CS 510/12

Program Representation

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Why Program Representations

- Original representations
  - Source code (cross languages).
  - Binaries (cross machines and platforms).
  - Source code / binaries + test cases.
- They are hard for machines to analyze.
- Software is translated into certain representations before analyses are applied.

Outline

- Control flow graphs.
- Program dependence graphs.
- Super control flow graphs.
- Call graph

Control Flow Graph

- Chapter 1.14 of "Foundations of Software Engineering"
- Available on the course website.
- The most commonly used program representation.

Program representation: Basic blocks

A basic block in program P is a sequence of consecutive statements with a single entry and a single exit point. Thus a block has unique entry and exit points.

Control always enters a basic block at its entry point and exits from its exit point. There is no possibility of exit or a halt at any point inside the basic block except at its exit point. The entry and exit points of a basic block coincide when the block contains only one statement.

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Control Flow Graph (CFG)

A control flow graph (or flow graph) G is defined as a finite set N of nodes and a finite set E of edges. An edge (i, j) in E connects two nodes n_i and n_j in N. We often write G= (N, E) to denote a flow graph G with nodes given by N and edges by E.

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Control Flow Graph (CFG)

In a flow graph of a program, each basic block becomes a node and edges are used to indicate the flow of control between blocks.

An edge (i, j) connecting basic blocks b_i and b_j implies that control can go from block b_i to block b_j.

We also assume that there is a node labeled Start in N that has no incoming edge, and another node labeled End, also in N, that has no outgoing edge.

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Paths

Consider a flow graph G= (N, E). A sequence of k edges, k>0, (e_1, e_2, … e_k) , denotes a path of length k through the flow graph if the following sequence condition holds.

Given that n_p, n_q, n_r, and n_s are nodes belonging to N, and 0< i<k, if $e_i = (n_p, n_q)$ and $e_{i+1} = (n_r, n_s)$ then $n_q = n_r$. }

Complete path: a path from start to exit
Subpath: a subsequence of a complete path

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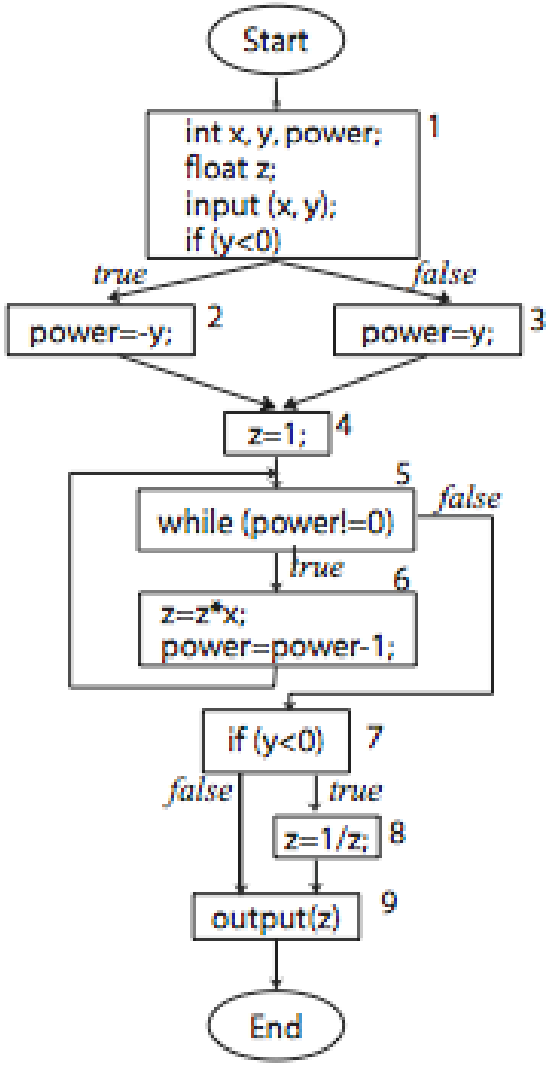
Paths: infeasible paths

A path p through a flow graph for program P is considered feasible if there exists at least one test case which when input to P causes p to be traversed.

p_1= (Start, 1, 3, 4, 5, 6, 5, 7, 8, 9, End)
p_2= (Start, 1, 2, 4, 5, 7, 9, End)



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Number of paths

There can be many distinct paths through a program. A program with no condition contains exactly one path that begins at node Start and terminates at node End.

