CSC2/455 Software Analysis and Improvement
Interprocedural Analyses - II

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URCS

Outline

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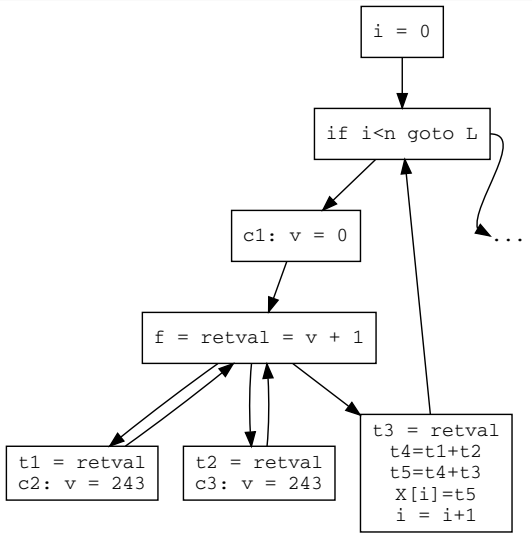
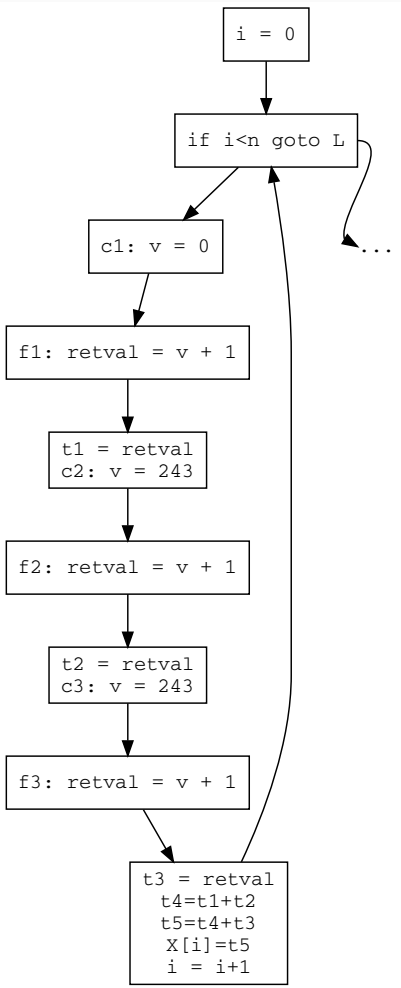
Cloning-based Context-Sensitive Analysis

```
   for(i = 0; i < n; i++) {
c1:      t1 = f1(0);
c2:      t2 = f2(243);
c3:      t3 = f3(243);
         X[i] = t1 + t2 + t3;
   }

   int f1(int v) {
       return (v+1);
   }

   int f2(int v) {
       return (v+1);
   }

   int f3(int v) {
       return (v+1);
   }
```

- Create a clone for each unique calling context and then apply context-insensitive analysis
- Is this the same as inlining?
  - See textbook for a differentiating example

CFG after context-sensitive cloning





The CFG on the left does not distinguish context, the one on the right does

k-level Context-Sensitive Analysis

```
   for(i = 0; i < n; i++) {
c1:      t1 = g(0);
c2:      t2 = g(243);
c3:      t3 = g(243);
         X[i] = t1 + t2 + t3;
   }

   int g(int v) {
       if(v > 1)
          return f(v);
       else
          return (v+1);
   }

   int f(int v) {
       return (v+2);
   }
```

To what depth shall we clone functions?

