Interprocedural Data-Flow Analysis

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Motivation for Interprocedural DFA

- All DFA and optimizations that we have studied so far are intraprocedural
  - are performed on one procedure at a time
  - assume that procedures invoked may alter all the “visible” variables
  - imprecise, conservative, but simple
- Interprocedural analysis operates across an entire program
  - makes information flow from caller to callee and vice-versa

Motivation for Interprocedural DFA

- Procedure *inlining* is a simple method to enable such information flow
  - applicable only if target of a call is known
  - not possible if call is via a pointer or is “virtual”
- Interprocedural analysis in O-O languages can sometimes determine if the target of even a “virtual call” is “static”
  - now, either a “static” call or inlining can be used
- However, inlining should be applied with care
  - increases memory foot print

Applications of Interprocedural Analysis

- Convering virtual method calls to static method calls
- Interprocedural pointer analysis helps in making "points-to" sets more precise
  - reaching definitions, available expressions etc., can now be computed with more precision
- Interprocedural analysis eliminates spurious data dependencies, interprocedural constant propagation makes loop bounds known
  - exposes more parallelism during parallelization
- Interprocedural analysis helps in detecting
  - lock-unlock pattern of critical regions
  - disable-enable of interrupts
  - SQL injection (lack of input validation in Web applications)
  - vulnerabilities due to buffer overflows (frequently, array bounds are not checked)

Call Graphs

- A call graph for a program is a set of nodes and edges such that
  - There is one node for each procedure
  - There is one node for each call site
  - If call site c may call procedure p, then there is an edge c → p
- C and Fortran make procedure calls directly by name
  - hence call target of each invocation can be determined statically

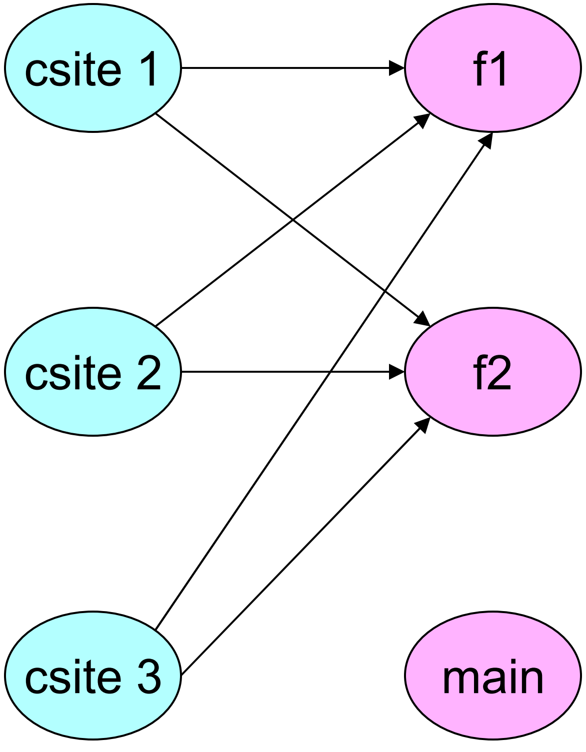
Call Graphs

- If the program includes a procedure parameter or a function pointer
  - target is not known until runtime
  - target may vary from one invocation to another
  - call site can link to many or even all procedures in the call graph (considering only return types of functions)
- Ex: virtual method invocations in C++/Java
  - calls through the base class pointer cannot be resolved till runtime

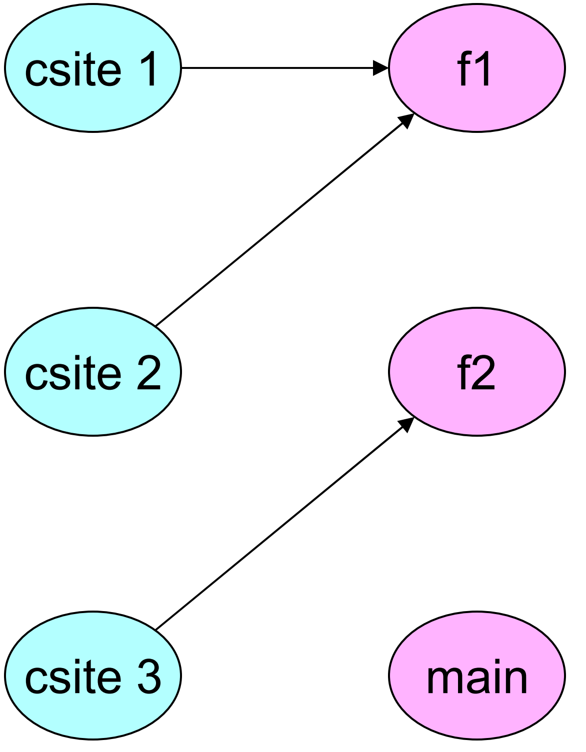
Example of Call Graph

```
int (*fp) (int);
int  f1(int x) {
      if (x > 100) return (*fp)(x-1); // csite 1
      else  return x;
}
int  f2(int y) {
      fp = &f1; return (*fp)(y); // csite 2
}
void main() {
        fp = &f2;  (*fp)(200); // csite 3
}
```

