A little more on structural testing...

Where Coverage Goes Wrong...

- Testing can only reveal a fault when execution of the faulty element causes a failure, but…
- Execution of a line containing a fault does not guarantee a failure.
  - (a <= b) accidentally written as (a >= b) - the fault will not manifest as a failure if a==b in the test case.
- Merely executing code does not guarantee that we will find all faults.

Don’t Rely on Metrics

- There is a *small* benefit from using coverage as a stopping criterion.
- But, auto-generating tests with coverage as the goal produces poor tests.
- Two key problems - sensitivity to how code is written, and whether infected program state is noticed by oracle.

Sensitivity to Structure

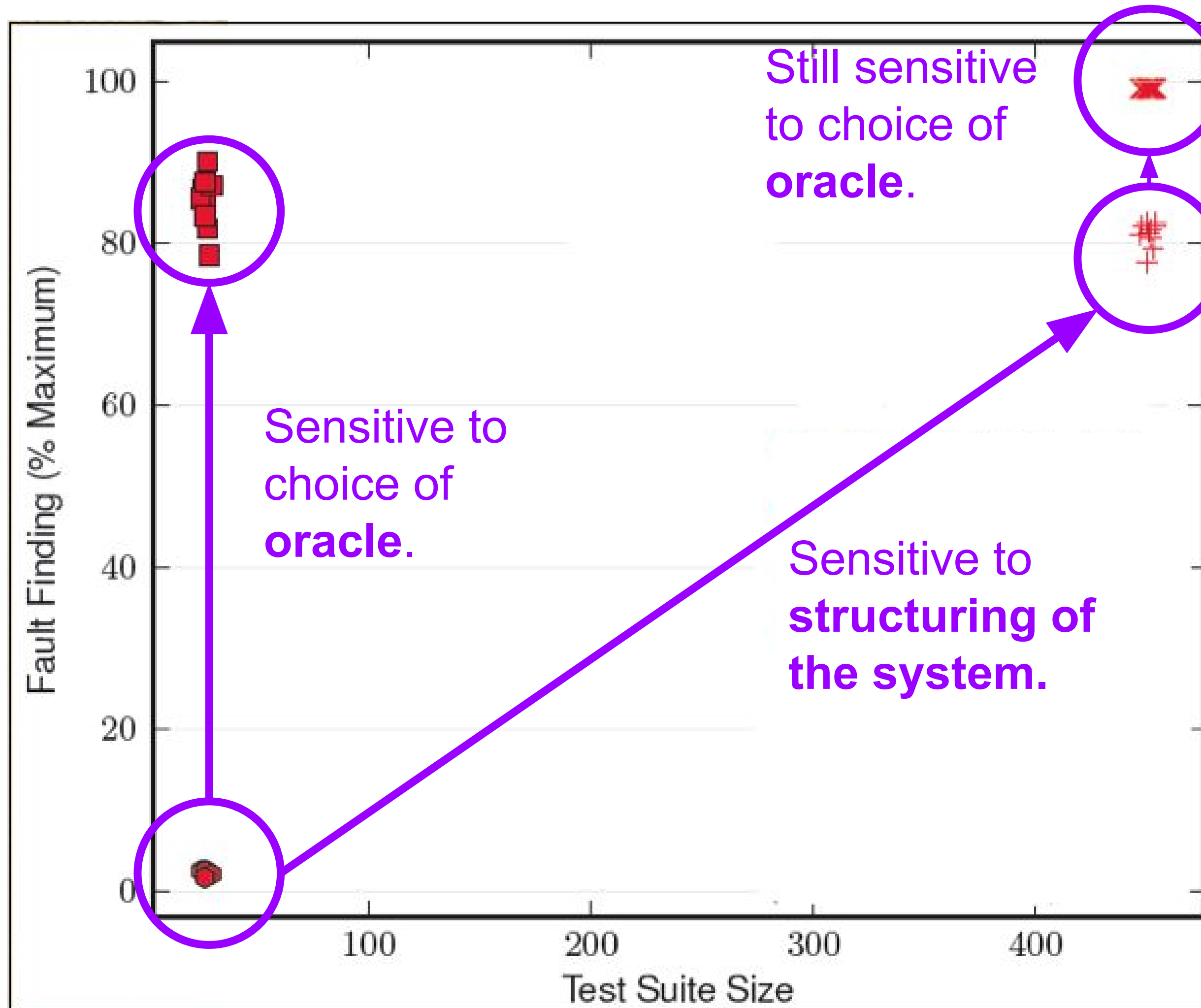
```
expr_1 = in_1 || in_2;
out_1 = expr_1 && in_3;

out_1 = (in_1 || in_2) && in_3;
```

- Both pieces of code do the same thing.
- How code is written impacts the number and type of tests needed.
- Simpler statements result in simpler tests.

