Advanced Topics in Malware Analysis

Software Representation

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Software Abstractions

Learning Objectives

- Describe software representation
- Describe basic blocks of software
- Reconstruct control flow graph
- Describe various types of paths
- Utilize paths to observe dependencies

Why Create Abstractions of Software?

- Original representations are hard for humans to analyze
    - Source code
        - Programs written in multiple languages
        - Millions of lines
        - External dependencies
    - Binaries
        - Across machines and platforms
        - Lack of semantic info. --- No symbols
    - Source code + binaries + test cases
        - Who thinks GDB is fun? I do… ☺

- These are even harder for a machine to analyze!

- And, wouldn’t it be nice to make a machine do the reverse engineering for us??

Software Representations

- Software is translated into certain representations before analyses are applied

Outline:

- Basic blocks
- Control flow graphs
- Data flow graphs
- Program dependence graphs
- Super control flow graphs
- Call graph

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Basic Blocks

Program Representation: Basic Blocks

- A basic block is a sequence of consecutive statements with a **single entry** and a **single exit**
- Each block has a **unique** entry point and exit point
- **Control** always **enters** a basic block at its **entry** point and **exits** from its **exit** point
- There is **no possibility** of **exit** or **halt** at any point **inside** the basic block
- The entry and exit points of a basic block may **coincide** when the block contains only a **single statement**

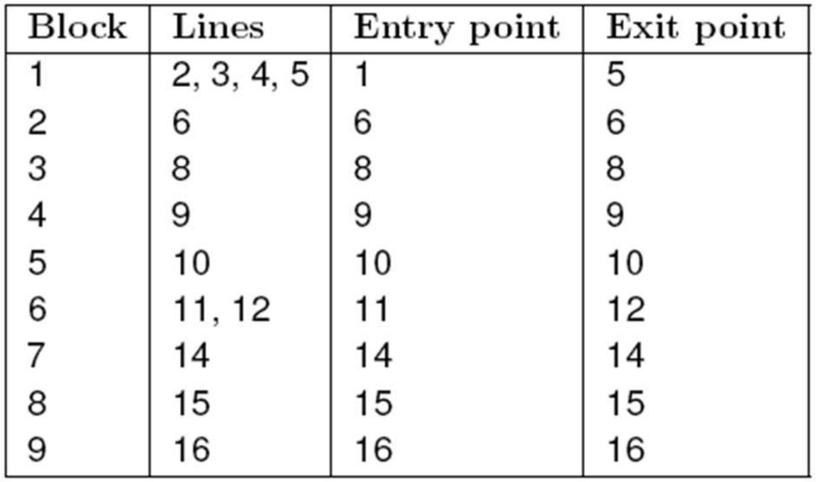
Basic Blocks:
Source Code Example

- Basic blocks are a **valid abstraction** for software analysis at any level!
  - Both source code and binary analysis

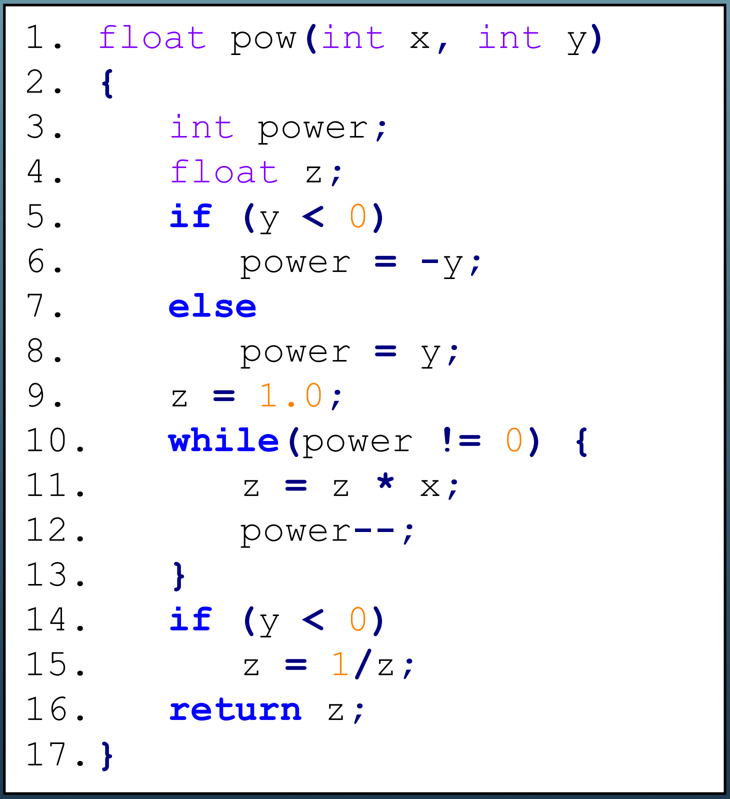
```
float pow(int x, int y)
{
    int power;
    float z;
    if (y < 0)
        power = -y;
    else
        power = y;
    z = 1.0;
    while(power != 0) {
        z = z * x;
        power--;
    }
    if (y < 0)
        z = 1/z;
    return z;
}
```

Basic Blocks:
Source Code Example

- Basic blocks are a **valid abstraction** for software analysis at any level!
  - Both source code and binary analysis



