Data Flow Analysis

CSCE 747 - Lecture 9 - 02/07/2017

Data Flow

- Another view - program statements compute and transform data…
  - So, look at how that data is passed through the program.
- Reason about **data** dependence
  - A variable is used here - where does its value come from?
  - Is this value ever used?
  - Is this variable properly initialized?
  - If the expression assigned to a variable is changed what else would be affected?

Data Flow

- Basis of the optimization performed by compilers.
- Used to derive test cases.
  - Have we covered the dependencies?
- Used to detect faults and other anomalies.
  - Is this string tainted by a fault in the expression that calculates its value?

Definition-Use Pairs

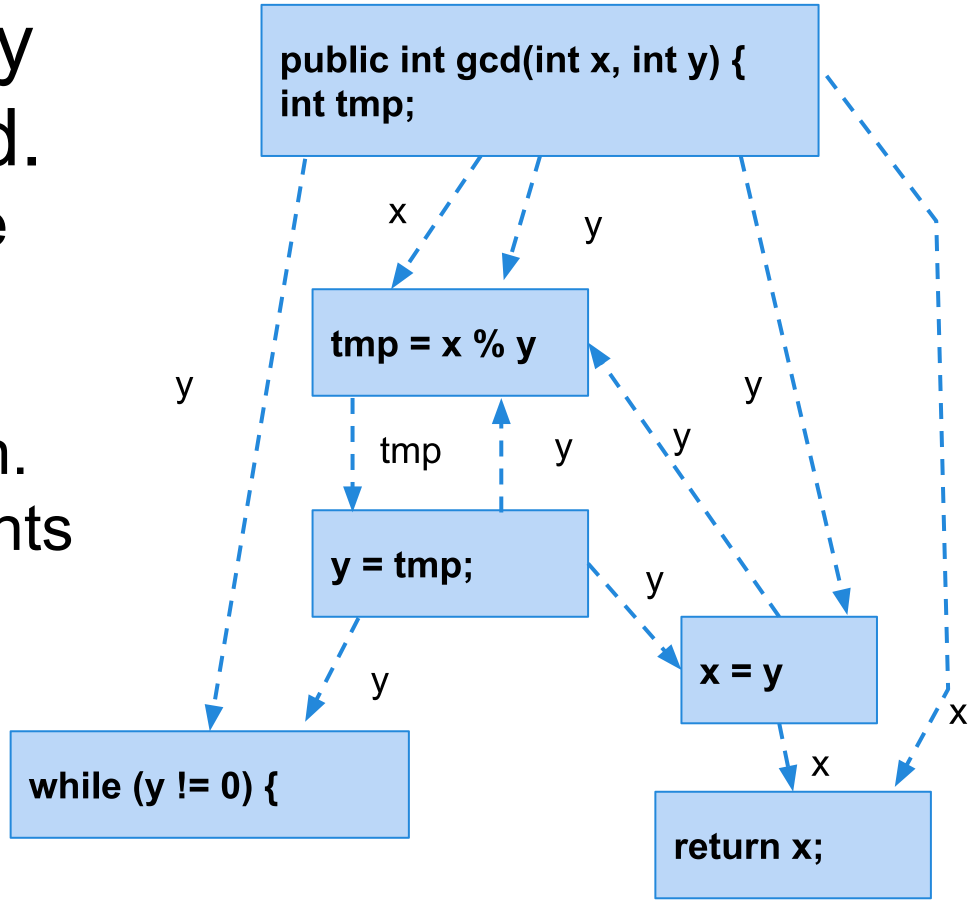
- Data is defined.
  - Variables are declared and assigned values.
- … and data is used.
  - Those variables are used to perform computations.
- Associations of definitions and uses capture the flow of information through the program.
  - Definitions occur when variables are declared, initialized, assigned values, or received as parameters.
  - Uses occur in expressions, conditional statements, parameter passing, return statements.

Data Dependence

- If a definition is impacted by a fault, all uses of that definition will be too.
- Uses are *dependent* on definitions.
- Tests and analyses that focus on these dependencies are likely to detect faults.
- Tests and analyses can be designed to cover different def-use pairs.