Sensitivity to Oracle

- The oracle judges test correctness.
  - We need to choose what results we check when writing an oracle.
- Typically, we check certain output variables.
  - However, masking can prevent us from noticing a fault if we do not check the right variables.
  - We can’t monitor and check all variables.
  - But, we can carefully choose a small number of bottleneck points and check those.
    - Some techniques for choosing these, but still more research to be done.

Coverage Effectiveness



Masking

Why do we care about faults in masked expressions?

- Effect of fault is only masked out for *this* test. It is still a fault. In another execution scenario, it might not be masked.
- We just haven't noticed it yet.
  - The fault isn't gone, we just have bad tests.
- One solution - ensure that there is a path from assignment to output where we will **notice the fault**.

One Solution - Observability

Program `P` containing expression `e` is a transformer from inputs to outputs: `P: I → O`

$P[v/e_n]$ (computed value for n^{th} instance of `e` is replaced by value `v`).

observable(`e`, `t`) = ∃ $v.P(t) \;!= P[v/e_n](t)$

Observable MC/DC

MC/DC + **observability** = Observable MC/DC

Given test suite T, MC/DC obligations are:

$(\forall c_m \in Cond(P) .$

$(\exists t \in T. \; (P(t) != P[true/c_m](t))) \wedge$

$\wedge \; (\exists t \in T. \; (D(t) != D[false/c_n](t))))$

$(\exists t \in T. \; (P(t) != P[false/c_n]$

Idea: Lift observability from decision level to program level.

Tagging Semantics

Assign each condition a **tag set**:

`(ID, Boolean Outcome)`

Evaluation determines tag propagation:

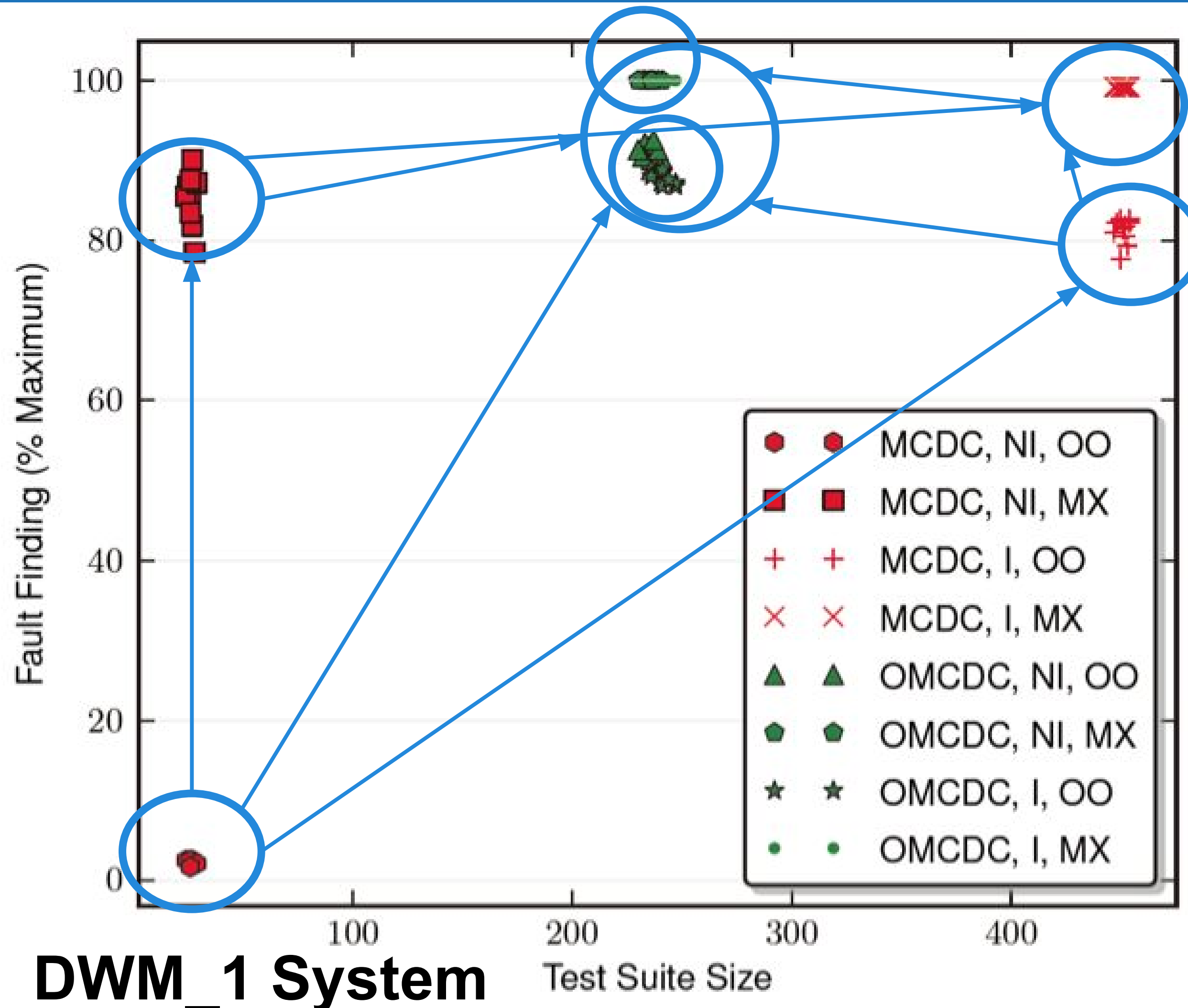
`exp1=c1 && c2;`	[~~(c1,true)~~, (c2,false)]
`exp2=c3 || c4;`	[(c3,true), ~~(c4,false)~~]
`out=if (c5) then exp1 else exp2;`	[(c5,true),<exp1>,<exp2>] [(c5,true),(c2,false), ~~<exp2>~~]