Block	Lines	Entry point	Exit point
1	2, 3, 4, 5	1	5
2	6	6	6
3	8	8	8
4	9	9	9
5	10	10	10
6	11, 12	11	12
7	14	14	14
8	15	15	15
9	16	16	16



```
1.  float pow(int x, int y)
2.  {
3.     int power;
4.     float z;
5.     if (y < 0)
6.        power = -y;
7.     else
8.        power = y;
9.     z = 1.0;
10.    while(power != 0) {
11.       z = z * x;
12.       power--;
13.    }
14.    if (y < 0)
15.       z = 1/z;
16.    return z;
17. }
```

Basic Blocks: Binary Example – Binary Code (1 of 3)

```
.text:0000000000000000 pow             proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal   = dword ptr -1Ch
.text:0000000000000000 var_Y           = dword ptr -18h
.text:0000000000000000 var_X           = dword ptr -14h
.text:0000000000000000 var_Z           = dword ptr -8
.text:0000000000000000 var_Power       = dword ptr -4
.text:0000000000000000
.text:0000000000000000                 push    rbp
.text:0000000000000001                 mov     rbp, rsp
.text:0000000000000004                 mov     [rbp+var_X], edi
.text:0000000000000007                 mov     [rbp+var_Y], esi
.text:000000000000000A                 cmp     [rbp+var_Y], 0
.text:000000000000000E                 jns     short loc_1A     ; if ( y < 0 )
.text:0000000000000010                 mov     eax, [rbp+var_Y]
.text:0000000000000013                 neg     eax              ; power = -y
.text:0000000000000015                 mov     [rbp+var_Power], eax
.text:0000000000000018                 jmp     short loc_20
```

Compiled on 64-bit Linux

Basic Blocks: Binary Example – Binary Code (2 of 3)

```
.text:000000000000001A
.text:000000000000001A loc_1A:
.text:000000000000001A                 mov     eax, [rbp+var_Y] ; else power = y
.text:000000000000001D                 mov     [rbp+var_Power], eax
.text:0000000000000020
.text:0000000000000020 loc_20:
.text:0000000000000020                 mov     eax, cs:const_float_1_0
.text:0000000000000026                 mov     [rbp+var_Z], eax ; z = 1.0
.text:0000000000000029                 jmp     short loc_42
```

Compiled on 64-bit Linux

Basic Blocks: Binary Example – Binary Code (3 of 3)

```
.text:000000000000002B loc_2B:
.text:000000000000002B                 cvtsi2ss xmm0, [rbp+var_X]
.text:0000000000000030                 movss    xmm1, [rbp+var_Z]
.text:0000000000000035                 mulss    xmm0, xmm1      ; z = z * x
.text:0000000000000039                 movss    [rbp+var_Z], xmm0
.text:000000000000003E                 sub      [rbp+var_Power], 1 ; power = power - 1;
.text:0000000000000042
.text:0000000000000042 loc_42:
.text:0000000000000042                 cmp      [rbp+var_Power], 0 ; while ( power != 0 )
.text:0000000000000046                 jnz      short loc_2B
.text:0000000000000048                 cmp      [rbp+var_Y], 0  ; if ( y < 0 )
.text:000000000000004C                 jns      short loc_60
.text:000000000000004E                 movss    xmm0, cs:const_float_1_0
.text:0000000000000056                 divss    xmm0, [rbp+var_Z] ; z = 1 / z;
.text:000000000000005B                 movss    [rbp+var_Z], xmm0
.text:0000000000000060
.text:0000000000000060 loc_60:
.text:0000000000000060                 mov      eax, [rbp+var_Z]
.text:0000000000000063                 mov      [rbp+var_ReturnVal], eax ; return value = z
.text:0000000000000066                 movss    xmm0, [rbp+var_ReturnVal]
.text:000000000000006B                 pop      rbp
.text:000000000000006C                 retn
.text:000000000000006C pow             endp
```

Prev. Slide Jumps Here ←

Compiled on 64-bit Linux

Finding The Basic Blocks (1 of 3)

```
.text:0000000000000000 pow             proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal   = dword ptr -1Ch
.text:0000000000000000 var_Y           = dword ptr -18h
.text:0000000000000000 var_X           = dword ptr -14h
.text:0000000000000000 var_Z           = dword ptr -8
.text:0000000000000000 var_Power       = dword ptr -4
.text:0000000000000000
.text:0000000000000000                 push    rbp
.text:0000000000000001                 mov     rbp, rsp
.text:0000000000000004                 mov     [rbp+var_X], edi
.text:0000000000000007       Block 1   mov     [rbp+var_Y], esi
.text:000000000000000A                 cmp     [rbp+var_Y], 0
.text:000000000000000E                 jns     short loc_1A    ; if ( y < 0 )
.text:0000000000000010                 mov     eax, [rbp+var_Y]
.text:0000000000000013                 neg     eax             ; power = -y
.text:0000000000000015        Block 2  mov     [rbp+var_Power], eax
.text:0000000000000018                 jmp     short loc_20
.text:000000000000001A ; -----------------------------------------------------------------
```

Finding The Basic Blocks (2 of 3)

