CS711 Advanced Programming Languages

Pointer Analysis
Overview and Flow-Sensitive Analysis

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Pointer Analysis

- Informally: determine where pointers (or references) in the program may point to.
- Significant amount of research in past 15 years
  - … still going
- It is a fundamental problem in program analysis
  - Required by virtually all other analyses, optimizations, program understanding tools, bug-finding tools, etc.
  - Worst-case assumptions are too conservative
    - Especially for type-unsafe languages (e.g., C)

Points-To vs. Alias Analysis

- Points-to analysis: Compute the set of memory locations that each pointer may point to.
  - Hence, a may analysis
  - E.g., `pt(x)={z,t}`, `pt(t)={u}`, `pt(y)={z}`
  - Essentially, a points-to graph

$$\begin{tikzcd} x \arrow[r] \arrow[dr] & t \arrow[r] & u \\ y \arrow[r] & z & \end{tikzcd}$$

- (Pointer) alias analysis computes alias pairs
  - E.g. `(*x,z)`, `(*x,t)`, `(*t,u)`, `(**x,u)`, `(*y,z)`
  - Points-to graphs = a compact representation of alias pairs
  - Used in older analyses, e.g., [LR92]

Classifying Points-To Analyses

- Flow-sensitivity
  - Flow analyses
    - compute a points-to graph at each program point
  - Flow-insensitive analyses
    - Assignments can execute in any order, any number of times
    - Obviously models program execution
    - A points-to graph for the entire program
    - Two main kinds:
      - Steensgaard, a.k.a. unification-based
      - Andersen, a.k.a. inclusion-based
- Context-sensitivity
  - Distinguish the behavior of a function based on its calling context

Classifying Points-To Analyses

C analyses (yellow)
Java analyses (green)

	Flow-Insensitive Steensgaard		Flow-Insensitive Andersen	Dataflow
Context Sensitive	[RH98] [FRD00]	[DLFR01]	[WL04]	[EGH94] [WL95]
Context Insensitive	[Ste96]	[SH98] [Das00] [SGSB05]	[And94] [BLQ+03]	[Ruf95]

Points-To Analysis

- "compute set of locations where each pointer may point to"
- Ambiguities:
  - What are locations?
  - What about heap-allocated pointers?
  - What about aggregate structures: records, arrays, etc?
  - What about different instances of the same variable?
- We're missing a notion of memory abstraction

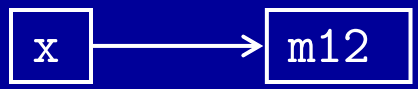
Memory Model

- An abstraction of the memory
  – Map concrete locations to "abstract locations/nodes"
    - One abstract node may represent one or more concrete memory locations
    - Approximate unbounded concrete program state using a finite abstraction
  – Analysis clients need to know about this abstraction
  – Difficult to compare (results for) different abstractions

Heap Abstraction

- Heap abstraction
  - Typically: one abstract node for each allocation site
  - Think: “one global variable per malloc”

```
12: x = malloc(...)
```



- Alternatives:
  - Less precise: one node for the entire heap
  - More precise: different nodes for locations allocated in different calling contexts
    - Aka “context-sensitive heap abstraction”
    - Think malloc wrappers
- Model is imprecise for recursive structures
  - Shape analysis is significantly more precise here

Records and Structures

- Option A: Model each field of each struct variable
  - A.k.a. "field-sensitive". Think "`x.f`"

```
struct { int a, b; } x, y;   →   x.a   x.b
                                 y.a   y.b
```

- Option B: Merge all fields of each struct variable
  - A.k.a. "field-independent", "field-insensitive". Think "`x.*`"

```
struct { int a, b; } x, y;   →   x.*   y.*
```

- Option C: Model each field of all struct variables
  - A.k.a. "field-based". Think "`*.f`"

```
struct { int a, b; } x, y;   →   *.a   *.b
```

Unions

- Unions are type-unsafe
  - Sound approach: merge all fields
    - As in “field-independent” (B)

```
union { int a; char b; } x;   →   x.*
```

  - Unsound approach: assume fields don’t interfere
    - As in “field-sensitive” (A)

```
union { int a; char b; } x;   →   x.a   x.b
```

Arrays

- Merge all array elements together

```
int a[10];
```

$\rightarrow$ $\boxed{\texttt{a[*]}}$

- Or use a separate abstraction for the first element

```
int a[10];
```

$\rightarrow$ $\boxed{\texttt{a[0]}}$ $\boxed{\texttt{a[1..10]}}$

Nested Arrays and Structures

- Recurse through nested structure
  - Merge array elements
  - Separate all structure fields
    - even if structure is nested in an array

```
struct { int a[3], b; } x[3];
```

→ `x[*].a[*]` `x[*].b`

x[0] x[1] x[2]

The Flow Analysis

- Program assignments:

address-of	copy	load	store
`x = &y`	`x = y`	`x = *y`	`*x = y`

- Dataflow information = points-to graphs
  - Use pt(x) = points-to set of x
- Merge operator = set union
- Transfer functions
  - `x = &y` : pt'(x) = {y}
  - `x = y` : pt'(x) = pt(y)
  - `x = *y` : pt'(x) = U pt(z), for all z $\in$ pt(y)
  - `*x = y` : pt'(z) U= pt(y), for all z $\in$ pt(x)

Strong vs. Weak Updates

- "strong updates" = update value
- "weak updates" = accumulate value

- Strong updates = more precise
- Weak updates if can't tell which concrete location is written
  - `*x = y`
  - `x[i] = y`