Data Dependence

- Data dependency can be visualized.
    - Data dependence graph
    - Paired with control-flow graph.
    - Nodes = statements
    - Edges = data dependence



public int gcd(int x, int y) {
int tmp;

tmp = x % y

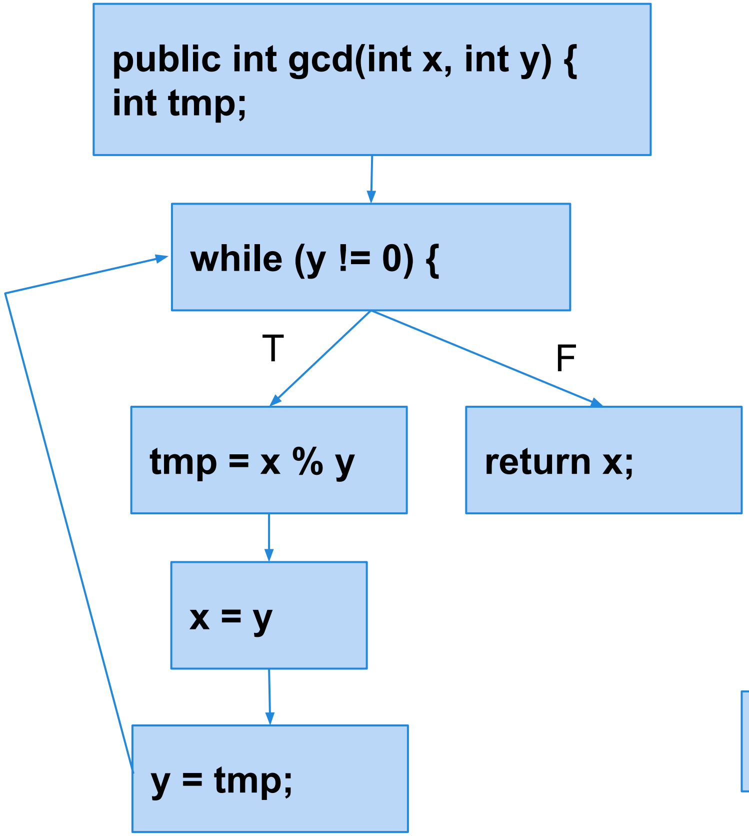
y = tmp;

x = y

while (y != 0) {

return x;

Forming the Data Dependence Graph



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while (y != 0) {

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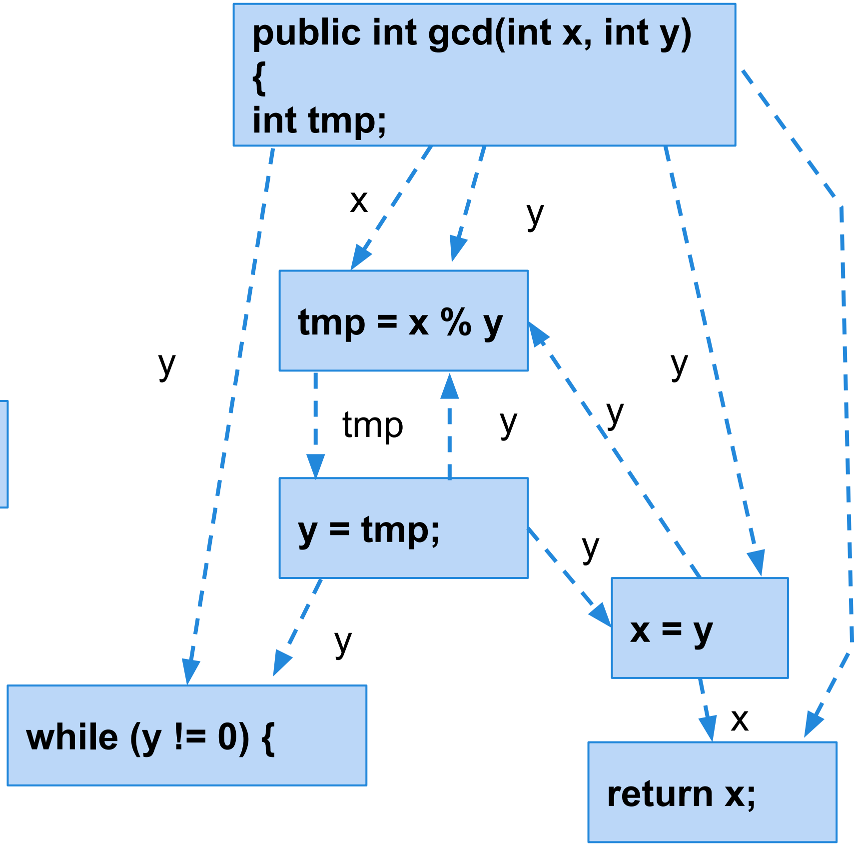

