?
  – how many can we create?

• To what extent can we safely alter the layout?
Types of Objects to Consider

• Scalars

• Structures & Pointers

• Arrays
Scalars

- Locals
- Globals
- Procedure arguments

Is cache performance a concern here?
If so, what can be done?

```c
int x;
double y;
foo(int a){
    int i;
    ...
    x = a*i;
    ...
}
```
Structures and Pointers

• What can we do here?
  – within a node
  – across nodes

```c
struct {
    int count;
    double velocity;
    double inertia;
    struct node *neighbors[N];
} node;
```

• What limits the compiler’s ability to optimize here?
Arrays

double A[N][N], B[N][N];
...
for i = 0 to N-1
  for j = 0 to N-1
    A[i][j] = B[j][i];

- usually accessed within loops nests
  - makes it easy to understand “time”
- what we know about array element addresses:
  - start of array?
  - relative position within array
Handy Representation: “Iteration Space”

for \( i = 0 \) to \( N-1 \)
for \( j = 0 \) to \( N-1 \)
\[ A[i][j] = B[j][i]; \]

- each position represents an iteration
Visitation Order in Iteration Space

for \( i = 0 \) to \( N-1 \)
   for \( j = 0 \) to \( N-1 \)
       \( A[i][j] = B[j][i] \);

• Note: iteration space \( \neq \) data space
When Do Cache Misses Occur?

for $i = 0$ to $N-1$
    for $j = 0$ to $N-1$
        $A[i][j] = B[j][i]$;
When Do Cache Misses Occur?

for $i = 0$ to $N-1$
    for $j = 0$ to $N-1$
        $A[i+j][0] = i \times j$;
Optimizing the Cache Behavior of Array Accesses

• We need to answer the following questions:
  – when do cache misses occur?
    • use “locality analysis”
  – can we change the order of the iterations (or possibly data layout) to produce better behavior?
    • evaluate the cost of various alternatives
  – does the new ordering/layout still produce correct results?
    • use “dependence analysis”
Examples of Loop Transformations

- Loop Interchange
- Cache Blocking
- Skewing
- Loop Reversal
- ...

(we will briefly discuss the first two next week)
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Pointer Analysis & Memory Optimizations (Intro)

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