Each additional condition in the program can increases the number of distinct paths by at least one.

Depending on their location, conditions can have a multiplicative effect on the number of paths.

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A Simplified Version of CFG

- Each statement is represented by a node
  - For readibility.
  - Not for efficient implementation.

Dominator

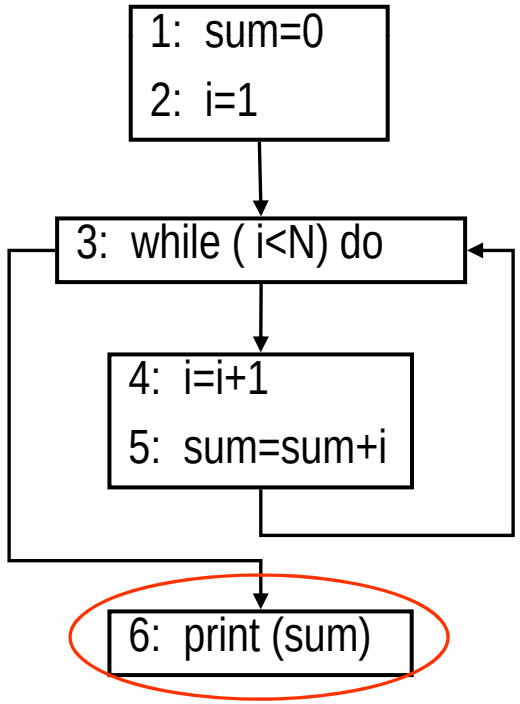
- X dominates Y if all possible program paths from START to Y have to pass X.

Dominator

- X strictly dominates Y if X dominates Y and X!=Y

```
1:    sum=0
2:    i=1
3:    while ( i<N) do
4:          i=i+1
5:          sum=sum+i
      endwhile
6:  print(sum)
```

SDOM(6)={1,3}

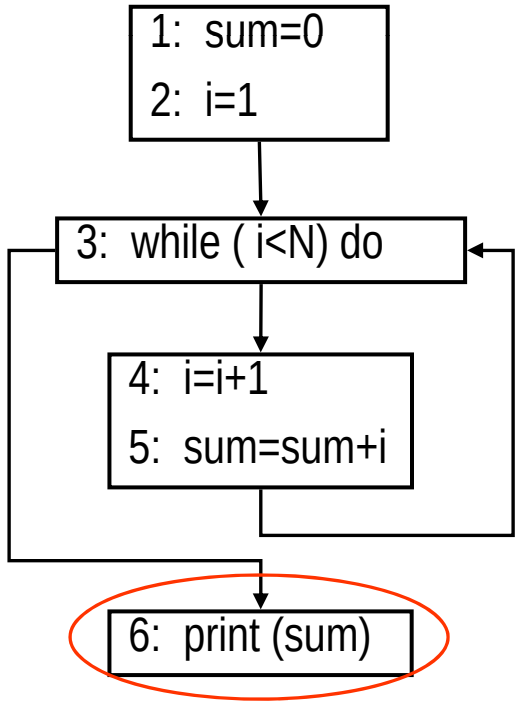


Dominator

- X is the immediate dominator of Y if X is the last dominator of Y along a path from Start to Y.

```
1:    sum=0
2:    i=1
3:    while ( i<N) do
4:          i=i+1
5:          sum=sum+i
      endwhile
6:  print(sum)
```