Call Graph Example



Conservative call graph



Exact call graph

Analysis of Call Graph

- Presence of references or pointers to functions or methods
  - helps us in getting a static approximation of the values of all procedure parameters, function pointers, and receiver object types
- With interprocedural analysis
  - more targets can be discovered and new edges can be inserted into the call graph
- This iterative procedure is repeated until convergence is reached

Context Sensitivity

```
i = 9;
while (i >= 0) {
      t1 = test(100); // call site 1
      t2 = test(200); // call site 2
      t3 = test(300); // call site 3
      val[i--] = t1 + t2 + t3;
}
int test (int v) {
    return (v*2);
}
```

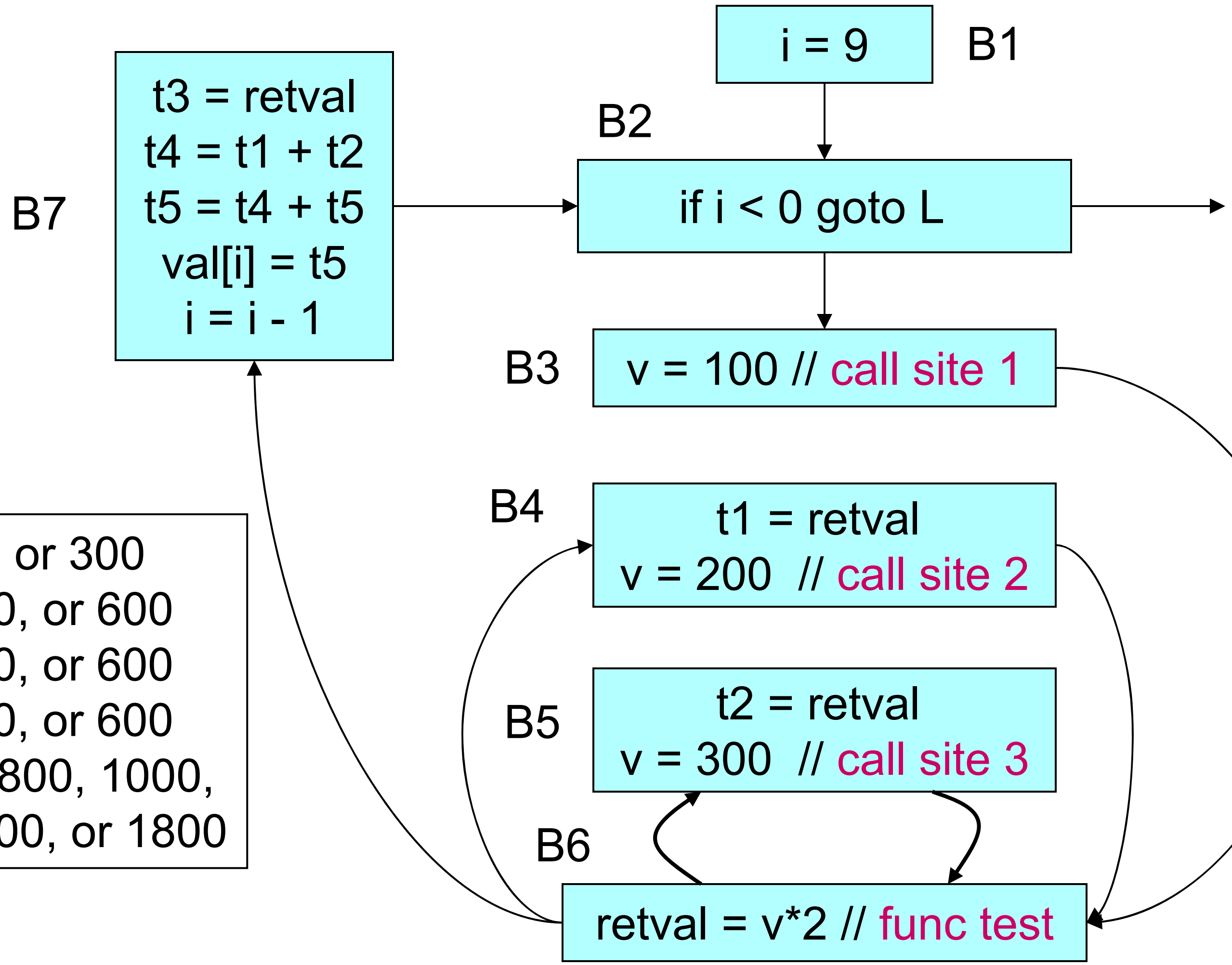
- A context-sensitive analyis returns 200, 400, and 600 for t1, t2, and t3 (resp.), and 1200 for val[i]