public int gcd(int x, int y)
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int tmp;

tmp = x % y

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while (y != 0) {

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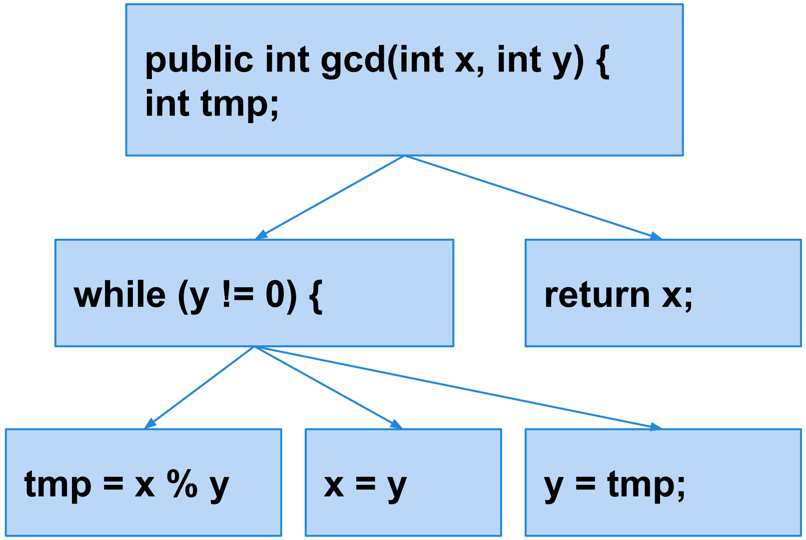
Control-Dependence

- A node that is reached on every execution path from entry to exit is control dependent only on the entry point.
- For any other node N, that is reached on some - but not all - paths, there is some branch that controls whether that node is executed.
- Node M *dominates* node N if every path from the root of the graph to N passes through M.