Benefits of Observability

OMC/DC should improve test effectiveness by accounting for **program structure** and **oracle composition**:

- We select what points the oracle monitors, OMC/DC requires propagation path to those points.
- No sensitivity to structure because impact must be propagated at monitoring points.
  - i.e., we place conditions on the path taken.

Evaluation - Results



DWM_1 System

Still Not a Solved Problem

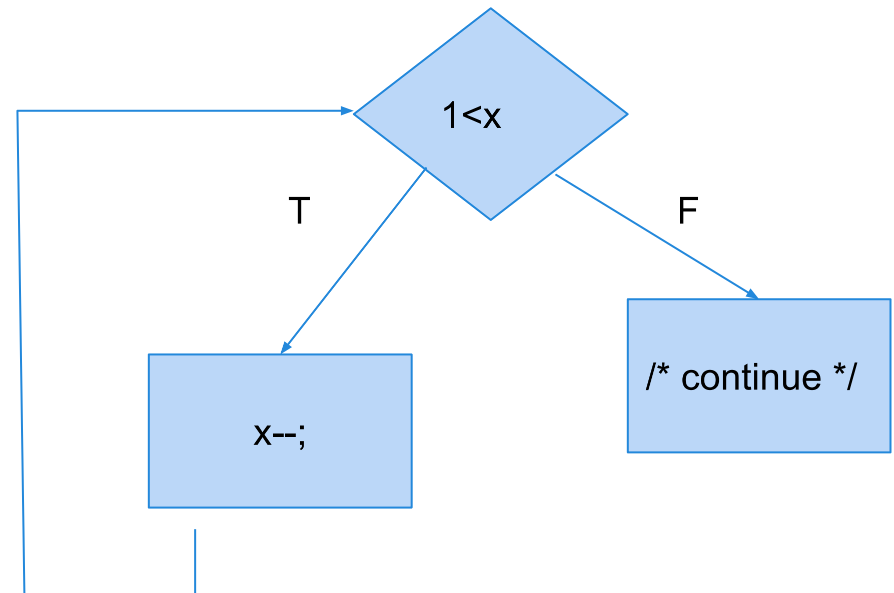
- OMC/DC often prescribes a large number of infeasible obligations.
- Tests can be difficult to derive.
- Often results in better fault-finding, but not 100% fault-finding (especially in complex systems).
- New coverage metrics and structural coverage methods are being formulated.

Data Flow Analysis

CSCE 747 - Lecture 8 - 02/04/2016

Control Flow

- Capture dependencies between parts of the program, based on "passing of control" between those parts.
- We care about the effect of a statement when it affects the path taken.
  - but deemphasize the information being transmitted.



Data Flow

- Another view - program statements compute and transform data…
  - So, look at how that data is passed through the program.
- Reason about 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