k-level Context-sensitive analysis

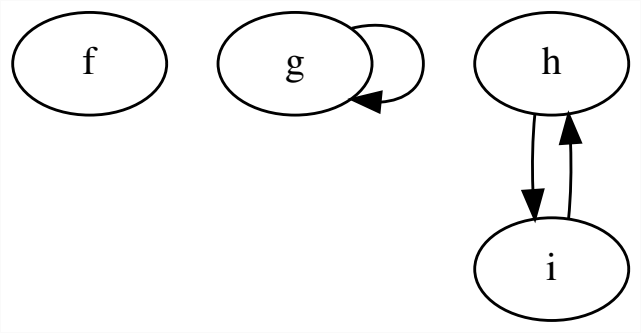
- A function call may be distinguished by its context
  - Calling functions or
  - Call-sites (i.e. call stack)
- If we do not distinguish contexts,
  - context-insensitive
  - $k = 0$
- Different values of k may yield different precision
- No value of k may be sufficient
  - recursive function calls
  - indirect function calls

Some numbers

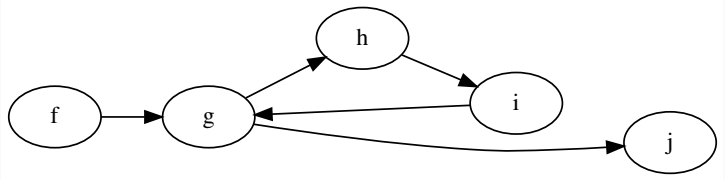
- If there are N functions in a program, how many calling contexts are possible
  - if no recursion is involved?
  - if recursion is involved?

Handling Recursion in Contexts

- Consider nodes in a call graph
  - non-recursive functions
  - self-recursive functions
  - mutually recursive functions
- Look for strongly-connected components
  - trivial (non-recursive)
  - non-trivial (the latter two)



Methods to “finitize” Recursion



- Model them using regular expressions
  - `f(g h i)*j`
- Eliminate all call information within SCC
  - `f g j`

Have contexts, will analyze!

- Cloning-based analysis
  - Clone functions, once per context
  - Followed by context-insensitive analysis
- Summary-based analysis
  - (Bottom-up phase) Compute summaries of each function for an analysis (e.g. constant propagation) in terms of input parameters
  - (Top-down phase) Pass inputs to summaries, one per context OR merge contexts using meet operator
  - Based on Region-based analysis

Outline

Region-based Analysis Framework

- Operates on *regions* of the control flow graph
- A region is defined (informally) as a portion of code with a single entry and single exit
    - Basic blocks are regions
- Recall we need to iterate (in iterative data flow analysis, IDFA) because of loops
- Can we get rid of loops in some way?

Region

A region is a subset N of the nodes, and E of the edges of a (control) flow graph such that:

- There is a header node h that dominates all nodes in N
- If there is a path from m to n that does *not* go through h, then $m \in N$
- E is the set of edges that connect two nodes n_1 and n_2 in N
    - edges into h from outside the region are not part of E

Additionally, if the flow graph is *reducible*, we can organize the regions into a hierarchy

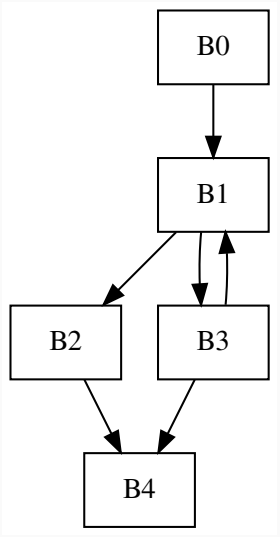
Reducible Graphs

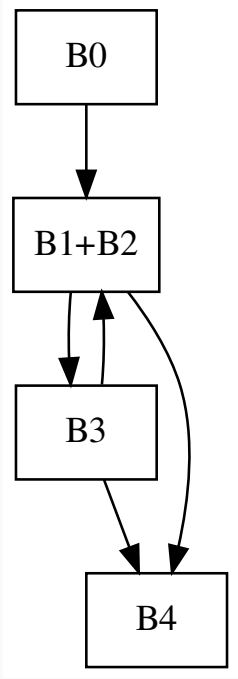
The T1–T2 definition of reducible graphs:

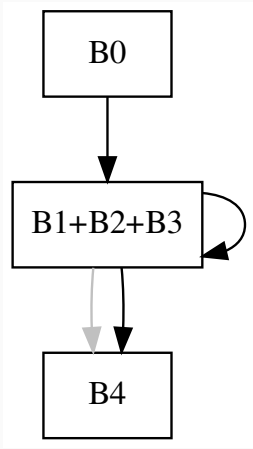
- T1: Remove all self edges on a node
- T2: If a node n has a single predecessor m, combine them into a single node x. Edges into m and out of n are connected to x instead.
- Repeat until neither T1 nor T2 can be applied

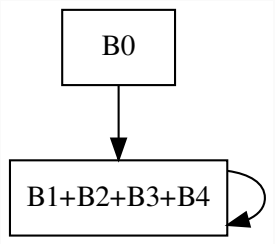
A graph is a reducible if at the end of the above procedure the entire graph is reduced to a single node.

Example: Repeated applications of T2

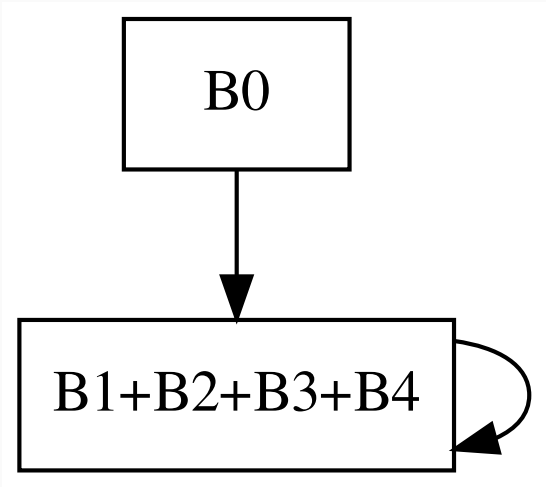


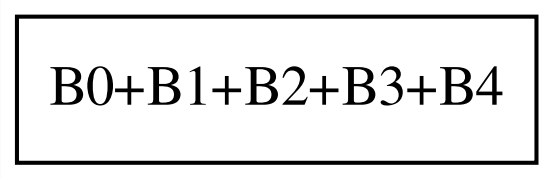






Example: Application of T1 and T2





Non-reducible (or Irreducible) graphs

- Structured code usually produces reducible graphs
- Can you construct an irreducible graph?
- Textbook details some ways of transforming irreducible graphs into reducible graphs

Region Hierarchy

- The smallest regions form *leaf* regions
  - Basic blocks are leaf regions
- Using a process similar to T1/T2 we combine regions into bigger regions
- Until we obtain a single large region

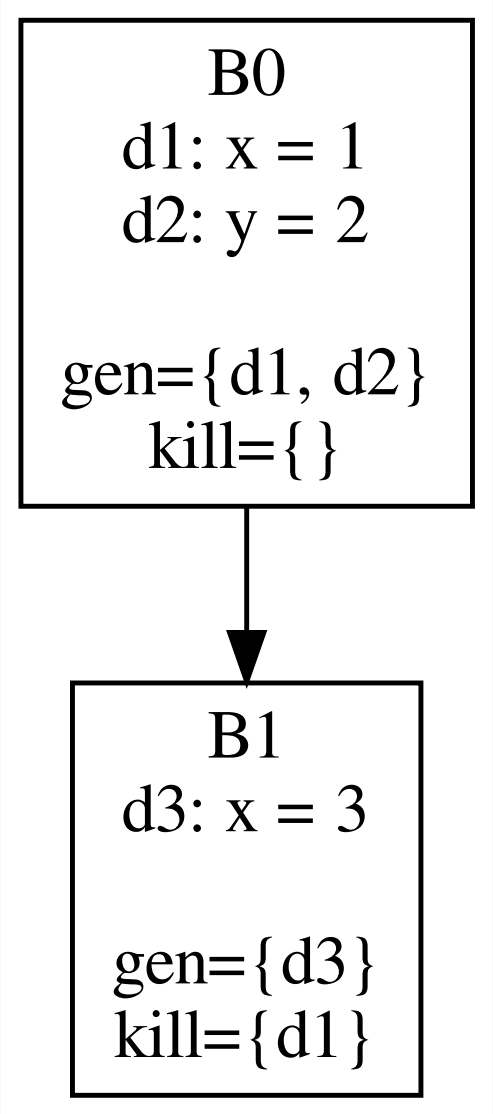
The largest region (i.e. final node) has no loops, and if we could construct an appropriate transfer function, we could analyze this region just as we analyze a basic block.