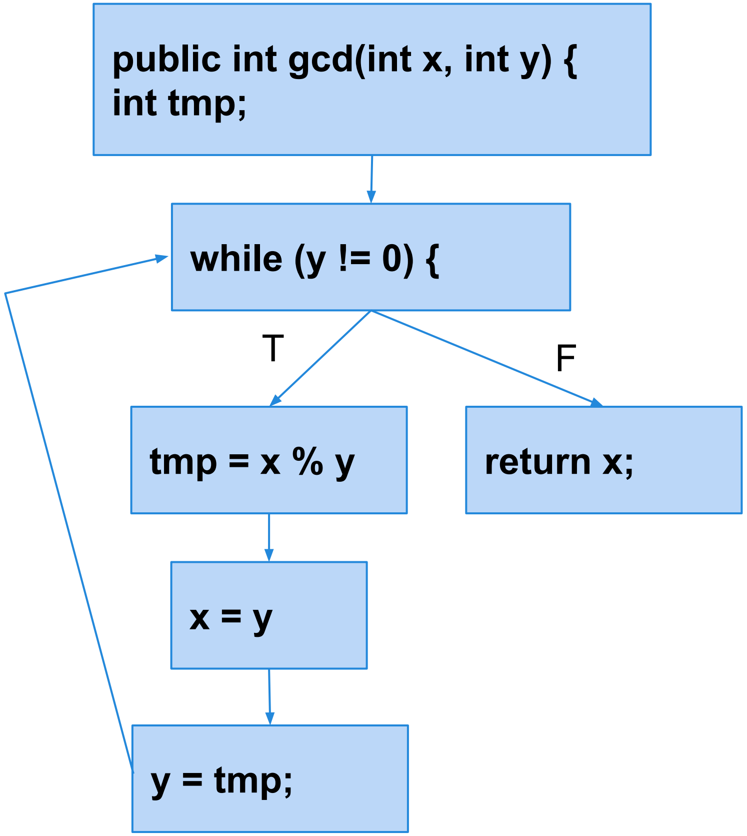
Control Dependence Graph

Which statement controls the execution of a statement of interest?

- In a CFG, order is imposed whether it matters or not.
  - If there is dependency, then the order does matter.
- CDG shows only dependencies.
- Often combined with DDG.



Forming the Control Dependence Graph



public int gcd(int x, int y) {
int tmp;

while (y != 0) {

T

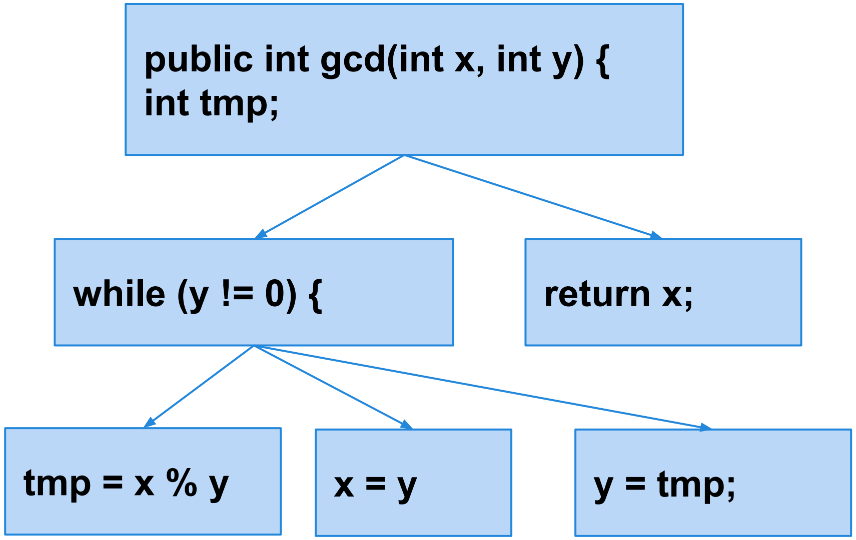
F

tmp = x % y

return x;

x = y

y = tmp;



public int gcd(int x, int y) {
int tmp;

while (y != 0) {

return x;

tmp = x % y

x = y

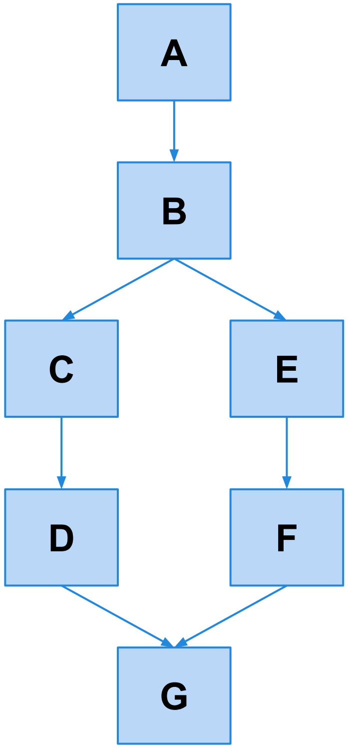
y = tmp;

Domination

- Nodes typically have many dominators.
- Except for the root, a node will have a unique ***immediate dominator***.
  - Closest dominator of N on any path from the root and which is dominated by all other dominators of N.
  - Forms a dependency tree.
- **Post-Domination** can also be calculated in the reverse direction of control flow, using the exit node as root.

