Pointer Analysis

Static Program Analysis

Christian Hammer

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Pointer Analysis (Points-to Analysis)

CISPA Center for IT-Security, Privacy and Accountability

- Which objects may each pointer in a program point to at run-time
- Required by compiler analyses and optimizations, program understanding and verification tools
- e.g. resolving dynamic binding

- ```
  class A { String foo() { return "A"; }}
  class B extends A {
   @override foo() {
    return "B";
   }
  }
  ...
  A x;
  ```
- x.foo(); <- which method is invoked here? What is the return value?
  ```

Alias Analysis

- When do two pointers (references) point to the same object?

- Can be introduced due to assignments
  a = new A()
  b = a
- Also field assignments/reads
  o.f = a
  b = o.f
- Or via parameter passing
  foo(a, a)
  foo(Object x, Object y) {...}

Dimensions/Challenges in Pointer Analysis

- Intraprocedural / interprocedural
- Flow-sensitive / flow-insensitive
- Context-sensitive / context-insensitive
- Definiteness
  - May versus must
- Heap modeling
- Representation

Flow-Sensitivity

- Flow-insensitive: Compute one solution for the whole program
  Which objects may this reference ever point to?
- Flow-sensitive: Compute a solution for each point in the program
  Which objects may this reference point to before this statement?
- Flow-sensitive analysis has been considered too expensive for practical use
  - in particular for realistic programs
  - depending on the language features can be NP-hard
  - e.g. with multiple level pointers
  - local flow-sensitivity can be achieved via SSA-form

Context-Sensitivity

- Hard in practice as no good summary-based analysis available
- Inlining with k-limited calling contexts used widely

- Scaling to hundreds of thousands LOC using
  - BDDs (Binary Decision Diagrams)
  - Datalog
  - Databases with fast Datalog interpreters

- Alternative: Object-sensitive Analysis
  Target object used as calling context

Definiteness

- May-aliasing required for e.g. reaching definitions (gen-sets)

  x.f = a
  ...
  b = y.f
- if x and y are may-aliased b is potentially dependent on the value of a

- must-aliasing required to determine kill-sets

  x.f = a
  ...
  y.f = b
  ...
  c = x.f
- if x and y are must-aliases the first definition of field f is overwritten (killed) by the second definition of field f

Abstract Semantics

- Need to model the “flow” of objects into references and fields
- x = new A
  - x ⊇ {A}, meaning loc(A) ∈ pt(x)
- y = x
  - y ⊇ x (Andersen), y = x (Steensgaard)
- a.f = x, y = a.f
  - ??? (depends on value of reference a)

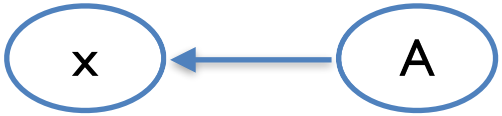
- Steensgaard scales better, but less precise
  - Union-Find-Algorithm O(nα(n)) (almost linear)
  - Disadvantage: Leads to typing issues for e.g. Java programs
  - Not used much for strongly typed languages and virtual binding resolution

Problem

- We need an abstraction for dynamic object creation sites:

```
for (…) {
  x = new A()
  …
}
x.foo()
```

- Insight: exact instance of class A not required, type is enough here!
- Solution: One equivalence class for all objects created at the allocation site
- $x \supseteq \{A\}$



Analysis Rules

	Allocation	Assignment	Field store	Field load
Instruction	$l := new\ C$	$l_i := l_j$	$l_i.f := l_j$	$l_i := l_j.f$
Edge	$new\ C \rightarrow l$	$l_j \rightarrow l_i$	$l_j \rightarrow l_i.f$	$l_j.f \rightarrow l_i$
Rules	$\dfrac{new_i \rightarrow l}{new_i \in pt(l)}$	$\dfrac{l_j \rightarrow l_i \quad new_i \in pt(l_j)}{new_i \in pt(l_i)}$	$\dfrac{l_j \rightarrow l_i.f \quad new_i \in pt(l_j) \quad new_j \in pt(l_i)}{new_i \in pt(new_j.f)}$	$\dfrac{l_j.f \rightarrow l_i \quad new_i \in pt(l_j) \quad new_j \in pt(new_i.f)}{new_j \in pt(l_i)}$

Example


- ```
  String[][] st = new String[3][4];
  s = "Something";
  st[1][0] = s;
  s = "Hello";
  s = st[1][0];
  int i6=0;
  String s6 = s;
  if (i6==0) s6 = "something else";
  ```

- Which strings can s6 point to in the end?
  ```