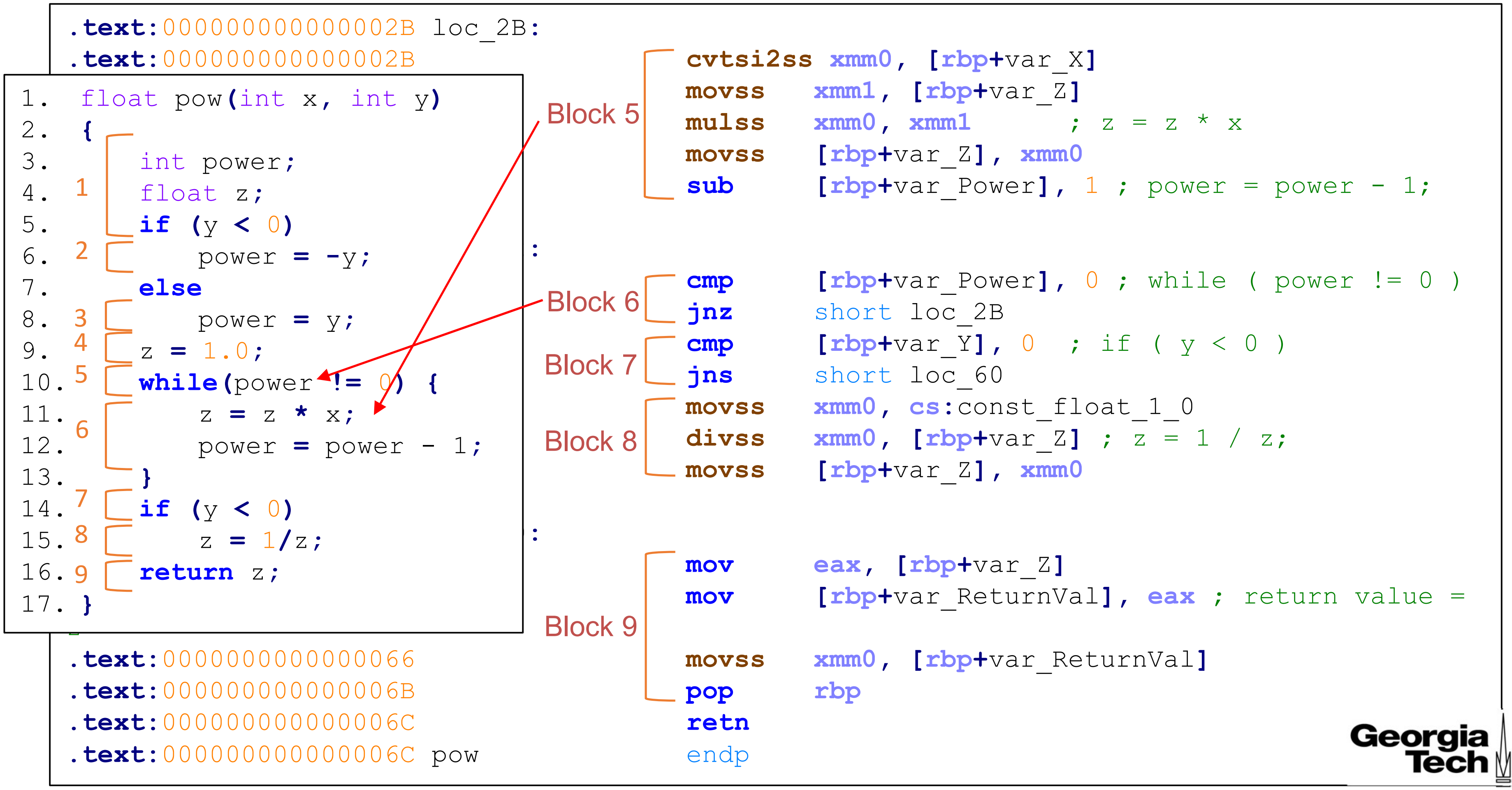
```
..text:000000000000001A loc_1A:
.text:000000000000001A          Block 3 [ mov     eax, [rbp+var_Y] ; else power = y
.text:000000000000001D                  [ mov     [rbp+var_Power], eax
.text:0000000000000020
.text:0000000000000020 loc_20:
.text:0000000000000020                  [ mov     eax, cs:const_float_1_0
.text:0000000000000026         Block 4  [ mov     [rbp+var_Z], eax ; z = 1.0
.text:0000000000000029                  [ jmp     short loc_42
.text:000000000000002B loc_2B:
.text:000000000000002B                  [ cvtsi2ss xmm0, [rbp+var_X]
.text:0000000000000030                  [ movss   xmm1, [rbp+var_Z]
.text:0000000000000035         Block 5  [ mulss   xmm0, xmm1      ; z = z * x
.text:0000000000000039                  [ movss   [rbp+var_Z], xmm0
.text:000000000000003E                  [ sub     [rbp+var_Power], 1 ; power = power - 1;
```