Domination Example

- A pre-dominates all nodes
- G post-dominates all nodes
- F and G post-dominate E
- G is the immediate post-dominator of B
- C does *not* post-dominate B
- B is the immediate pre-dominator of G
- F does *not* pre-dominate G

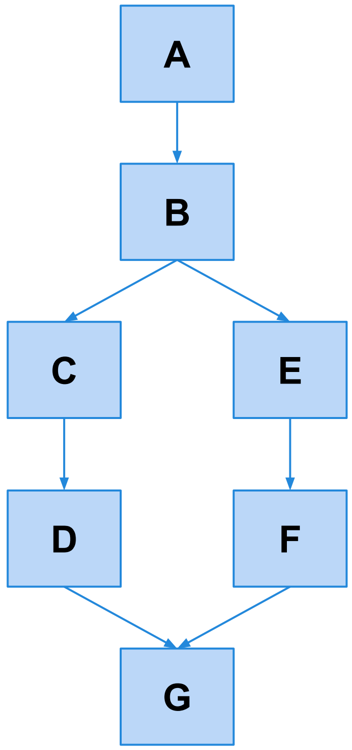


Post-Dominators and Control Dependency

- Node N is reached on some paths.
- N is control-dependent on a node C if that node:
    - Has two or more successor nodes.
    - Is not post-dominated by N.
    - Has a successor that is post-dominated by N.

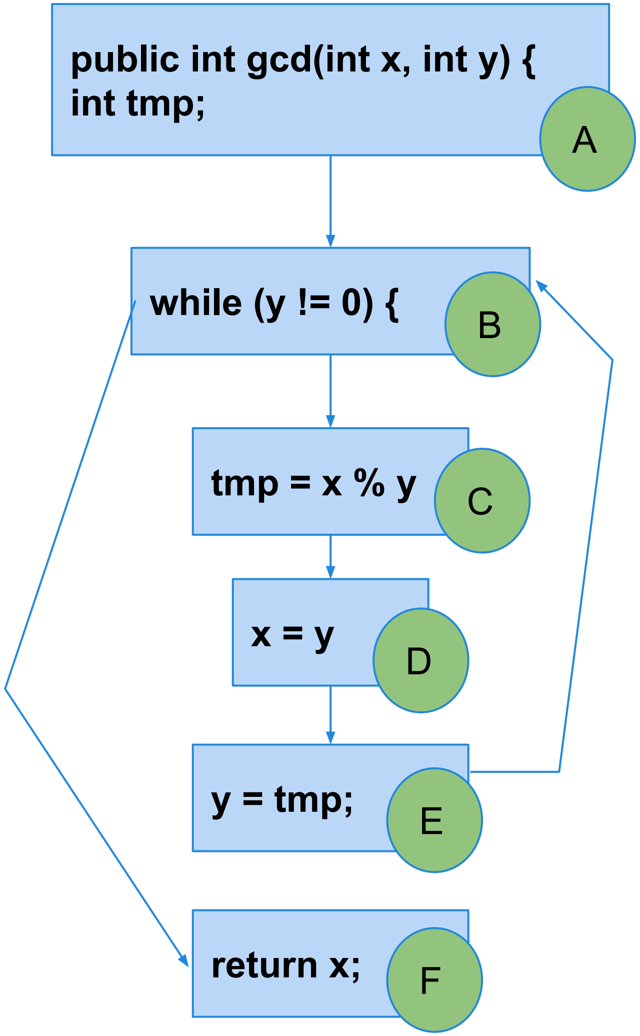
Control-Dependency Example

- Execution of F is not inevitable at B.
- Execution of F is inevitable at E.
- F is control-dependent on B - the last point at which it is not inevitable.