Basic ideas

- If the region consists of a "linear" sequence of basic blocks
  - Say B_1 followed by B_2, with transfer functions f_1 and f_2 respectively
  - We need to construct the composition $f_2 \circ f_1$
  - This can be extended to regions, i.e. if we have a linear sequence of regions
- If you encounter alternate paths (akin to join nodes)
  - Apply the meet operator *on the transfer functions* (not the values!)
  - i.e. $(f_1 \wedge_f f_2)(x)$, which is defined as $f_1(x) \wedge f_2(x)$
  - Note the second $\wedge$ is the meet operator on data-flow values

Example: Composition for Reaching Definitions

- Recall that reaching definitions has a gen, kill form for its transfer functions
  - $f_b(x) = gen_b \cup (x - kill_b)$
- Here:
  - $f_1(x) = \{d1, d2\} \cup (x - \emptyset)$
  - $f_2(x) = \{d3\} \cup (x - \{d1\})$
- The composed function is:
  - $(f_2 \circ f_1)(x) = \{d2, d3\} \cup (x - \{d1\})$
  - Which is also in gen–kill form



Working out the composed gen-kill form

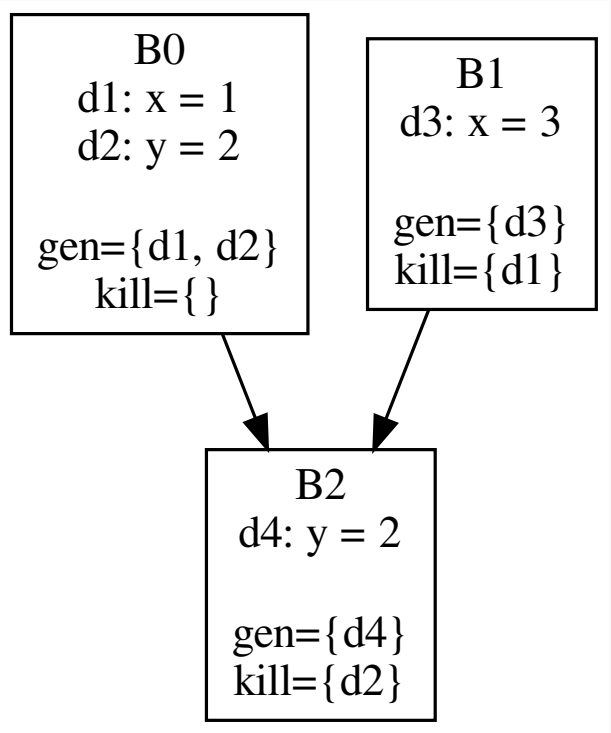
- Here:
  - $f_1(x) = \{d1, d2\} \cup (x - \emptyset)$
  - $f_2(x) = \{d3\} \cup (x - \{d1\})$
- Working it out:
  - $f_2(f_1(x)) = \{d3\} \cup ((\{d1, d2\} \cup (x - \emptyset)) - \{d1\})$
- Symbolic form worked out in the textbook

For gen–kill form

- Composition for gen–kill form is then
  - $kill_\circ$: Union of all kill sets
  - $gen_\circ$: Union of all gen sets - $kill_\circ$
- $f_\circ(x) = gen_\circ \cup (x - kill_\circ)$