IDOM(6)={3}

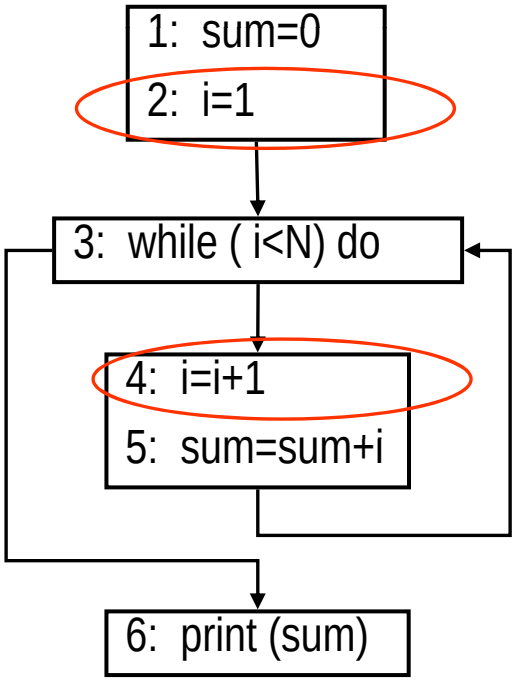


Postdominator

- X post-dominates Y if every possible program path from Y to End has to pass X.
  - Strict post-dominator, immediate post-dominance.

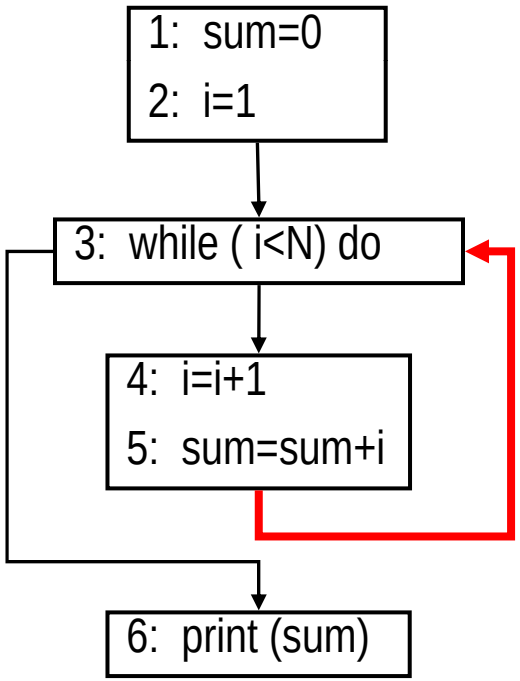
```
1:    sum=0
2:    i=1
3:    while ( i<N) do
4:          i=i+1
5:          sum=sum+i
      endwhile
6:  print(sum)
```

SPDOM(4)={3,6} IPDOM(4)=3



Back Edges

- A back edge is an edge whose head dominates its tail
  - Back edges often identify loops

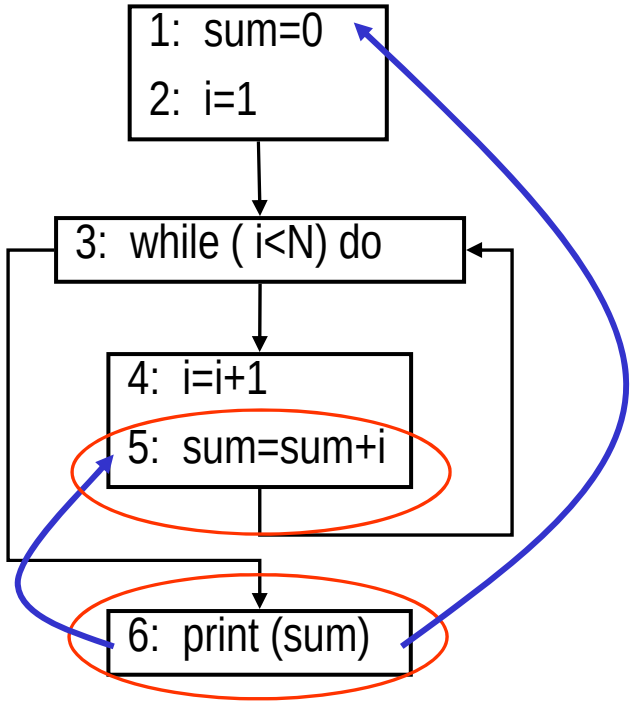


Program Dependence Graph

- Read Chapter 1.15 and 1.16 of "Foundations of Software Testing"
- The second widely used program representation.
- Nodes are constituted by statements instead of basic blocks.
- Two types of dependences between statements
  - Data dependence
  - Control dependence

Data Dependence

- X is data dependent on Y if (1) there is a variable v that is defined at Y and used at X and (2) there exists a path of nonzero length from Y to X along which v is not re-defined.