GCD Example

- B and F are inevitable
  - Only dependent on entry (A).
- C, D, and E (nodes in the loop) depend on the loop condition (B).



```
public int gcd(int x, int y) {
int tmp;
```

```
while (y != 0) {
```

```
tmp = x % y
```

```
x = y
```

```
y = tmp;
```

```
return x;
```

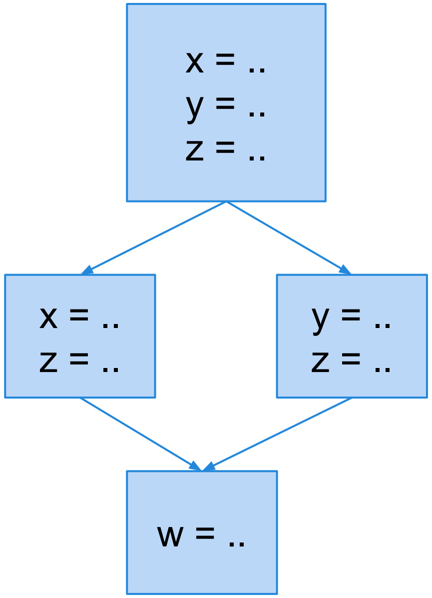
Data Flow Analysis

Reachability

- Def-Use pairs describe paths through the program's control flow.
  - There is a (*d*,*u*) pair for variable *V* only if at least one path exists between *d* and *u*.
  - If this is the case, a definition V_d **reaches** *u*.
    - V_d is a *reaching definition* at *u*.
  - If the path passes through a new definition V_e, then V_e *kills* V_d.

Computing Def-Use Pairs

- One algorithm: Search the CFG for paths without redefinitions.
  - Not practical - remember path coverage?
- Instead, summarize the reaching definitions at a node over all paths reaching that node.

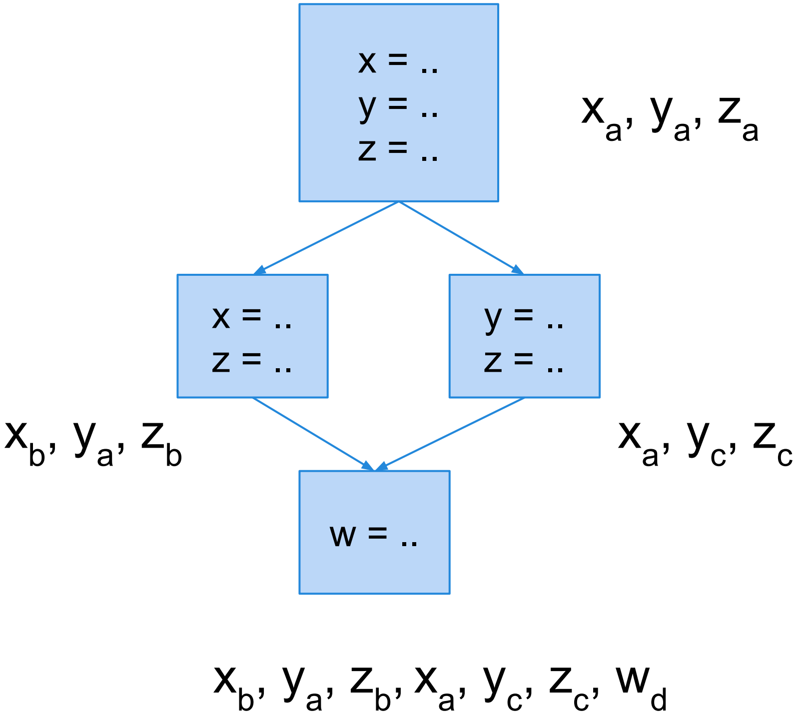


Computing Def-Use Pairs

- If we calculate the reaching definitions of node *n*, and there is an edge (*p*, *n*) from an immediate predecessor node *p*.
    - If p can assign a value to variable *v*, then definition v_p reaches *n*.
        - v_p is *generated* at *p*.
    - If a definition v_d reaches *p*, and if there is no new definition, then v_d is *propagated* from *p* to *n*.
        - If there is a new definition, v_p kills v_d and v_p propagates to n.

