CSC D70:
Compiler Optimization
Pointer Analysis

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The content of this lecture is adapted from the lectures of Todd Mowry, Greg Steffan, and Phillip Gibbons
Announcements

• Guest Lecture on March 23rd, by Kit Barton, IBM

• Topic: TBA
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
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?

  ```
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
- Treat entire array as a single location
- Treat first element separate from others

**Structures**
- Elements are treated as individual locations ("field sensitive")
- 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
\[
a_{S7}: \text{null} \quad \{\text{heapS1, heapS2, heapS4, heapS6}\}
\]
*(order doesn’t matter, union of all possibilities)*

Flow Sensitive
\[
a_{S7}: \text{null} \quad \{\text{heapS2, heapS4, heapS6}\}
\]
*(in-order, doesn’t know s5 & s6 are exclusive)*

Path Sensitive
\[
a_{S7}: \text{null} \quad \{\text{heapS2, heapS6}\}
\]
*(in-order, knows s5 & s6 are exclusive)*
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”, Smaragdakis et al., PLDI 2014
• “Sparse flow-sensitive pointer analysis for multithreaded programs”, Sui et al., CGO 2016
• “Symbolic range analysis of pointers”, Paisant et 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

```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);
}

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

\[ p_{s5} = \{ \text{heap\_S1, p, heap\_S4, heap\_S6, q, heap\_S8, local} \} \]
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>Expression</th>
<th>Points-to Relationship</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

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;
}

$P_{S5} = \{\text{heap\textunderscore S1, heap\textunderscore S4, local}\}$
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;
}

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

```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;
}
```

\[ p_{S5} = \{ \text{heap}_S4 \} \]

\[ p_{S9} = \{ \text{local}, \text{heap}_S1 \} \]
Pointer Analysis Using BDDs: Binary Decision Diagrams

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-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)
  - Overhead for verify
  - Expected speedup (if successful)
  - Probability of success

Speculate?

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

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

Results are inconclusive
int x, y, z, *b = &x;
void foo(int *a) {
  if(...) □0.1 taken(edge profile)
    b = &y;
  if(...) □0.2 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
The content of this lecture is adapted from the lectures of Todd Mowry and Phillip Gibbons
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
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 ≠ 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
- ...