Computing Data Dependence is Hard in General

- Aliasing
  - A variable can refer to multiple memory locations/objects.

```
1:   int x, y, z …;
2:   int * p;
3:   x=…;
4:   y=…;
5:   p = & x;
6:   p=p +z;
7:   … = *p;
```

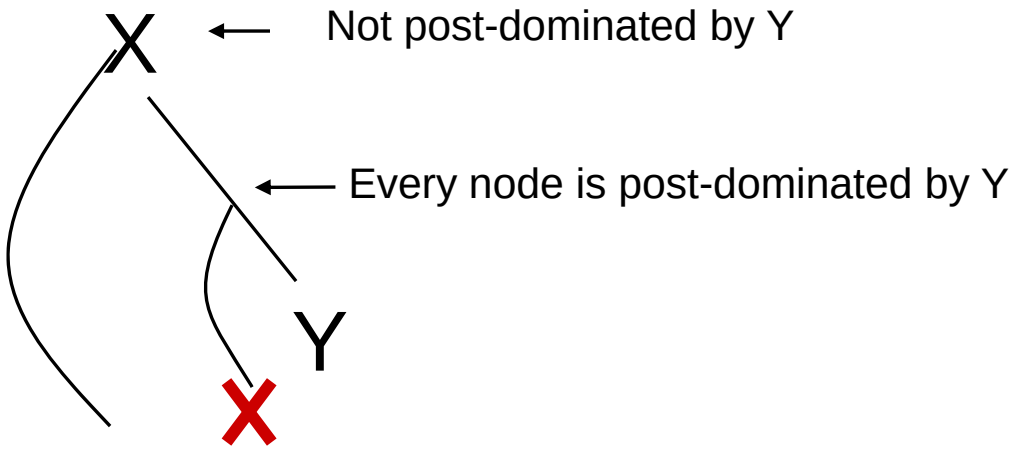
```
1:   foo (ClassX  x,    ClassY  y) {
2:      x.field= …;
3:      …=y.field;
4:   }
```

```
foo ( o, o);

o1=new ClassX( );
o2= new ClassY( );
foo ( o1, o2);
```

Control Dependence

- Intuitively, Y is control-dependent on X iff X directly determines whether Y executes (statements inside one branch of a predicate are usually control dependent on the predicate)
  - X is not strictly post-dominated by Y ⇒ There is a path from X to End that does not pass Y or X==Y
  - there exists a path from X to Y s.t. every node in the path other than X and Y is post-dominated by Y ⇒ No such paths for nodes in a path between X and Y.

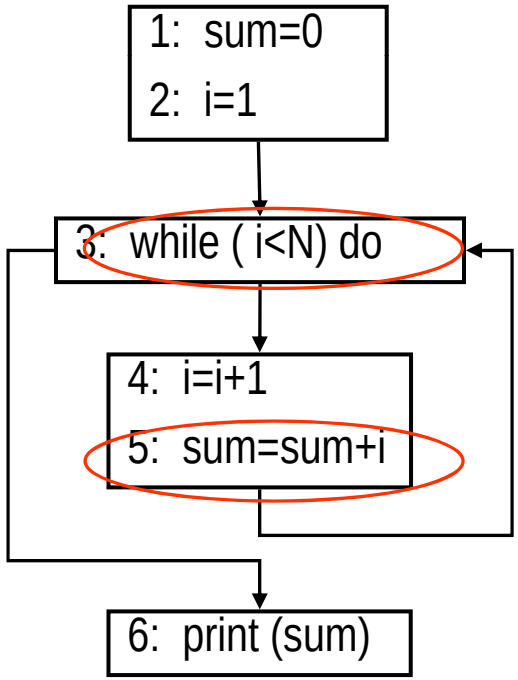


Control Dependence - Example

Y is control-dependent on X iff X directly determines whether Y executes

- X is not strictly post-dominated by Y
- there exists a path from X to Y s.t. every node in the path other than X and Y is post-dominated by Y

```
1:    sum=0
2:    i=1
3:    while ( i<N) do
4:          i=i+1
5:          sum=sum+i
      endwhile
6:  print(sum)
```