Computing Def-Use Pairs

- The reaching definitions flowing out of a node include:
  - All the reaching definitions flowing in
  - Minus the definitions that are killed
  - Plus the definitions that are generated



Flow Equations

- As node *n* may have multiple predecessors, we must merge their reaching definitions:
    - $\text{ReachIn}(n) = \bigcup_{p \in \text{pred}(n)} \text{ReachOut}(p)$
- The definitions that reach out are those that reach in, minus those killed, plus those generated.
    - $\text{ReachOut}(n) = (\text{ReachIn}(n) \setminus \text{kill}(n)) \cup \text{gen}(n)$

Computing Reachability

- Initialize
    - *ReachOut* is empty for every node.
- Repeatedly update
    - Pick a node and recalculate *ReachIn*, *ReachOut.*
- Stop when stable
    - No further changes to *ReachOut* for any node
    - Guaranteed because the flow equations define a *monotonic* function on the finite *lattice* of possible sets of reaching definition.

Iterative Worklist Algorithm

- Initialize the reaching definitions flowing out to

Keep a *worklist* of nodes to be processed.

At each step remove an element from the *worklist* and process it

- C

Calculate the flow equations.

If the recalculated value is different for the node add its successors to the worklist.

```
for(n ∈ nodes){
    ReachOut(n) = {};
}
workList = nodes;
while(workList != {}){
    n = a node from the workList;
    workList = workList \ {n};
    oldVal = ReachOut(n);
    ReachIn(n) = $\cup_{p \in pred(n)}$ ReachOut(p);
    ReachOut(n) = (ReachIn(n) \ kill(n)) ∪ gen(n)
    if(ReachOut != oldVal){
        workList = workList ∪ succ(n);
    }
}
```

Can this algorithm work for other analyses?

- ReachIn/ReachOut are flow equations.
    - They describe passing information over a graph.
    - Many other program analyses follow a common pattern.
- Initialize-Repeat-Until-Stable Algorithm
    - Would work for any set of flow equations as long as the constraints for convergence are satisfied.
- Another problem - expression availability.

Available Expressions

- When can the value of a subexpression be saved and reused rather than recomputed?
  - Classic data-flow analysis, often used in compiler construction.
- Can be defined in terms of paths in a CFG.
- An expression is *available* if - for all paths through the CFG - the expression has been computed and not later modified.
  - Expression is *generated* when computed.
  - … and *killed* when any part of it is redefined.

Available Expressions

- Like with reaching, availability can be described using flow equations.
- The expressions that become available (gen set) and cease to be available (kill set) can be computed simply.
- Flow equations:
    - $\text{AvailIn}(n) = \bigcap_{p \in \text{pred}(n)} \text{AvailOut}(p)$
    - $\text{AvailOut}(n) = (\text{AvailIn}(n) \setminus \text{kill}(n)) \cup \text{gen}(n)$

Iterative Worklist Algorithm

- Input:
  - A control flow graph G = (nodes, edges)
  - pred(n)
  - succ(n)
  - gen(n)
  - kill(n)
- Output:
  - AvailIn(n)

```
for(n ∈ nodes){
    AvailOut(n) = set of all expressions
    defined anywhere;
}
workList = nodes;
while(workList != {}){
    n = a node from the workList;
    workList = workList \ {n};
    oldVal = AvailOut(n);
    AvailIn(n) = $\bigcap_{p \in pred(n)}$ AvailOut(p)
    AvailOut(n) = (AvailIn(n) \ kill(n)) ∪
                  gen(n)
    if(AvailOut != oldVal){
        workList = workList ∪ succ(n);
    }
}
```

Analysis Types

- Both reaching definitions and expression availability are calculated on the CFG in the direction of program execution.
    - They are *forward* analyses.
- Definitions can reach across *any path*.
    - The in-flow equation uses a union.
    - This is a *forward*, *any-path* analysis.
- Expressions must be available on *all paths*.
    - The in-flow equation uses an intersection.
    - This is a *forward, all-paths* analysis.

Forward, All-Paths Analyses

- Encode properties as tokens that are generated when they become true, then killed when they become false.
  - The tokens are "used" when evaluated.
- Can evaluate properties of the form:
  - "G occurs on all execution paths leading to U, and there is no intervening occurrence of K between G and U."
  - Variable initialization check:
    - G = variable-is-initialized, U = variable-is-used
    - K = *variable-is-uninitialized* (kill set is empty)

Backward Analysis - Live Variables

- Tokens can flow backwards as well.
- Backward analyses are used to examine what happens *after* an event of interest.
- “Live Variables” - analysis to determine whether the value held in a variable may be used.
    - A variable may be considered live if there is any possible execution path where it is used.