- Function test is invoked with a constant in each of the call sites, but the value of the constant is context-dependent
- It is not possible to infer that t1, t2, and t3 are each assigned constant values (hence for val[i] as well) unless we recognize the context
- A naive analysis would infer that test can return 200, 400, or 600 from any of the three calls

Context Insensitive Analysis

- Treat each call and return as goto operations
- Create a super control flow graph
  - contains all the normal intraprocedural control-flow edges
  - edge connecting each call site to the beginning of the pocedure it calls
  - edge connecting return statement back to the call site
  - assignment statements to assign
    - each actual parameter to its corresponding formal parameter
    - the returned value to the receiving variable
- Apply standard analysis on the super CFG
- Simple, but imprecise, because a function is analyzed as a common entity for all its calls and only its input-output behaviour abstracted out

Super Control Graph and Context-Insensitive Analysis Example



v (B6): 100,200, or 300
t1 (B4): 200, 400, or 600
t2 (B5): 200, 400, or 600
t3 (B7): 200, 400, or 600
val[i] (B7): 600, 800, 1000, 1200, 1400, 1600, or 1800

Call Strings

- In the previous example, we needed just the call site to distinguish among the contexts
- In general, the entire call stack defines a calling context
- The string of call sites in the call stack is known as the call string
- We may choose to use the k entries just below any call site in the stack to distinguish between contexts
  - k-limiting context analysis
  - reduces precision and makes results more conservative
  - We take each call string, follow the calls, and perform data flow analysis, replacing the parameters and result variables as we go up and down the call string

k-limiting Call Strings

```
i = 9;
while (i >= 0) {
      t1 = f (100); // call site c1
      t2 = f (200); // call site c2
      t3 = f (300); // call site c3
      val[i--] = t1 + t2 + t3;
}
int f (int v) {
      return test (v); // call site c4
}
int test (int v) {
    return (v*2);
}
```

- There are 3 call strings to test: (c1,c4), (c2,c4), (c3,c4)
- The value of v in test does not depend on the last call site c4, but on the first element of each of the call strings
- In this case, 2-limiting context analysis is enough

Complete Call Strings

```
i = 9;
while (i >= 0) {
      t1 = f (100); // call site c1
      t2 = f (200); // call site c2
      t3 = f (300); // call site c3
      val[i--] = t1 + t2 + t3;
}
int f (int v) {
   if (v > 101)
      return f (v–1); // call site c4
   else
      return test (v); // call site c5
}
int test (int v) {
    return (v*2);
}
```

- There are 3 call strings to test
- (c1,c5), value returned is 200
- (c2,c4,c4,...,c4,c5): c4 is repeated 100 times, value returned is 202
- (c3,c4,c4,...,c4,c5): c4 is repeated 200 times, value returned is 202
- The value of v in test depends on the full call string
- In this case, k-limiting context analysis is not enough, for any k