Finding The Basic Blocks (3 of 3)

```
.text:0000000000000042 loc_42:
.text:0000000000000042           cmp    [rbp+var_Power], 0 ; while ( power != 0 )
.text:0000000000000046   Block 6  jnz    short loc_2B
.text:0000000000000048           cmp    [rbp+var_Y], 0  ; if ( y < 0 )
.text:000000000000004C   Block 7  jns    short loc_60
.text:000000000000004E           movss  xmm0, cs:const_float_1_0
.text:0000000000000056   Block 8  divss  xmm0, [rbp+var_Z] ; z = 1 / z;
.text:000000000000005B           movss  [rbp+var_Z], xmm0
.text:0000000000000060
.text:0000000000000060 loc_60:
.text:0000000000000060           mov    eax, [rbp+var_Z]
.text:0000000000000063           mov    [rbp+var_ReturnVal], eax ; return value = z
.text:0000000000000066   Block 9  movss  xmm0, [rbp+var_ReturnVal]
.text:000000000000006B           pop    rbp
.text:000000000000006C           retn
.text:000000000000006C pow       endp
```

Source Blocks != Binary Blocks

- Basic blocks may be a valid abstraction for software analysis at any level
- But they are not comparable across levels!
- As we have seen, compilation will significantly rearrange the logic of a program
- **Consider**: Our example has no optimization!



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Software Representation

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Control Flow Graphs (CFG)

Control Flow Graph (CFG)

- The **most commonly used** program representation
- A **CFG** abstracts the paths that might be traversed through a program during its execution guided solely by branching constructs
- A control flow graph (sometimes called 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 $\mathbf{n_i}$ and $\mathbf{n_j}$ in **N**
- We often write **G=(N, E)** to denote a control flow graph **G** with nodes given by **N** and edges by **E**

Control Flow Graph (CFG)

- In a control flow graph of a program, each **basic block** becomes a **node**
- Edges are used to indicate the flow of execution (i.e., control) between blocks
- A **CFG** edge **(i, j)** connecting basic blocks $\mathbf{b_i}$ and $\mathbf{b_j}$ implies that control can be transferred from block $\mathbf{b_i}$ to block $\mathbf{b_j}$
- We assume that there exists a node labeled Start in **N** that has **no** incoming edge
  - The Start node is assigned outgoing edges to all other nodes which have no incoming edge
- We also assume that there exists a node labeled End in **N** that has no outgoing edge
  - The End node is assigned incoming edges from all other nodes which have no outgoing edge
- The Start and End nodes are important to simplify automated analyses

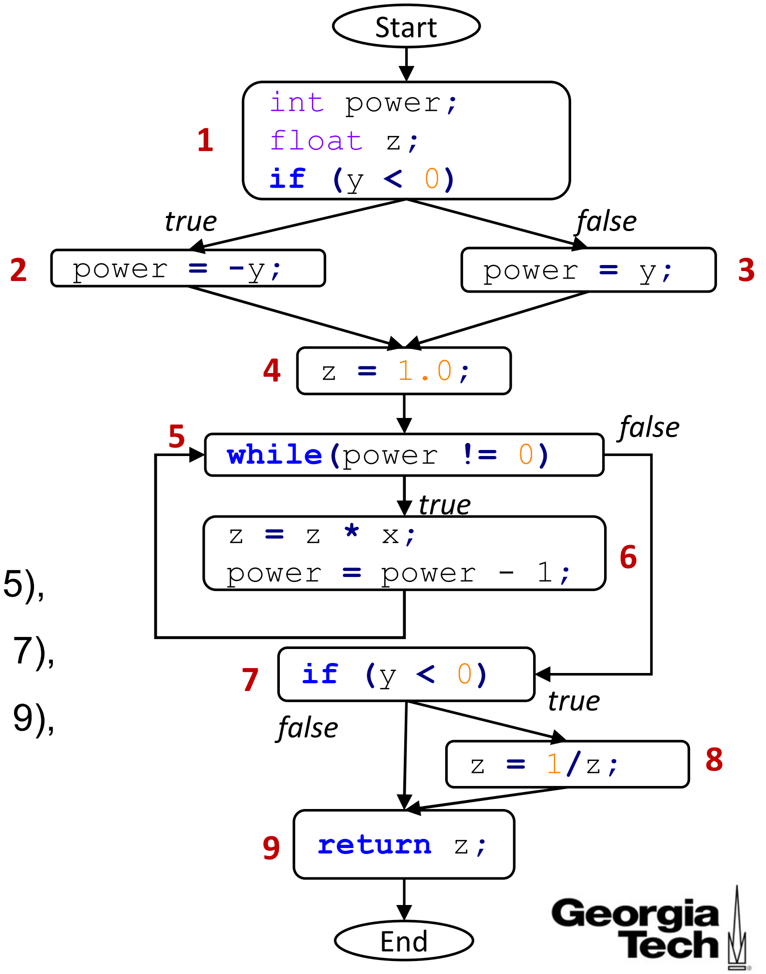
CFG Example

```
float pow(int x, int y)
{
1     int power;
      float z;
      if (y < 0)
2         power = -y;
      else
3         power = y;
4     z = 1.0;
5     while(power != 0) {
6         z = z * x;
          power = power - 1;
      }
7     if (y < 0)
8         z = 1/z;
9     return z;
}
```

CFG(pow) = (N,E)