Iterative Algorithm

initialize sets according to allocation edges
repeat
    propagate sets along each assignment edge $p \longrightarrow q$
    for each load edge $p.f \longrightarrow q$ **do**
        for each $a \in pt(p)$ **do**
            propagate sets $pt(a.f) \longrightarrow pt(q)$
    for each store edge $p \longrightarrow q.f$ **do**
        for each $a \in pt(q)$ **do**
            propagate sets $pt(p) \longrightarrow pt(a.f)$
until no changes

Worklist Algorithm (more efficient)

```
for each allocation edge o1 → p do
   pt(p) ∪= {o1}
   add p to worklist
repeat
   repeat
      remove first node p from worklist
      propagate sets along each assignment edge p → q,
      adding q to worklist whenever pt(q) changes
      for each store edge q → r.f where p = q or p = r
      do
         for each a ∈ pt(r) do
            propagate sets pt(q) → pt(a.f)
      for each load edge p.f → q do
         for each a ∈ pt(p) do
            propagate sets pt(a.f) → q
            add q to worklist if pt(q) changed
   until worklist is empty
   for each store edge q → r.f do
      for each a ∈ pt(r) do
         propagate sets pt(q) → pt(a.f)
   for each load edge p.f → q do
      for each a ∈ pt(p) do
         propagate sets pt(a.f) → q
         add q to worklist if pt(q) changed
until worklist is empty
```

Interprocedural Analysis

- Often simple inlining (context-insensitive analysis)
- Contexts for method calls only, sometimes even for allocation sites
- Special case: Objects-sensitive Pointer Analysis
  - context is target object (k-limiting k=1)
  - good precision in practice with moderate overhead
  - in particular, does not merge different container objects (Lists, Vectors,…)

- Vector v1 = new Vector(), v2 = new Vector()
  v1.add("Hello")
  v2.add("World")
  x = v1.get(1)
  - pt(x) = {"Hello"} only
- Call graph construction interleaved with pointer analysis
  - precision of pointer analysis removes infeasible dynamic dispatch
  - further improves the pointer analysis results

Example

- class A { String foo() { return “A” }}
  class B extends A {String foo() { return “B” }}
  main() { A a = new A(); A b = new B(); x = b.foo(); }
- A.foo returns “A”, B.foo returns “B”
- b has type A
- Class Hierarchy Analysis of this program determines that b.foo() could be dispatched to either A.foo or B.foo
- But only new B() is in pt(b)
  - thus the virtual call to b.foo() can only be dispatched to B.foo
- pt(x) = {“B”} and not {“A,B”}

Datalog

- Logical query language (from databases)
- Non-recursive rules are equivalent to the core relational algebra
- Implementation for Program Analysis: bddbddb (BDD-Based deductive DataBase)
- New startup: database with datalog support

Rule = Atom :- Literal, Literal, …, Literal.

Make this atom true…

Head

…for each assignment of values to variables that make all these true

Body

Literal = Atom | !Atom

Atom = Predicate(<list of arguments>)

Datalog Program

Rule =	Atom :- Literal, Literal, …, Literal.
Literal =	Atom | !Atom
Atom =	Predicate(<list of arguments>)

- A datalog program is a collection of rules
- Predicates can be external or internal
- EDB: Extensional Database (external information, e.g. stored in a table, from the CFG, prior analysis, …)
- IDB: Intensional Database (relation only defined by rules)
- Either IDB or EDB, never both
- No EDB in heads

Example: Reaching Definitions

- Reach(d,x,j) :- Reach(d,x,i), StatementAt(i,s), !Assign(s,x), Succ(i,j).

Reach(d,x,j)	definition d of variable x reaches node j
Reach(d,x,i)	definition d of variable x reaches node i
StatementAt(i,s)	statement s in node i
Assign(s,x)	x is assigned new value in s
Succ(i,j)	node j is a successor of node i

- Reach(s,x,j) :- StatementAt(i,s), Assign(s,x), Succ(i,j).

- New assignment always reaches successor

Negation vs. Fixed Points

- Negation tricky in recursive predicates:

P(X) = E(X), !P(X).

- Given E(X) is true, is P(X) true?
- Iteration 1: Yes, 2: No, 3: Yes, …

- Semantics of Negation:
  - No Negation allowed [Ullman 1988]
  - Stratified Datalog [Chandra 1985]
  - Well-founded Semantics [Van Gelder 1991]

Evaluation of Negated Predicates

- Requirement: Evaluation order < over IDB Predicates

$$P \text{ :- } \ldots, !Q, \ldots . \quad \Rightarrow \; Q \text{ is EDB} \vee Q < P$$

- Intuition: Negations can be evaluated before the formula that they are used in.