Meet for Reaching Definitions

- Merging B0 and B1, we would get:
  - $f_{B0}(x) = \{d1, d2\} \cup (x - \emptyset)$
  - $f_{B1}(x) = \{d3\} \cup (x - \{d1\})$
- Recall that $\wedge$ for reaching definitions is $\cup$
- $(f_{B0} \wedge_f f_{B1})(x) = f_{B0}(x) \cup f_{B1}(x)$
- $(f_{B0} \wedge_f f_{B1})(x) = \{d1, d2, d3\} \cup (x - \emptyset)$
  - $gen_{\wedge} = gen_{B0} \cup gen_{B1}$
  - $kill_{\wedge} = kill_{B0} \cap kill_{B1} = \emptyset$
- $f_{\wedge}(x) = gen_{\wedge} \cup (x - kill_{\wedge})$

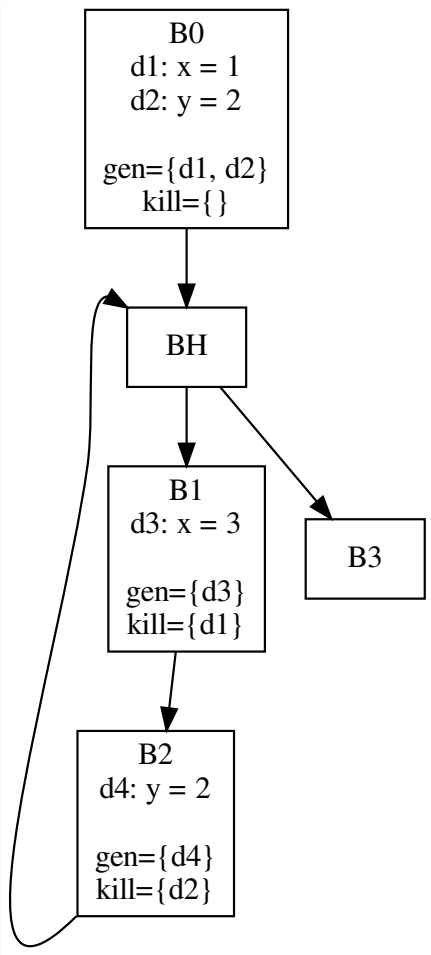


Working out the meet

- $f_{B0}(x) = \{d1, d2\} \cup (x - \emptyset)$
- $f_{B1}(x) = \{d3\} \cup (x - \{d1\})$
- $(f_{B0} \wedge_f f_{B1})(x) = f_{B0}(x) \cup f_{B1}(x)$
  - $(\{d1, d2\} \cup (x - \emptyset)) \cup (\{d3\} \cup (x - \{d1\})$
  - $\{d1, d2\} \cup \{d3\} \cup (x - \emptyset) \cup (x - \{d1\})$
  - $\{d1, d2, d3\} \cup (x - (\emptyset \cap \{d1\}))$
- Hints:
  - $X - Y = X \cap Y^C$
  - $(A^C \cup B^C) = (A \cap B)^C$