CD(5)=3

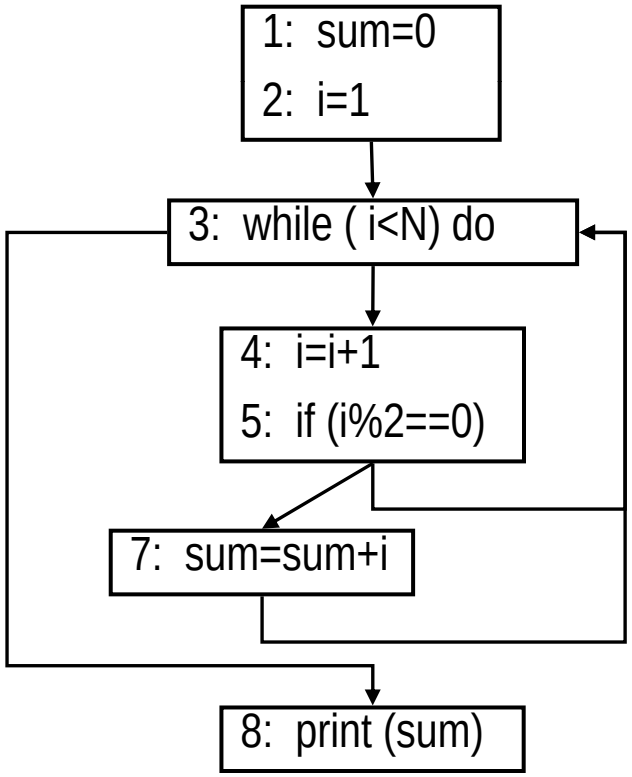
CD(3)=3, tricky!

Note: Control Dependence is not Syntactically Explicit

Y is control-dependent on X iff X directly determines whether Y executes

- X is not strictly post-dominated by Y
- there exists a path from X to Y s.t. every node in the path other than X and Y is post-dominated by Y

```
1:    sum=0
2:    i=1
3:    while ( i<N) do
4:          i=i+1
5:          if (i%2==0)
6:               continue;
7:          sum=sum+i
      endwhile
8:    print(sum)
```



Control Dependence is Tricky!

Y is control-dependent on X iff X directly determines whether Y executes

- X is not strictly post-dominated by Y
- there exists a path from X to Y s.t. every node in the path other than X and Y is post-dominated by Y

- Can a statement control depends on two predicates?

Control Dependence is Tricky!

Y is control-dependent on X iff X directly determines whether Y executes

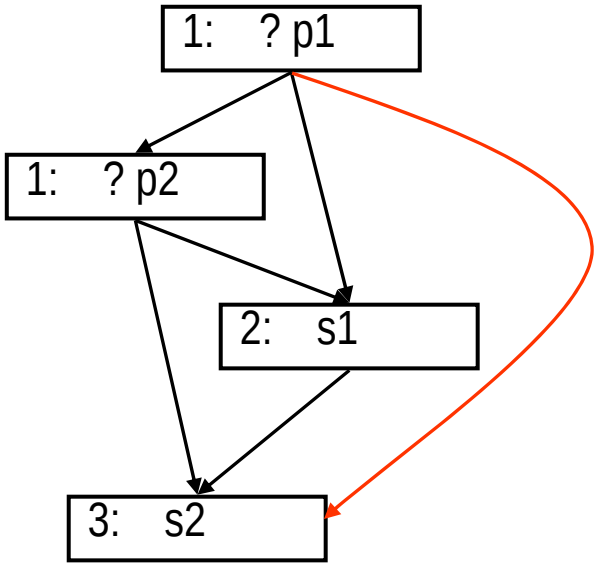
- X is not strictly post-dominated by Y
- there exists a path from X to Y s.t. every node in the path other than X and Y is post-dominated by Y