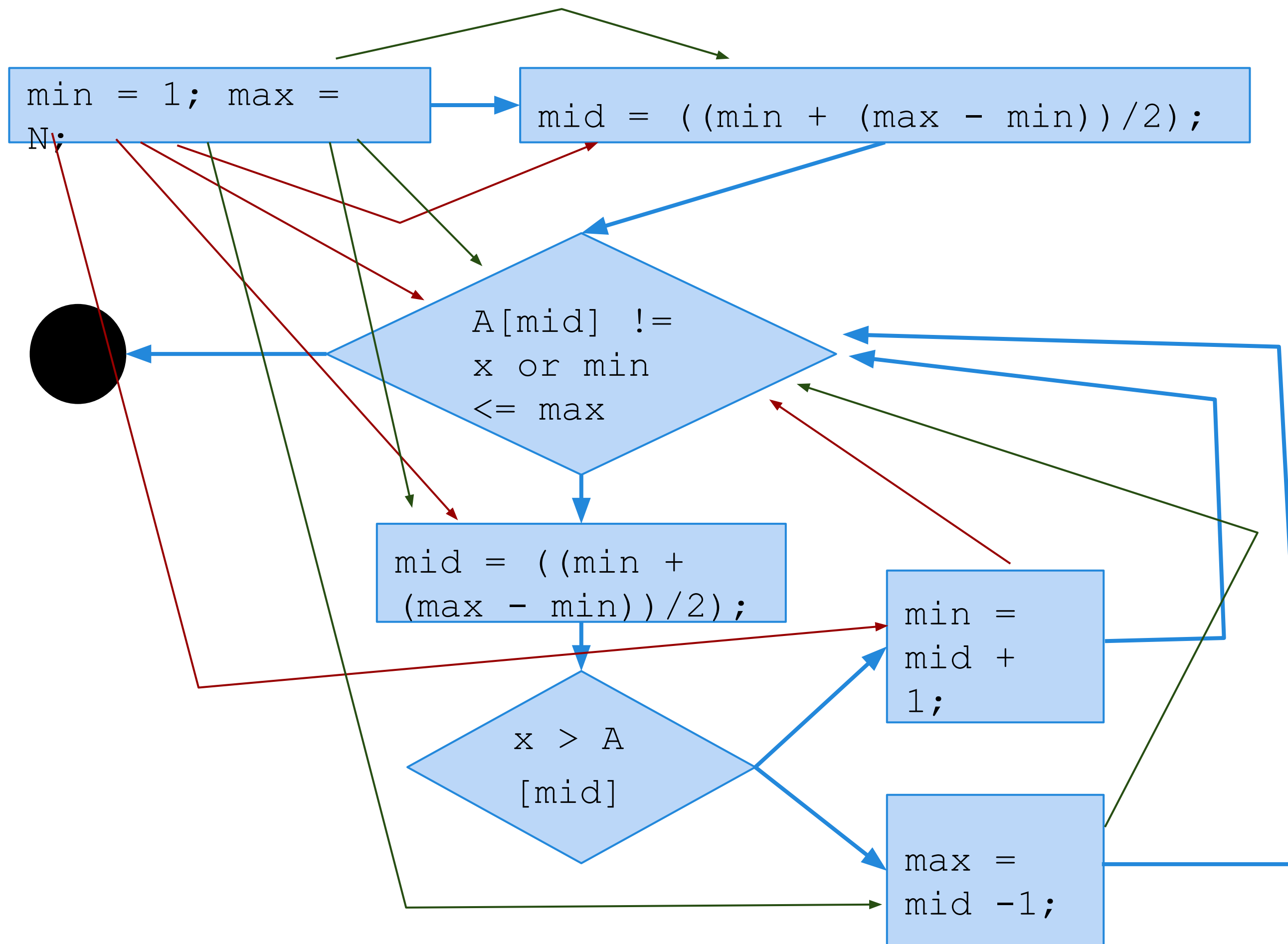
- Data is defined.
  - Variables are declared and assigned values.
- … and data is used.
  - Those variables are used to perform computations.
- Associations of definitions and uses capture the flow of information through the program.
  - Definitions occur when variables are declared, initialized, assigned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

Example - Definition-Use Pairs

```
 1.  min = 1;
 2.  max = N;
 3.  mid = ((min + (max - min))/2);
 4.  while (A[mid] != x or min <= max){
 5.      mid = ((min + (max - min))/2);
 6.      if (x > A[mid]){
 7.          min = mid + 1
 8.      } else {
 9.          max = mid - 1;
10.      }
11.  }
```

1. **def** - min
2. **def** - max, **use** - N
3. **def** - mid, **use** - min, max
4. **use** - A[mid], mid, x, min, max
5. **def** - mid, **use** - min, max
6. **use -** x, A[mid], mid
7. **def -** min, **use** - mid
8. -
9. **def -** max, **use -** mid

Example - Definition-Use Pairs



1. **def** - min
2. **def** - max, **use** - N
3. **def** - mid, **use** - min, max
4. **use** - A[mid], mid, x, min, max
5. **def** - mid, **use** - min, max
6. **use -** x, A [mid], mid
7. **def -** min, **use** - mid
8. -
9. **def -** max, **use -** mid

Def-Use Pairs

- We can say there is a def-use pair when:
  - There is a *def* (definition) of variable *x* at location A.
  - Variable *x* is *used* at location B.
  - A control-flow path exists from A to B.
  - and the path is *definition-clear* for x.
    - If a variable is redefined, the original def is *killed* and the pairing is between the new definition and its associated use.