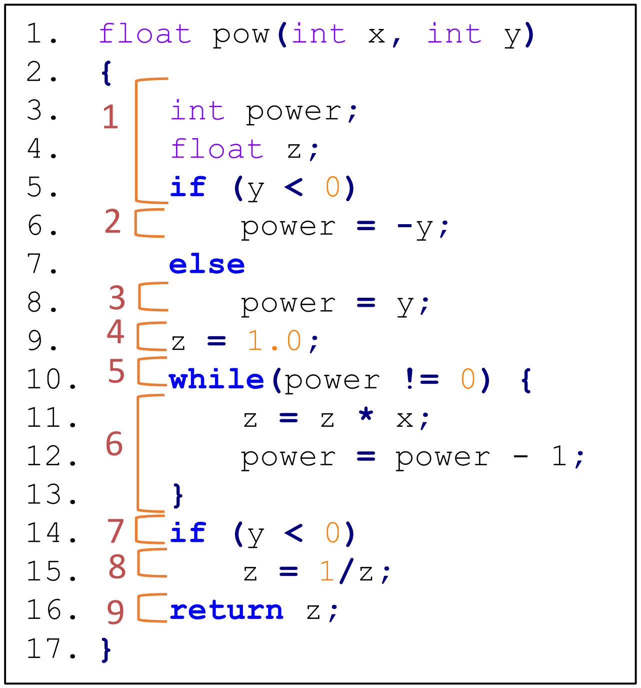
N={Start, 1, 2, 3, 4, 5, 6, 7, 8, 9, End}

E={(Start,1), (1, 2), (1, 3), (2,4), (3, 4), (4, 5), (5, 6), (6, 5), (5, 7), (7, 8), (7, 9), (8, 9), (9, End)}



CFG Example

- CFG nodes are typically represented by only their basic block number

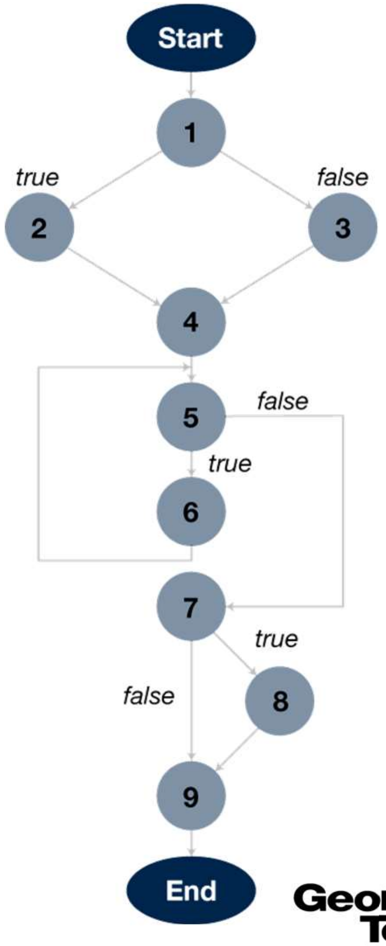


```
float pow(int x, int y)
{
   int power;
   float z;
   if (y < 0)
      power = -y;
   else
      power = y;
   z = 1.0;
   while(power != 0) {
      z = z * x;
      power = power - 1;
   }
   if (y < 0)
      z = 1/z;
   return z;
}
```

CFG(pow) = (N,E)

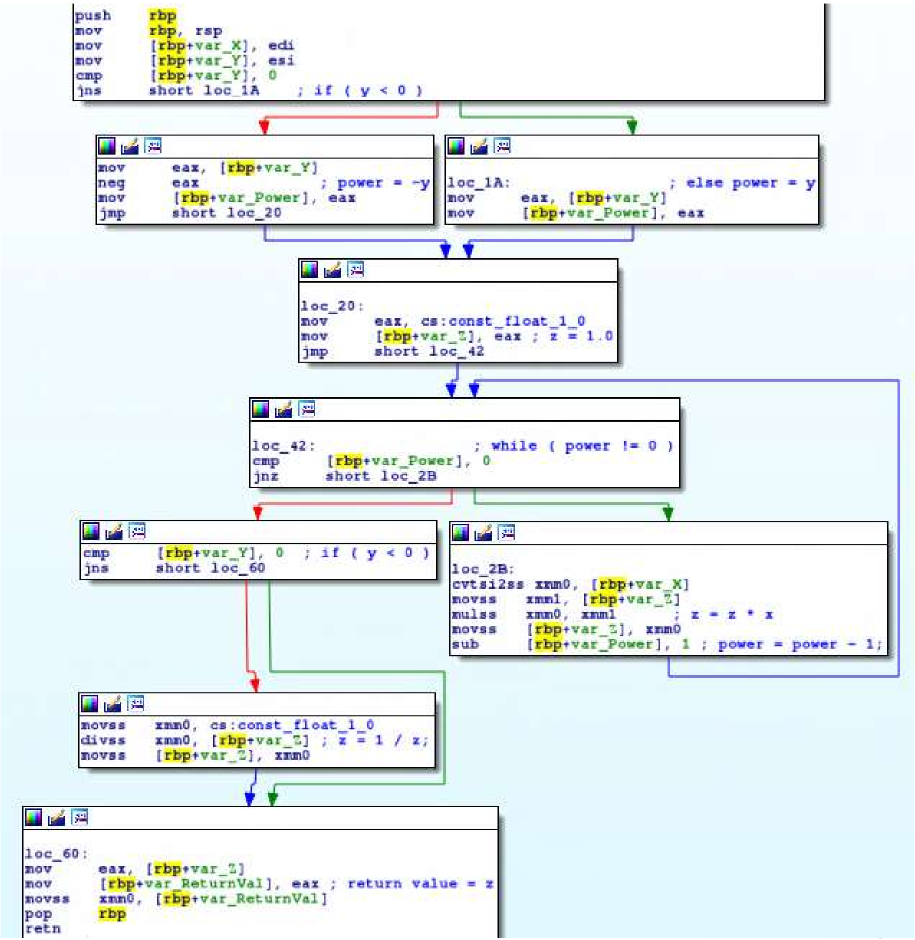
N={Start, 1, 2, 3, 4, 5,
6, 7, 8, 9, End}

