Interprocedural control-flow analysis

Nate Nystrom
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Call graphs

- Statically compute a precise call graph
  - Maps call sites to functions called
- Challenge:
  - Methods
  - Higher-order functions
- Can use precise call graph for:
  - optimization
    - reduce dispatch overhead
    - convert calls to lambdas to direct jumps
    - reduce code size
  - program understanding

Various techniques

- Unique Name [Calder and Grunwald, POPL'94]
- Class Hierarchy Analysis [Dean, Grove, Chambers, ECOOP'95] [Fernandez, PLDI'95]
- Optimistic Reachability Analysis
  - Rapid Type Analysis [Bacon and Sweeney, OOPSLA'96]
- Propagation-based analysis
  - 0-CFA [Shivers, PLDI'88]
  - *k*-CFA [Shivers '91]
- Unification-based analysis [Steensgaard, POPL'96]

- Interprocedural Class Analysis [DeFouw, Grove, Chambers, POPL'98]

Unique Name

- Does not build call graph, but does resolve virtual calls
- If only one method named m in entire program
  - Replace all virtual calls to a method named m with a non-virtual call
- Do at link time on object files
- Can resolve (1) only
- For C++ benchmarks, resolves 15% of virtual calls
- Can't handle same method name in different classes

```
class A {
    int foo() { return 1; }
}
class B extends A {
    int foo() { return 2; }
    int bar(int i) { return i+1; }
}
void main() {
    B p = new B();
    int r1 = p.bar(1); // 1: B.bar
    int r2 = p.foo();  // 2: B.foo
    A q = p;
    int r3 = q.foo();  // 3: B.foo
}
```

Class Hierarchy Analysis

- Use static type of receiver and the class hierarchy to narrow set of possible targets
- Whole program analysis
- Flow insensitive
- *O*(*N*)
- Can resolve (1) and (2)
- For C++ benchmarks, resolves 51% of virtual calls

```
class A {
    int foo() { return 1; }
}
class B extends A {
    int foo() { return 2; }
    int bar(int i) { return i+1; }
}
void main() {
    B p = new B();
    int r1 = p.bar(1);  // 1: B.bar
    int r2 = p.foo();   // 2: B.foo
    A q = p;
    int r3 = q.foo();   // 3: B.foo
}
```

Rapid Type Analysis

- Do CHA to build call graph
- If no object of class C allocated in the program,
  - Remove edges to methods of C
- *O*(*N*)
- Slightly more expensive than CHA
- Can resolve (1), (2), and (3)
- For C++ benchmarks, resolves 71% of virtual calls

```
class A {
    int foo() { return 1; }
}
class B extends A {
    int foo() { return 2; }
    int bar(int i) { return i+1; }
}
void main() {
    B p = new B();
    int r1 = p.bar(1); // 1: B.bar
    int r2 = p.foo();  // 2: B.foo
    A q = p;
    int r3 = q.foo();  // 3: B.foo
}
```

Disjoint polymorphism

- Multiple related object types used independently
  - e.g., Square and Circle objects are never mixed together in, say, a Collection of Shapes
- Pathological case:
  - Derived1 and Derived2 are disjoint
  - No Base objects allocated
  - All calls are through Base pointers

```
class Base {
   void m() { assert(false); }
   void p() { assert(false); }
}

class Derived1 extends Base {
   void m() { ... }
}

class Derived2 extends Base {
   void p() { ... }
}
```

Unification-based analysis

- Partitions variables in program and maps each partition to a set of classes
- Initialize with each variable in own partition
- If classes can flow between variables, unify the classes for those variables

```
target = source;
```

```
T1 m(T2 target) { ... }
m(source);
```

- Resolves (4), but not (5)
- $O(N\alpha(N,N))$

```
class A {
    int foo() { return 1; }
}
class B extends A {
    int foo() { return 2; }
}
void main() {
    A p = new B();
    int r1 = p.foo();  // 4: B.foo
    A q = new A();
    q = new B();
    int r2 = q.foo();  // 5: B.foo
}
```

Interprocedural class analysis

- Framework integrates
  - propagation-based analysis (0-CFA)
  - unification-based analysis
  - optimistic reachability analysis (RTA)
- Computes set of classes for each program variable
- Builds call graph as side effect

Flow graph representation

- Node for each variable, method, new, call
- Algorithm computes set of classes for each node

- Edge between two nodes if classes can flow between them

```
target = source;

T1 m(T2 target) { ... }
m(source);
```

Basic algorithm (0-CFA)