Example - GCD

```
1.  public int gcd(int x, int y){
2.        int tmp;
3.        while(y!=0){
4.              tmp = x % y;
5.              x = y;
6.              y = tmp;
7.        }
8.        return x;
9.  }
```

1. def: x, y
2. def: tmp
3. use: y
4. use: x, y
   def: tmp
5. use: y
   def: x
6. use: tmp
   def: y
7. -
8. use: x

Example - GCD

```
1.  public int gcd(int x, int y){
2.        int tmp;
3.        while(y!=0){
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6.              y = tmp;
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```
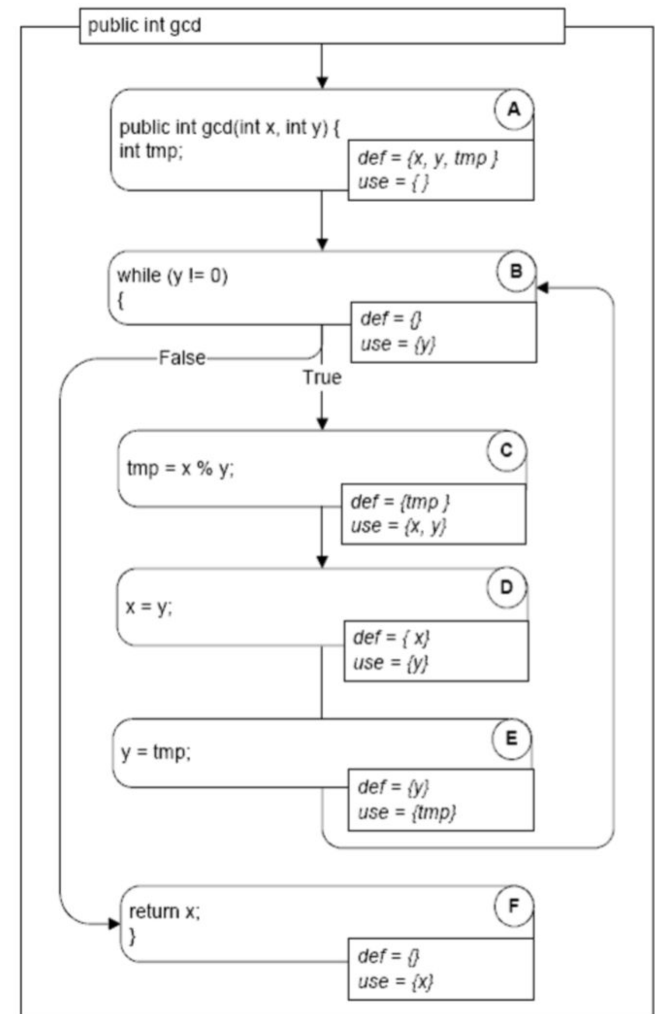
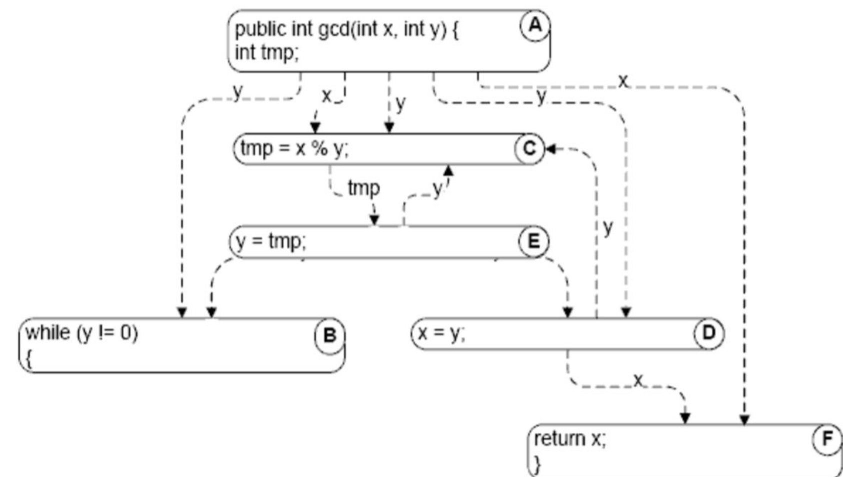

1. def: x, y
2. def: tmp
3. use: y
4. use: x, y def: tmp
5. use: y def: x
6. use: tmp def: y
8. use: x



Data Dependence

- If a definition is impacted by a fault, all uses of that definition will be too.
- Uses are *dependent* on definitions.
- Tests that focus on these dependencies are likely to trigger faults.
- Data dependency can be visualized.