E={(Start,1), (1, 2), (1, 3),
(2,4), (3, 4), (4, 5),
(5, 6), (6, 5), (5, 7),
(7, 8), (7, 9), (8, 9),
(9, End)}



Where Have I Seen This Before?

- IDA’s Graph View displays a **CFG**
- IDA detects basic blocks based on control transfer instructions and its (very limited) knowledge of the control transfer targets
- IDA’s basic blocks will often be wrong if the control transfer target is aliased or dynamically computed



```
push    rbp
mov     rbp, rsp
mov     [rbp+var_X], edi
mov     [rbp+var_Y], esi
cmp     [rbp+var_Y], 0
jns     short loc_1A    ; if ( y < 0 )
```

```
mov     eax, [rbp+var_Y]
neg     eax                     ; power = -y
mov     [rbp+var_Power], eax
jmp     short loc_20
```

```
loc_1A:                         ; else power = y
mov     eax, [rbp+var_Y]
mov     [rbp+var_Power], eax
```

```
loc_20:
mov     eax, cs:const_float_1_0
mov     [rbp+var_Z], eax ; z = 1.0
jmp     short loc_42
```

```
loc_42:                         ; while ( power != 0 )
cmp     [rbp+var_Power], 0
jnz     short loc_2B
```

```
cmp     [rbp+var_Y], 0  ; if ( y < 0 )
jns     short loc_60
```

```
loc_2B:
cvtsi2ss xmm0, [rbp+var_X]
movss   xmm1, [rbp+var_Z]
mulss   xmm0, xmm1          ; z = z * x
movss   [rbp+var_Z], xmm0
sub     [rbp+var_Power], 1 ; power = power - 1;
```

```
movss   xmm0, cs:const_float_1_0
divss   xmm0, [rbp+var_Z] ; z = 1 / z;
movss   [rbp+var_Z], xmm0
```

```
loc_60:
mov     eax, [rbp+var_Z]
mov     [rbp+var_ReturnVal], eax ; return value = z
movss   xmm0, [rbp+var_ReturnVal]
pop     rbp
retn
```

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Paths

Paths

- A CFG represents all paths (that we know of) which **might** be traversed during execution
- To reason about **actual** executions we need to define the notion of a Path
- Consider a control flow graph **G= (N, E**)

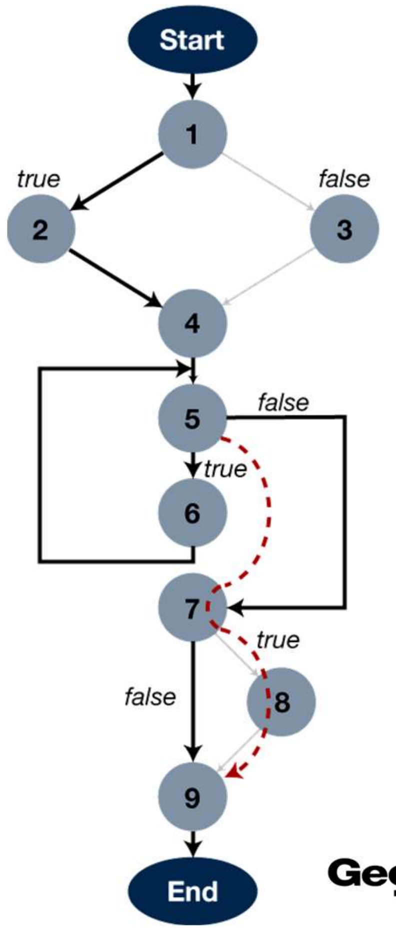
Paths (Cont.)

- A Path **P** consists of **k** edges from **E**, where **k>0**
  - That is: P = (e_1, e_2, … e_k)

- P denotes a path of length k through the control flow graph **if** the following sequence condition on the sequence of edges holds true
- Given that $\mathbf{n_p}$, $\mathbf{n_q}$, $\mathbf{n_r}$, and $\mathbf{n_s}$ are nodes belonging to **N** and **0<i<k**
- If $\mathbf{e_i = (n_p , n_q)}$ and $\mathbf{e_i+1 = (n_r , n_s)}$ then $\mathbf{n_q}$ must be $\mathbf{n_r}$

- Put simply: Every node in a Path must be reachable by a single traversal from the Path’s first node to its last

Complete Paths vs. SubPaths (Cont.)