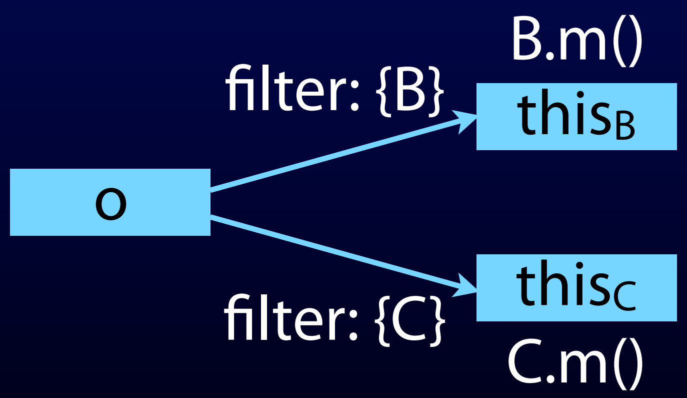
- Construct nodes and edges for top-level variables, statements, and expressions (e.g., main)
- Propagate classes through flow graph starting with main and top-level new expressions
- When call encountered, add edge to target and construct flow graph for target method (if not already done)
- If method not reachable, it will be pruned (as in RTA)

Edge filters

- Edges may have a filter set
  - encode constraints ensured by type declarations or by dynamic dispatch
- Don’t propagate class if filter does not include that class
- Makes algorithm more precise than 0-CFA

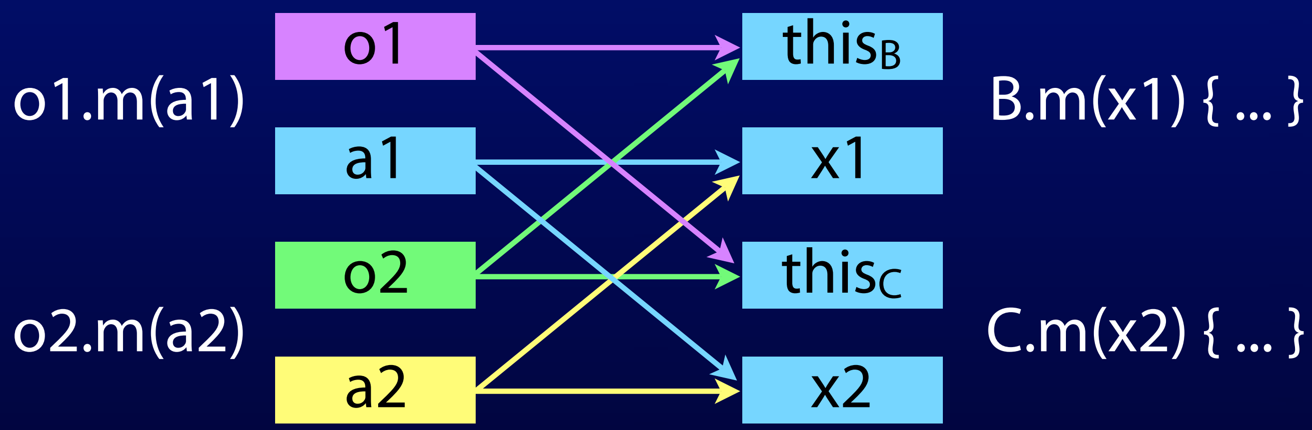
```
class B { m() { ... this ... } }
class C ext B { m() { ... this ... } }

B o = new C();
o.m()
```

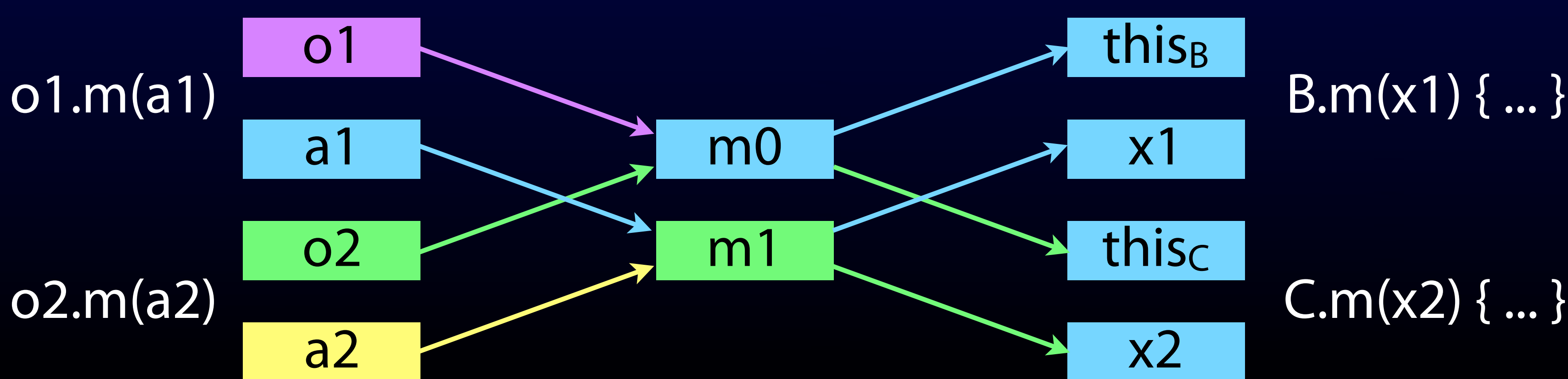


Call merging

- Analysis parameterized by *MergeCalls*
- When *MergeCalls* = false:



- When *MergeCalls* = true:

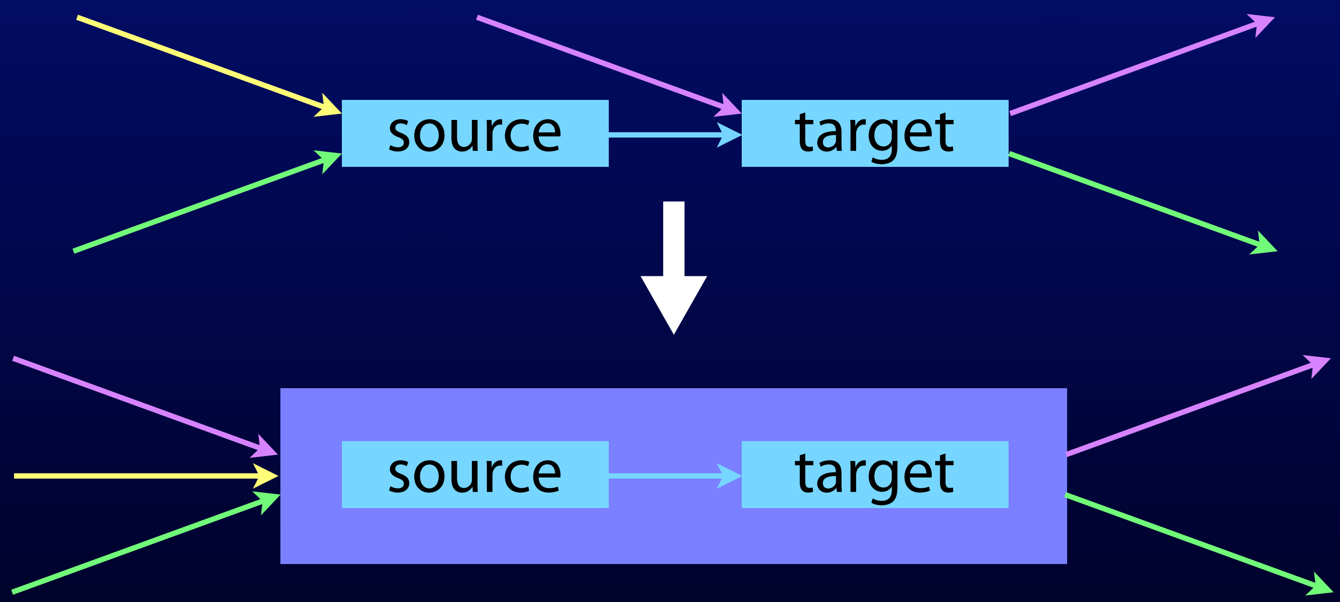


Node merging

- Can speedup analysis by merging nodes into *supernodes*
- Nodes merged with successors

target = source;

T1 m(T2 target) { ... }
m(source);



- Always merging is equivalent to unification-based analysis

Merging parameters

- Analysis parameterized by P and *MergeWithGlobal*
- When $P = k$, merge node with its successors if node visited more than k times
- When $P = 0$, always merge
- When $P = N$, never merge
- When *MergeWithGlobal* = true, use only one global supernode

Instantiations

Algorithm	P	*MergeWithGlobal*	*MergeCalls*	Complexity
0-CFA	N	N/A	false	$O(N^3)$
linear-edge 0-CFA	N	N/A	true	$O(N^2)$
bounded 0-CFA	$O(1)$	false	false	$O(N^2\alpha(N,N))$
bounded linear-edge 0-CFA	$O(1)$	false	true	$O(N\alpha(N,N))$
simply bounded 0-CFA	$O(1)$	true	false	$O(N^2)$
simply bounded linear-edge 0-CFA	$O(1)$	true	true	$O(N)$
equivalence class analysis	0	false	true	$O(N\alpha(N,N))$
RTA	0	true	true	$O(N)$

Analysis time

- Analysis time increases slightly with *P*
  - Mostly flat when *P* small, finite
- *MergeWithGlobal* = true (simply bounded)
  - saves ~10% on Cecil
  - negligible improvement for Java
    - **but all the benchmarks are Java compilers**
  - 250% for one case when *P* = *N*
- *MergeCalls* = true (linear edge)
  - up to 3x for Cecil, or more
  - only 5-20% savings for Java
    - no multimethods, so less edge filtering?
  - some programs can **only** be analyzed with linear edge (or small *P*)

Precision

- Larger *P* more precise (less merging)
  - Run-time speedup 0-10% for $P = 0$, 10-350% for $P = N$
- *MergeCalls* = true (linear edge)
  - About as precise as quadratic edge
  - Less so for Java, but no difference in speedup
- *MergeWithGlobal* = true (simply bounded)
  - Slightly less precision
  - but on some Cecil benchmarks, improved precision of *MergeWithGlobal* = false caused 2.5x speedup
    - precision lost on hot virtual calls?

Questions

- All of these analyses are whole-program
  - Can they be modularized?
- Integrating alias analysis, or more precise points to analysis
- Extend class analysis to incorporate context as in *k*-CFA