Cloning-Based Context-Sensitive Analysis

Simple, context-insensitive analysis is enough on the cloned call graph

```
i = 9;
while (i >= 0) {
      t1 = f1 (100); // call site c1
      t2 = f2 (200); // call site c2
      t3 = f3 (300); // call site c3
      val[i--] = t1 + t2 + t3;
}
int f1 (int v) {
      return test1 (v); // call site c4.1
}
int test1 (int v) {
    return (v*2);
}
```

```
int f2 (int v) {
      return test2 (v); // call site c4.2
}
int test2 (int v) {
    return (v*2);
}
int f3 (int v) {
      return test3 (v); // call site c4.3
}
int test3 (int v) {
    return (v*2);
}
```

Recursive programs cannot be handled

Summary-Based Context-Sensitive Analysis

- Each procedure is represented by a concise description ("summary") that encapsulates some observable behaviour of the procedure
- In reaching definitions or available expressions analysis, the appropriate OUT sets of the "procedure end" blocks would serve the purpose
- We now explain one method of doing such an analysis
- Recursion can also be handled using fixpoint computation

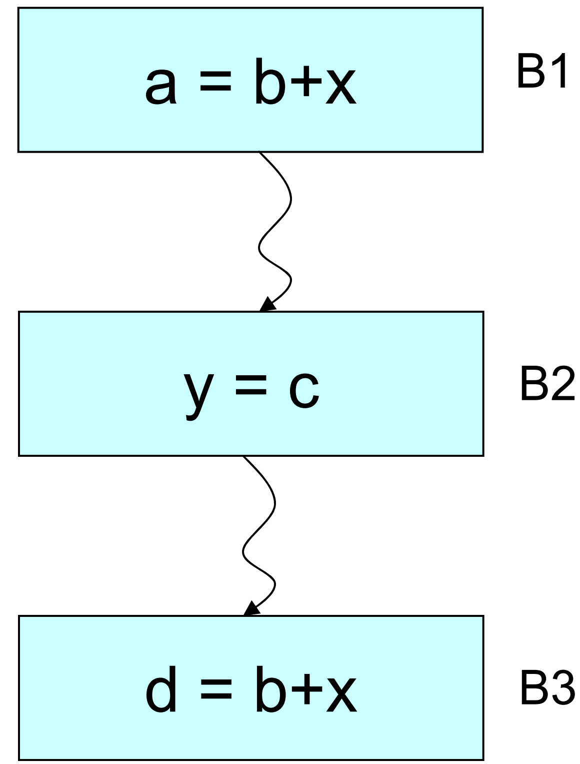
The Problem of Aliases

- b+x will change in B3 if y is an alias of either b or x
- How can aliases arise?
- Consider a procedure

procedure p(x,y)

and calls to p: p(z,z)

or a call of p(u,v) from another procedure q(u,v) but q is called as q(z,z).



Aliases

- In reaching definitions, it is conservative not to regard variables as aliases when in doubt
  - So, we do not kill definitions when in doubt
- But, in available expressions, it is exactly the opposite
  - In the above example, if b+x is to be available in B3, we must be *certain* that b and x are not aliases of y
  - If in doubt, we assume aliasing and kill b+x

Alias Analysis

- Assume a language with recursive procedures but no nesting of procedures
- Parameters are passed by reference

1. Rename variables in procedures (if necessary) so that all names are different
2. If there is a procedure $p(x_1, x_2, \ldots, x_n)$ and a call $p(y_1, y_2, \ldots, y_n)$, then set $x_i \equiv y_i$, for all i
3. Take reflexive and transitive closure of $\equiv$

Alias Analysis Example

```
global g,h;
    procedure main() {
        local i;
        g = ...; one(h,i);
    }
    procedure one(w,x) {
        x = ...;
        two(w,w); two(g,x);
    }
procedure two(y,z) {
    local k;
    h = ...; one(k,y);
}
```

- **main**: h ≡ w, i ≡ x
- **one**: w ≡ y, w ≡ z,
  g ≡ y, x ≡ z
- **two**: k ≡ w, y ≡ x
- All variables are aliases of each other

Change Computation

- change[p]: a set of global variables and formal parameters of p, that might be changed during an execution of p. No aliasing is considered at this time
- def[p]: a set of formal parameters of p and globals having explicit definitions within p (not including those defined because of procedure calls made within p)