  - Nodes = statements
  - Edges = data dependence



Control-Dependence

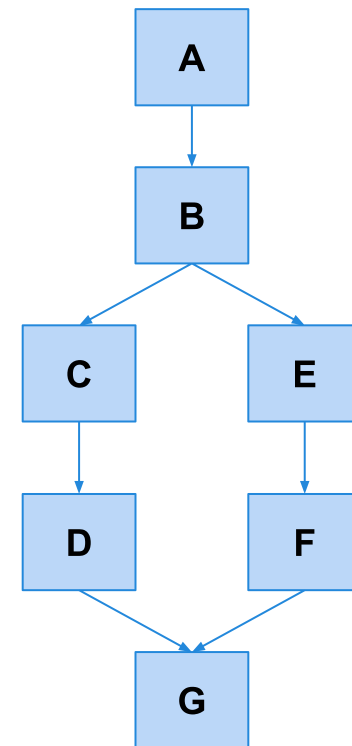
- A node that is reached on every execution path from entry to exit is control dependent only on the entry point.
- For any other node N, that is reached on some - but not all - paths, there is some branch that controls whether that node is executed.
- Node M *dominates* node N if every path from the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

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.
- Domination can also be calculated in the reverse direction of control flow, using the exit node as root.
  - Dominators in this direction are called post-dominators.

Domination Example

- To understand control-dependence, look at pre and post-dominators.
  - 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

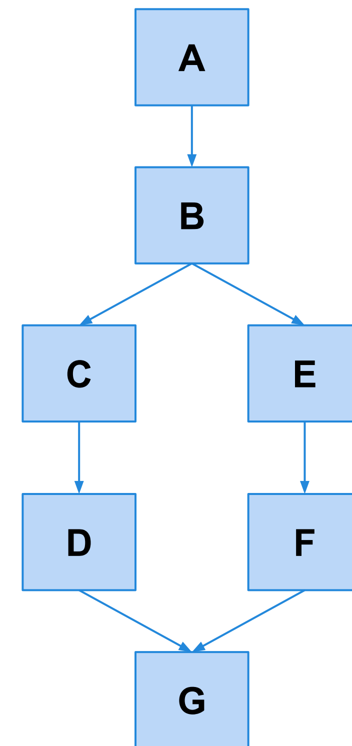


Post-Dominators and Control Dependency

- 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.