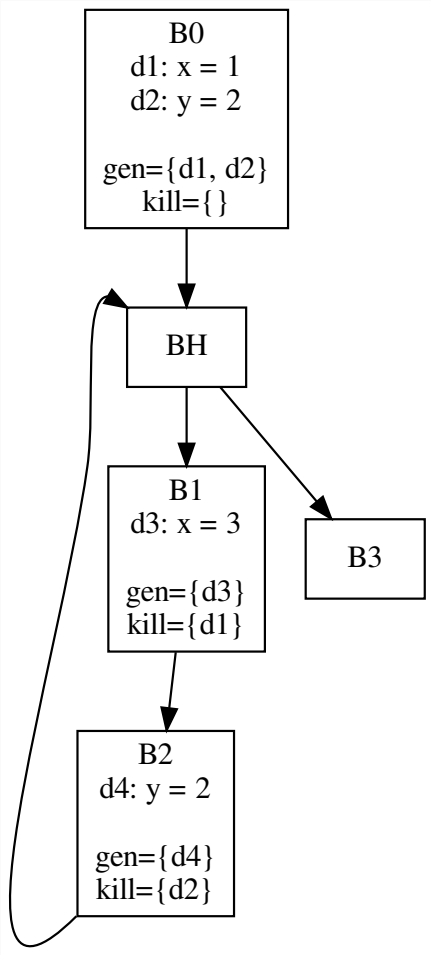
Loop regions for reaching definitions

- Loop region (L) is BH, B1, and B2
- If L is not executed:
  - $f_L^0(x) = x$
- If L is executed once?
  - BH $\rightarrow$ B1 $\rightarrow$ B2 $\rightarrow$ BH (ignore edge from B0 to BH)
  - $f_L^1(x) = \{d3, d4\} \cup (x - \{d1, d2\})$
- If L is executed twice?
  - $f_L^2(x) = f_L(f_L(x))$
  - $f_L^2(x) = \{d3, d4\} \cup (x - \{d1, d2\})$



Loop regions for reaching definitions (2)

- Loop region (L) is BH, B1, and B2
- We have:
  - $f_L^0(x) = x$
  - $f_L^1(x) = \{d3, d4\} \cup (x - \{d1, d2\})$
  - $f_L^2(x) = f_L(f_L(x))$
  - $f_L^n(x) = \{d3, d4\} \cup (x - \{d1, d2\})$
- The gen set for a loop is simply the gen set of its body, and likewise for its kill set



Dealing with loop regions

- If the region consists of a loop,
  - Compose the transfer functions for the body, obtaining f_{body}
  - Compute the effect of one iteration (or one cycle), f
  - Compute the closure of f, denoted f^*
  - f^* is the transfer function of the loop region
- $f^* = \bigwedge_{n \geq 0} f^n$
  - f^n is f applied to itself n times
  - f^0 is loop does not execute, so identity
- Informally:
  - Compute the transfer function of not going into the loop (essentially, identity), meet it with
  - Compute the transfer function of executing the loop once, and meet it with
  - the transfer function of executing the loop twice, and meet it with
  - ...

Loop regions for Reaching Definitions

- $f^* = f^0 \wedge f^1 \wedge f^2 ...$
- $f^* = x \cup (gen \cup (x - kill)) \cup (gen \cup (x - kill)) ...$
- $f^* = x \cup (gen \cup (x - kill))$
- $f^* = x \cup gen \cup x$
- $f^* = gen \cup (x - \emptyset)$

For a loop region, in reaching definitions, the transfer function (i.e., the closure) only generates definitions, but doesn't kill any definition

Why we need reducible graphs

- In reducible graphs:
  - loops are properly nested or are disjoint
- Repeat composition, meet and closure until you obtain the transfer function for the whole region

The Region-based Analysis Framework

- Compute regions of the flow graph
- Compute, in a bottom-up fashion (from innermost region to outermost), the transfer functions for each region
- Compute, in a top-down fashion (from outermost to innermost), the results of the analysis

- Algorithm 9.53 in the Dragon Book
- Work out Example 9.54 in the Dragon book
- Example 12.8 in the textbook uses summary-based analysis for interprocedural constant propagation

Outline

Recall

Recall how we compute and update pointsTo sets from last class...

Flavours

- Flow-sensitive/Flow-insensitive
- Context-insensitive
- Context-sensitive
  - Cloning-based
  - Summary-based

What the textbook describes

- Flow-insensitive
- Context-sensitive
  - With non-trivial SCCs treated as a single node
- Cloning-based

Additionally, the Dragon book formulates the points-to analysis as a (datalog) logical formula to be solved.

Dynamic Call Graph Construction

```
class t {
    t n() { return new r(); }  /* call site g */
}

class s extends t {
    t n() { return new s(); }  /* call site h */
}

class r extends s {
    t n() { return new r(); }  /* call site i */
}

main() {
    t a = new t();             /* call site j */
    a = a.n();
}
```

What is a potential call graph for `a.n()` from the points-to relationships?

Outline

References

- Chapter 12 of the Dragon Book
  - Region-based analysis is from Chapter 9, Section 9.7
- Paper recommended:
  - Reps et al. "Precise interprocedural dataflow analysis via graph reachability"