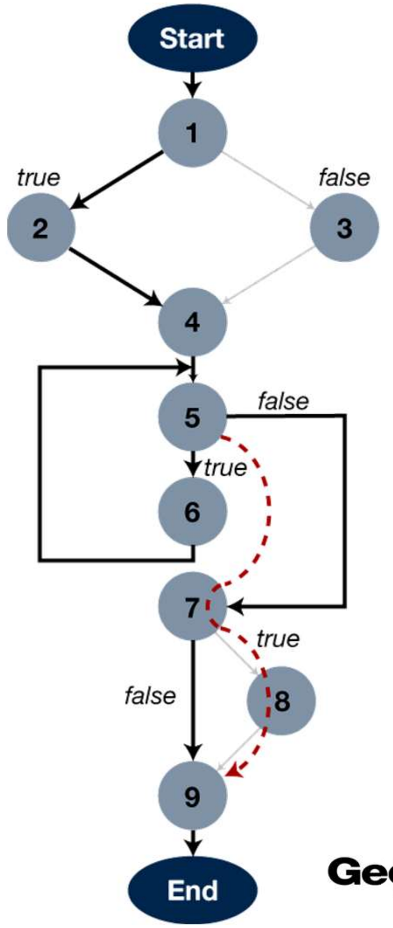


- Our definition of a **Path** allows for **two** types of **valid** Paths:
  - **Complete Path**: A valid Path (by our previous definition) which includes both the Start and End nodes from the **CFG**
  - **Subpath**: A valid Path (by our previous definition) which forms a subsequence of a Complete Path

Complete Paths vs. SubPaths (Count.)

In the figure:

- The set of bold edges forms a **Complete Path**:
  - P1 = (Start, 1, 2, 4, 5, 6, 5, 7, 9, End)
  - Specified unambiguously using edges:
    - P1= ((Start, 1), (1, 2), (2, 4), (4, 5), (5, 6), (6, 5), (5, 7), (7, 9), (9, End))
  - The set of dashed edges forms a Subpath:
    - P2 = (5, 7, 8, 9)
- **NOT a valid Path**:
  - P0 = (Start, 1, **2, 3,** 4, 5, 6, 5, 7, 9, End)



Georgia Tech

Feasible Paths vs. Infeasible Paths

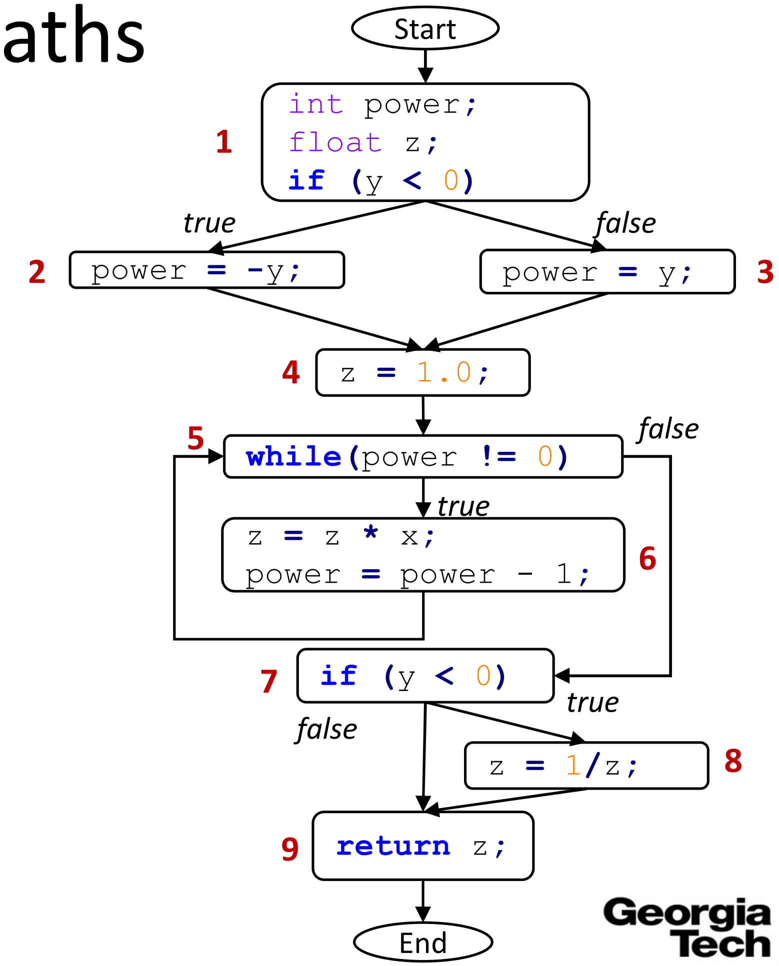
- One of the most important Path analyses is **Path Feasibility** is used in:
  - **Security** (e.g., can the malware execute that payload?)
  - **Software engineering** (e.g., how can we optimize the sequence of these program components?)
  - **Debugging** (e.g., given our current state, which branch will the program take next?)
  - **Compilers** (e.g., is this dead code able to be removed?)