Live Variables

- A variable is live if its current value may be used before it is changed.
- Can be expressed as flow equations.
    - $\text{LiveIn}(n) = \bigcup_{p \in \text{succ}(n)} \text{LiveOut}(p)$
        - Calculated on successors, not predecessors.
    - $\text{LiveOut}(n) = (\text{LiveIn}(n) \setminus \text{kill}(n)) \cup \text{gen}(n)$
- Worklist algorithm can still be used, just using successors instead of predecessors.

Backwards, Any-Paths Analyses

- General pattern for backwards, any-path:
  - “After D occurs, there is at least one execution path on which G occurs with no intervening occurrence of K.”
    - D indicates a property of interest. G is when it becomes true. K is when it becomes false.
    - Useless definition check, D = variable-is-assigned, G = variable-is-used, K = variable-is-reassigned.

Backwards, All-Paths Analyses

- Check for a property that must inevitably become true.
- General pattern for backwards, all-path:
  - “After D occurs, G always occurs with no intervening occurrence of K.”
  - Informally, “D inevitably leads to G before K”
    - D indicates a property of interest. G is when it becomes true. K is when it becomes false.
    - Ensure interrupts are reenabled, files are closed, etc.

Analysis Classifications

	Any-Paths	**All-Paths**
Forward (pred)	**Reach** *U* may be preceded by G without an intervening *K*	**Avail** *U* is always preceded by G without an intervening *K*
Backward (succ)	**Live** *D* may lead to *G* before *K*	**Inevitability** *D* always leads to *G* before *K*

Crafting Our Own Analysis

- We can derive a flow analysis from run-time analysis of a program.
- The same data flow algorithms can be used.
    - Gen set is “facts that become true at that point”
    - Kill set is “facts that are no longer true at that point”
    - Flow equations describe propagation

Monotonicity Argument

- **Constraint**: The outputs computed by the flow equations must be monotonic functions of their inputs.
- When we recompute the set of “facts”:
  - The gen set can only get larger or stay the same.
  - The kill set can only grow smaller or stay the same.

Example - Taint Analysis

- Built into Perl. Prevents program errors from data validation by detecting and preventing use of “tainted” data in sensitive operations.
- Tracks sources that variables are derived from. Looks for data derived from tainted data, and tracks corrupted program state.
    - String created from concatenating a tainted and a safe string is corrupted by the tainted string.
- Signals an error if tainted data is used in a potentially dangerous way.

Taint Analysis Variant

- Perl monitors values dynamically.
- Alternative - analysis that prevents data that could be tainted from ever being used in an unsafe manner.
- Forward, any-path analysis.
    - Tokens = tainted variables
    - Gen set = any variable assigned a tainted value
    - Kill set = variable cleansed of taintedness

Taint Analysis Variant

- Gen and kill sets depend on the set of tainted variables, which is not constant.
  - Circularity - tainted variable set also depends on gen and kill sets.
- Monotonicity property ensures soundness of the analysis.
  - We evaluate taintedness of an expression with the set {a,b}, then again with {a,b,c}. If it is tainted the first time, it must be tainted the second time.

We Have Learned

- Control-flow and data-flow both capture important paths in program execution.
- Analysis of how variables are defined and then used and the dependencies between definitions and usages can help us reveal important faults.
- Many forms of analysis can be performed using data flow information.

We Have Learned

- Analyses can be *backwards* or *forwards.*
  - … and require properties be true on *all-paths* or *any-path*.
  - Reachability is forwards, any-path.
  - Expression availability is forwards, all-paths.
  - Live variables are backwards, any-path.
  - Inevitability is backwards, all-paths.
- Many analyses can be expressed in this framework.

Next Class

- Data flow test adequacy criteria
- Data flow analysis with arrays and pointers.

- Reading: Chapter 13
- Assignment 2 out - due February 23