- Strong updates = key difference between flow-sensitive and flow-insensitive analyses

Inter-Procedural Analysis [EGH'94]

- Analyze callee for each function call
  - "map" the points-to information in the caller
  - Analyze callee with mapped information
  - "unmap" result and return to caller

- Mapping process:
  - Use "invisible variables" to model variables that are not in the current scope, but accessible through pointers
  - Store mapping information, use it during unmap

```
foo() { int a, *b = &a;
        bar(&b); }
bar(int** p) { ... }
```

Call site graph: `b` $\mapsto$ `a`

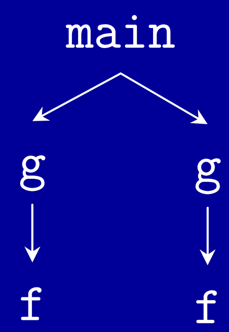
Mapped graph: `p` $\mapsto$ `p_1` $\mapsto$ `p_2`

Mapping info: `(b,p_1) (a,p_2)`

Invocation Graph

- Use an "invocation graph" for context-sensitivity
  - Unroll call-graph, turn it into a tree

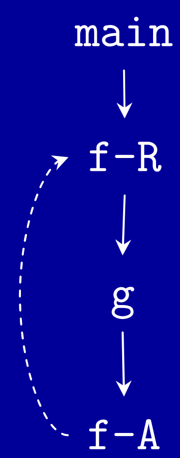
```
main() { g(); g(); }
g()    { f(); }
f()    { ... }
```



Invocation Graph

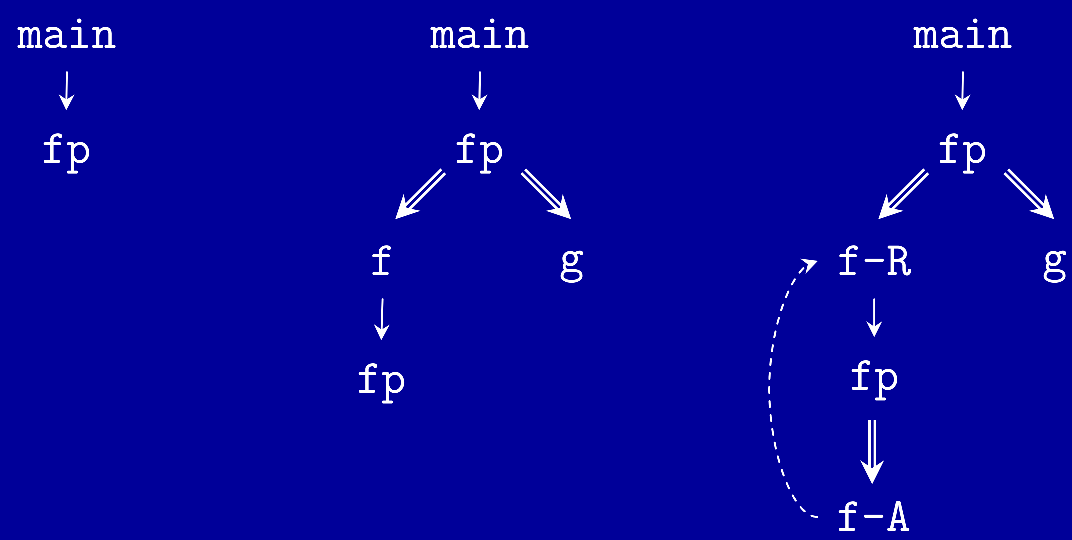
- Use an "invocation graph" for context-sensitivity
  - For recursion:
    - Use two nodes: "approximate" and "recursive"
    - Perform a fixed-point computation along the back edge
    - Use summaries for each node

```
main() { f(); }
f()    { if (...) g(); }
g()    { f(); }
```



Function Pointers

- Indirect calls: a “chicken-and-egg” problem
  - Need points-to information to resolve such calls
  - Need to resolve the calls to compute the points-to info
  - Solution: compute both at the same time
  - Once a call is resolved: analyze each callee, merge the results



Evaluating an Analysis

- What is the right metric?
  - An ongoing debate
  - Option 1: size of points-to sets
    - At loads and stores, at indirect calls
    - Difficult to compare analyses that use different abstractions
  - Option 2: evaluate effect on analysis clients
    - E.g, how many virtual calls are disambiguated? Or how many false data dependencies are being removed?
    - How much faster do programs run because of a better points-to analysis?
    - How is the false positive ratio improved in a bug-finding tool?

Experiments [EGH'94]

- Programs ranging from 0.1 K to 2.2 K LOC
- Small points-to set sizes at indirect accesses (avg. 1.13)
- Many indirect with one single target (28%)
  - But only 19% where the target is a program variable
- Invocation Graph statistics:
  - Average ratio IG size / call-sites = 1.45 (up to 2.5)
  - Ratio IG size / procedures larger (up to 21)
  - In theory, IG size is exponential

Memoization [WL'95]

- [Wilson,Lam,PLDI'95] "Efficient Context-Sensitive Pointer Analysis for C Programs"
  - Always use procedure summaries (not just for recursion)
    - Called "partial transfer functions" (PTFs)
  - Do not build an Invocation Graph
  - Build "invisible variables" lazily
  - Memory abstraction using triples (b, f, s), with base b, offset f,and stride s
  - Ratio PTFs / procedures : between 1.00 and 1.39
  - Report a program with 37 procedures that generates an invocation graph with more than 700,000 nodes