- Iterative Evaluation algorithm:
  - Start with EDB predicates and leave all IDB predicates un-evaluated
  - Iteratively evaluate IDB rules in order of strata (low to high) (order between IDB of the same stratum does not matter)
  - End when no change to IDB rules (fixed point)

(Simplified) Intra-Procedural Pointer analysis: Relations

- CFG etc. are modeled as EDB

- Input vP0 (variable: V, heap H)
  // vP0(v,h) true iff the program places a reference to heap obj h in v
- Input fldst (bytecode: B, base: V, field: F, source: V)
  // fldst(b,v1,f,v2) means that bytecode b executes v1.f = v2
- Input fldld (bytecode: B, dest: V, field: F, base: V)
  // fldld(b,v1,f,v2) means that bytecode b executes v1 = v2.f
- Input assign (dest: V, source: V)
  // assign(v1,v2) true iff the program contains assignment v1=v2
- Output vP (variable: V, heap: H)
  // vP(v,h) iff v points to heap obj h at any point during execution
- Output hP (base: H, field: F, target: H)
  // hP(h1,f,h2) true iff heap object h1.f may point to h2

(Simplified) Intra-Procedural Pointer Analysis: Rules

- Input vP0 (variable: V, heap H)
  Input fldst (bytecode: B, base: V, field: F, source: V)
  Input fldld (bytecode: B, dest: V, field: F, base: V)
  Input assign (dest: V, source: V)
  Output vP (variable: V, heap: H)
  Output hP (base: H, field: F, target: H)

```
vP(v,h)       :-    vP0(v,h).    //initialize points-to relation
vP(v1, h)     :-    assign(v1,v2), vP(v2,h). //transitive closure (assignments)
hP(h1,f,h2)   :-    fldst(_, v1, f, v2), vP(v1,h1), vP(v2,h2).
        //stores to fields, e.g. o.f = x;
vP(v2,h2)     :-    fldld(_,v1,f,v2),   vP(v1,h1), hP(h1,f,h2).
        //loads of fields, e.g. x = o.f;
```

(Context-Insensitive) Pointer Analysis in BDDBDDB

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- # Type 0 is Object
  aT(t0,t1) :- aT0(t0,t1).
  aT(t0,t2) :- aT(t0,t1), aT(t1,t2).
  aT(0,t1) :- aT0(t1,_).
  vT(v0,t0) :- vT0(v0,t0).
  vT(v0,t0) :- vT0(v0,t0).
  vT(v0,0) :- !vT0(v0,_).

- vP(v,h) :- vP0(v,h).
  IE(i,m) :- IE0(i,m).
  vPfilter(v,h) :- vT(v,tv), aT(tv,th), hT(h,th).
  vP(v1,h) :- A(v1,v2), vP(v2,h), vPfilter(v1,h).
  hP(h1,f,h2) :- S(v1,f,v2), vP(v1,h1), vP(v2,h2).
  vP(v2,h2) :- L(v1,f,v2), vP(v1,h1), hP(h1,f,h2), vPfilter(v2,h2). split
  A(v1,v2) :- formal(m,z,v1), IE(i,m), actual(i,z,v2).
  A(v2,v1) :- Mret(m,v1), IE(i,m), Iret(i,v2).
  A(v2,v1) :- Mthr(m,v1), IE(i,m), Ithr(i,v2).

vP0 (v:V0, h:H0) input
vP (v:V0, h:H0) output printtuples
A (dest:V0, source:V1) input
hP0 (ha:H0, field:F0, hb:H1) input
hP (ha:H0, field:F0, hb:H1) output
S (base:V0, field:F0, src:V1) input
L (base:V0, field:F0, dest:V1) input
vT (var:V0, type:T0)
hT (heap:H0, type:T1) input
aT (type:T0, type:T1)
vT0 (var:V0, type:T1) input
aT0 (type:T0, type:T1) input
vPfilter (v:V0, h:H0)
cha (type:T1, name:N0, method:M0) input
actual (invoke:I0, num:Z0, actualparam:V1) input
formal (method:M0, num:Z0, formalparam:V0) input
Mret (method:M0, v:V1) input
Mthr (method:M0, v:V1) input
Iret (invoke:I0, v:V0) input
Ithr (invoke:I0, v:V0) input
mI (method:M0, invoke:I0, name:N0) input
IE0 (invoke:I0, target:M0) input
IE (invoke:I0, target:M0) output printtuples