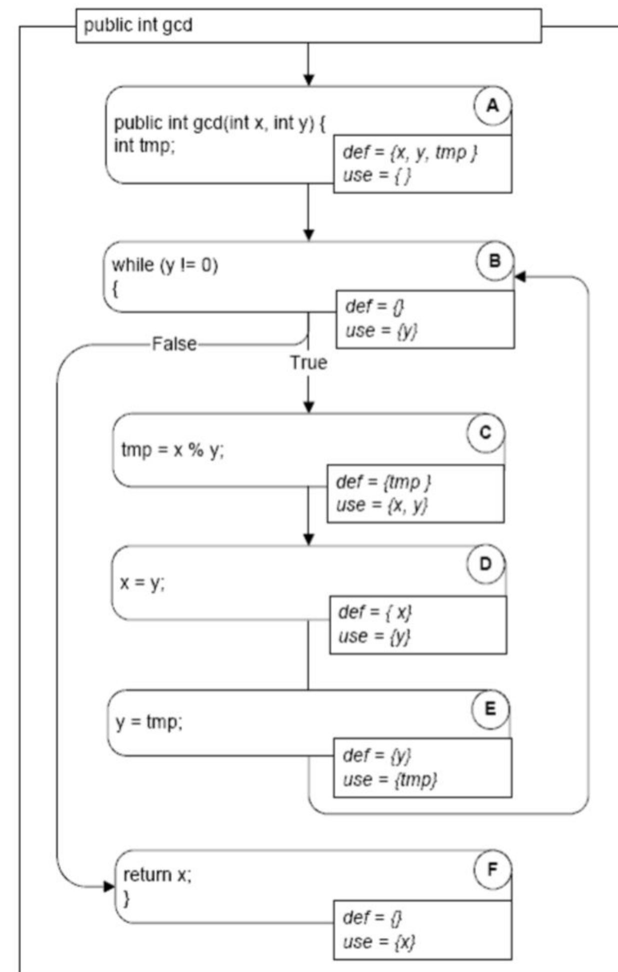
Control-Dependency Example

- 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).



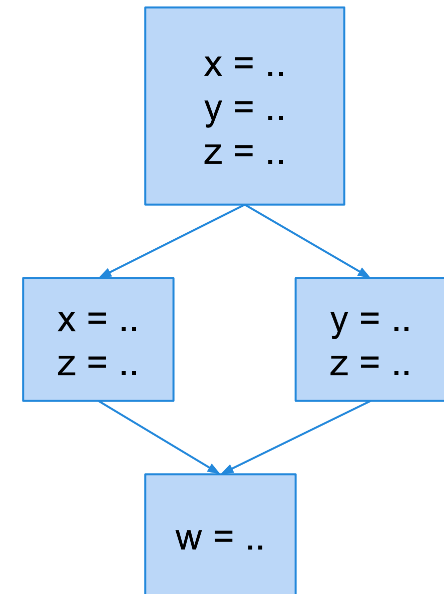
Data Flow Analysis

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.

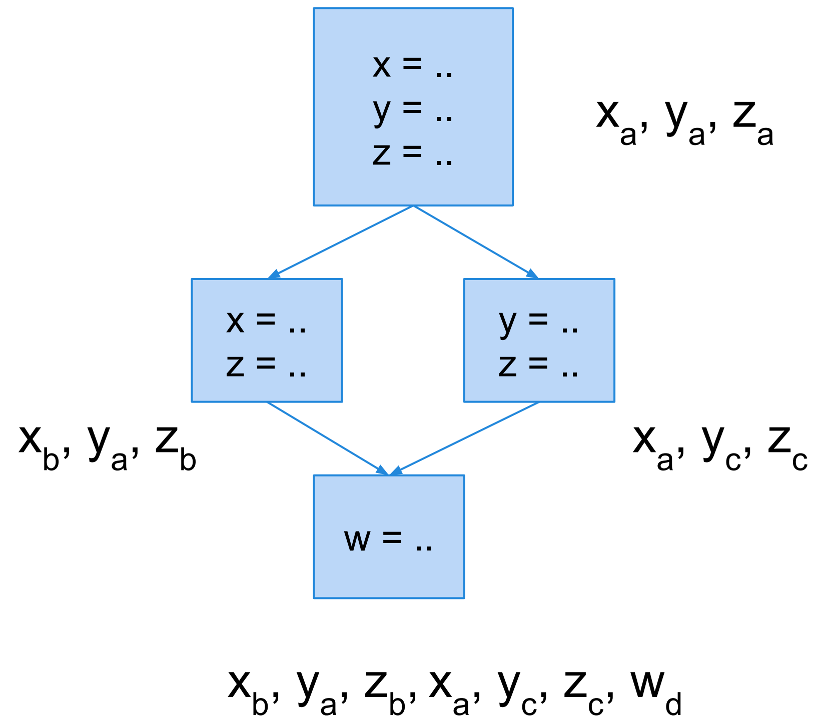


Computing Def-Use Pairs

- 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

- Reaching definitions flowing out at of a node are:
  - 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 defin *monotonic* function on the finite *lattice* of poss sets of reaching definition.

Iterative Worklist Algorithm

- Initialize the reaching definitions flowing out to
- C

Keep a *worklist* of nodes to be processed.

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

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) = ∪p∈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 commo
    pattern.
- Initialize-Repeat-Until-Stable Algorithm
  - Would work for any set of flow equations as lo