Change Computation

- change[p] = def[p] U A[p] U G[p], where
- A[p] = {a | a is a global variable or formal param of p, such that, for some proc q and integer i, p calls q with a as the i^{th} actual param and the i^{th} formal param of q is in change[q] }
- G[p] = {g | g is a global in change[q] and p calls q }
- We use a simplified calling graph whose nodes are procedures. There is an edge from p to q if p calls q somewhere in the program

Example for the set A[p]

procedure p(...)
{ call q(...,**a**,...)
  ...
}

procedure $q(b_1,b_2,\ldots,\mathbf{b_i},\ldots,b_n)$
{ ...
}

i^{th} actual parameter

i^{th} formal parameter and $\mathbf{b_i}$ is in change[q]

Change Computation

- Input: A calling graph with a collection of procedures, p_1, p_2,..., p_n. If the calling graph is acyclic, then we assume that p_i calls p_j only if $j<i$, otherwise, no assumptions
- Output: change[p]
- It is assumed that def[p] is precomputed

Change Computation

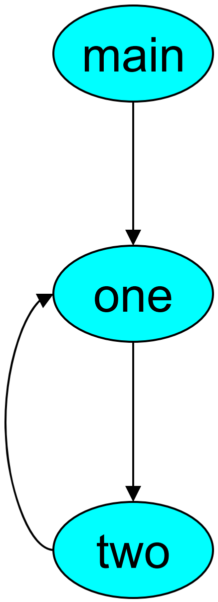
```
for each proc p do change[p] = def[p];
while changes to any change[p] occur do {
   for i = 1 to n do {
     for each proc q called by p_i do {
       1. add any globals in change[q] to change[p_i];// adding G[p_i]
       2. for each formal parameter x (j^th) of q do
              if x is in change[q] then
                  for each call of q by p_i do
                     if a, the j^th actual param of the call is a
                        global or formal parameter of p_i then
                        add a to change[p_i] // adding A[p_i]
      }
}
```

Alias Analysis Example

```
global g,h;
   procedure main() {
      local i;
      g = ...; one(h,i);
   }
   procedure one(w,x) {
      x = ...;
      two(w,w); two(g,x);
   }
```

```
procedure two(y,z) {
   local k;
   h = ...; one(k,y);
}
```

- **main**: h ≡ w, i ≡ x
- **one**: w ≡ y, w ≡ z,
  g ≡ y, x ≡ z
- **two**: k ≡ w, y ≡ x
- All variables are aliases of each other



def(main) = {g} = change(main), G(main) = Φ
def(two) = {h} = change(two), G(two) = Φ
def(one) = {x} = change(one), G(one) = {h}, since "one" calls "two", h is a global and change(two) contains h

Consider "two". "two" calls "one"
one(k, y) – actual params, k is local
one(w,x) – formal params, x is in change(one)
Therefore, A(two) = {y}, change(two) = {h,y}

Consider "one". "one" calls "two" twice
two(w, w) – actual params
two(y, z) – formal params, y is in change(two)
Therefore, A(one) = {w}
two(g, x) – actual params
two(y, z) – formal params, y is in change(two)
Therefore, A(one) = {w,g}, change(one) = {w,g,h,x}

Consider "main". "main" calls "one"
one(h, i) – actual params, i is local
one(w, x) – formal params, w is in change(one)
Therefore, A(main) = {h}, change(main) = {g,h}

Use of Change Information in computing Available Expressions – Method 1

- Each procedure call is a separate basic block
- Method 1: B is a block for call to proc p
  - a_gen[B] = Φ, for all proc call basic blocks
  - a_kill[B]: if a variable b is in change[p], then b kills all expressions involving b and its aliases
  - a_gen and a_kill for all other types of blocks are computed in the usual manner
  - Knowing a_gen[B] and a_kill[B] for proc call blocks, computing IN[B] and OUT[B] for all blocks in the whole procedure proceeds in the usual manner

Use of Change Information in computing Available Expressions – Method 2

- Compute IN and OUT for all blocks in all procedures as usual, after computing a_gen and a_kill for procedure calls as in method 1
- a_out at the return point from a procedure p can be taken as a_gen[p] for a block with a call to p (with no aliases applied)
  - However, consider only those expressions in a_out with all their variables in change[p]
  - We substitute actual params for the formal params and see what expressions are generated by the call
- Without changing a_kill for proc call blocks, computations of IN and OUT are repeated
- This procedure is repeated until no changes occur