- Can one statement control depends on two predicates?

```
1:    if ( p1 || p2 )
2:          s1;
3:    s2;
```

What if ?

```
1:    if ( p1 && p2 )
2:          s1;
3:    s2;
```



The Use of PDG

- A program dependence graph consists of control dependence graph and data dependence graph
- Why it is so important to software reliability?
  - In debugging, what could possibly induce the failure?
  - In security

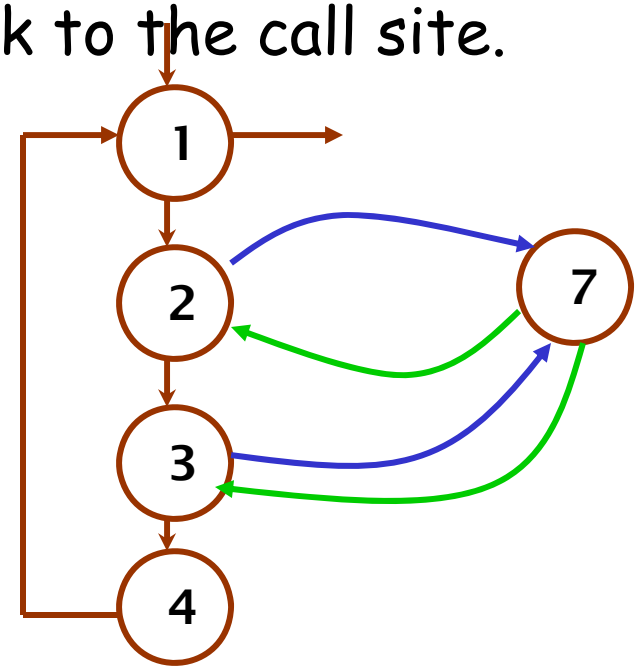
```
p=getpassword( );
…
send (p);
```

```
p=getpassword( );
…
if (p==“zhang”) {
    send (m);
}
```

Super Control Flow Graph (SCFG)

- Besides the normal intraprocedural control flow graph, additional edges are added connecting
  - Each call site to the beginning of the procedure it calls.
  - The return statement back to the call site.

```
1:    for (i=0; i<n; i++) {
2:       t1= f(0);
3:       t2 = f(243);
4:       x[i] = t1 + t2 + t3;
5:    }
6:  int  f (int v) {
7:    return (v+1);
8:  }
```



Call Graph (CG)

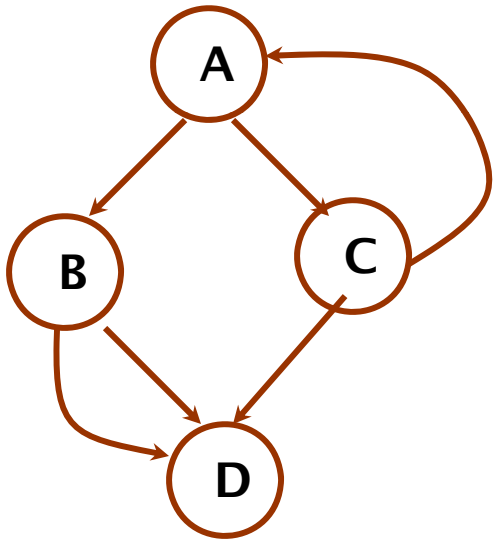
- Each node represents a function; each edge represents a function invocation

```
void A( ) {
   B( );
   C( );
}

void B( ) {
L1:   D( );
L2:   D( );
}

void C ( ) {
   D( );
   A( );
}

void D ( ) {
}
```



The Use of CG

- When reasoning across function boundaries is needed.
  - A mouse click suddenly drives a desktop application into a coma, and the operating system declares it "not responding". While the application usually responds eventually, no user actions can be taken during the wait.

Many Other Representations

- Points-to Graph.
- Static single assignment (SSA).

Tools

- C/C++: LLVM, CIL
- Java: SOOT, Wala
- Binary: Valgrind, Pin