    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:
  - $AvailIn(n) = \bigcap_{p \in pred(n)} AvailOut(p)$
  - $AvailOut(n) = (AvailIn(n) \setminus kill(n)) \cup gen(n)$

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) = ∩p∈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 easily as forwards in a CFG.
- 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.

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.

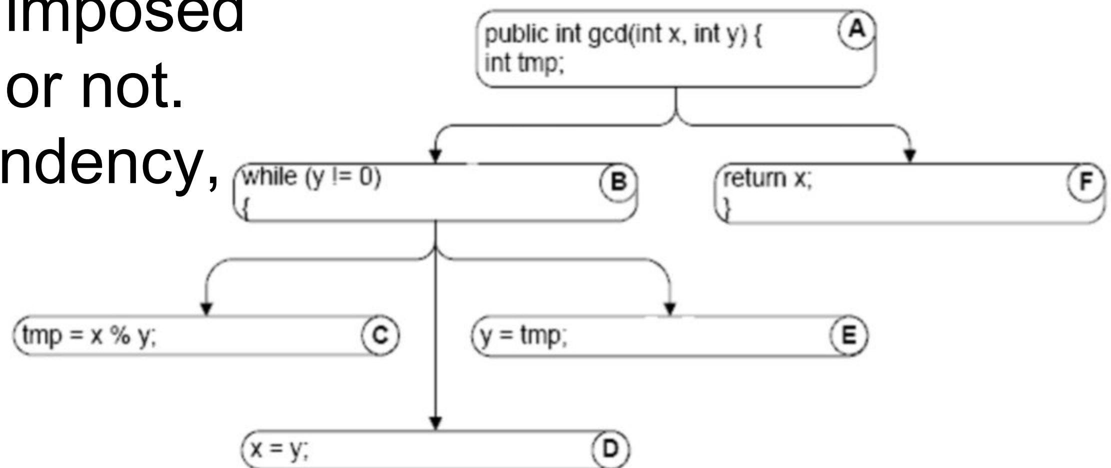
- Reading: Chapter 13
- Homework 1 due tonight.
- Reading assignment 2 out.

backup slides

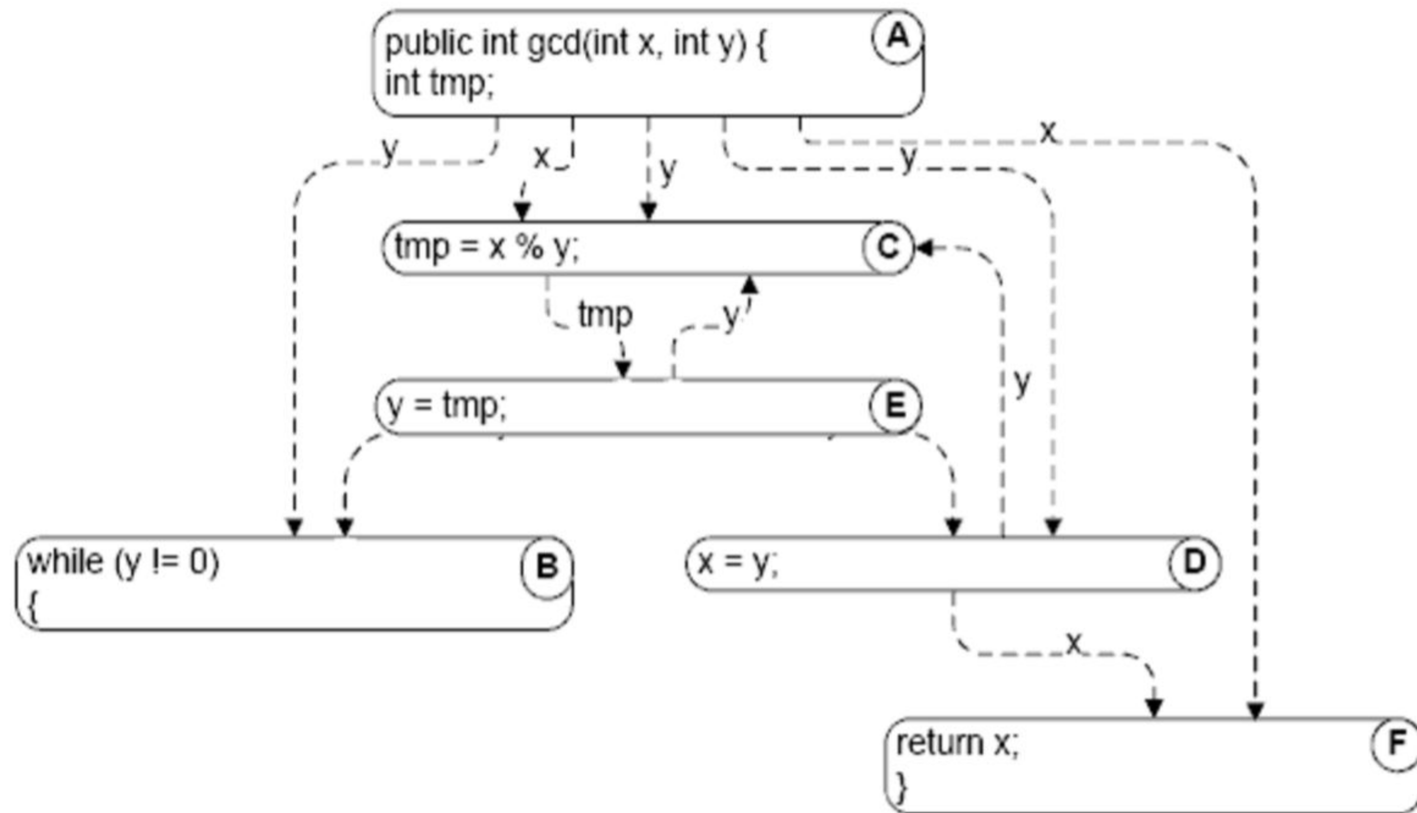
Control Dependence Graph

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.



Data Dependence Graph



Powerset Lattice

- Lattice is made up of subsets of a set.
  - Powerset of set A is the set of all subsets of A.
- If the subset grows larger as we follow the arrows, subset y >= x.
- A function is monotonically increasing if:
  - x >= y implies f(y) >= f(x)