- A path P through a CFG is considered **feasible** if there exists at least one test case which when input to the program causes **every** node in P to be traversed
- Note that by this definition, Subpaths can also be considered feasible
- In the face of bugs or exploits, a general solution for Path feasibility is not possible
- Techniques which solve localized versions of Path feasibility do exist (compilers do it)

Feasible Paths vs. Infeasible Paths

- Two Feasible and Complete Paths:
  - P1= (Start, 1, 2, 4, 5, 6, 5, 7, 8, 9, End)
  - P2= (Start, 1, 3, 4, 5, 6, 5, 7, 9, End)
- Two Feasible Subpaths:
  - P3= (Start, 1, 2, 4)
  - P4= (5, 7, 8, 9, End)
- Two Infeasible Paths:
  - P1= (Start, 1, 3, 4, 5, 6, 5, 7, 8, 9, End)
  - P2= (Start, 1, 2, 4, 5, 7, 9, End)

Notice that Paths can be Complete but Infeasible

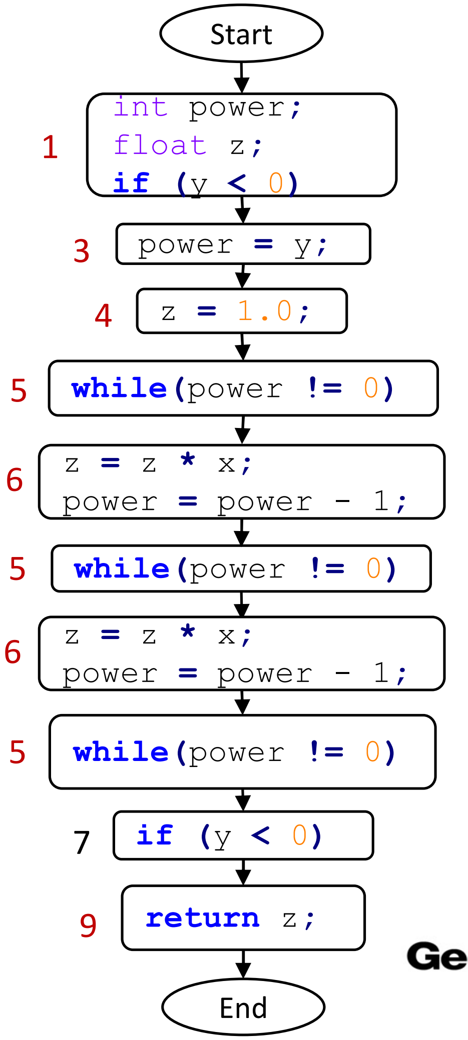


Number of Paths

- There can be many distinct paths through a program
- A program with no conditional statements contains exactly one path
  - It begins at the Start node, traverses every node, and terminates at the End node
- Every additional condition in the program can increase the number of distinct paths by **at least** one
- Depending on their location in the CFG, conditional statements can have a **multiplicative** effect on the number of paths
- This leads to a problem that nearly ALL static analysis techniques suffer from: **Path Explosion**!
- Research tools are always struggling to scale to real world programs because exploring all their paths becomes impossible!

Reasoning Along Paths

- Just like basic blocks make analysis easier by giving structure to sequences of statements…
- Many problems which are **globally intractable** (i.e., cannot be solved for entire programs) can be **solved locally** (i.e., on a single Path)
- This is because a single Path allows for **direct inference** of execution behaviors
- **Example**: What was the value of Y that produced this path?
- Now how can we teach an algorithm to figure that out??



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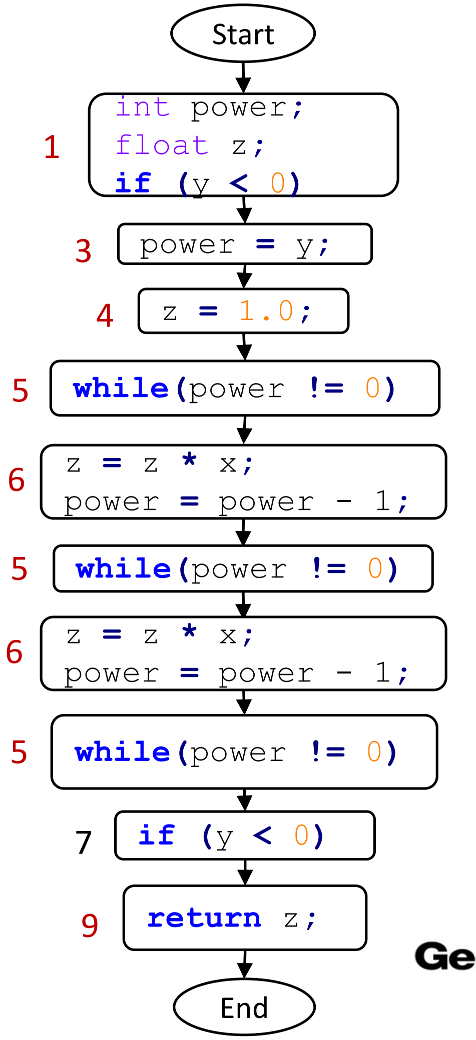
Dominator Analysis

Dependency Analysis

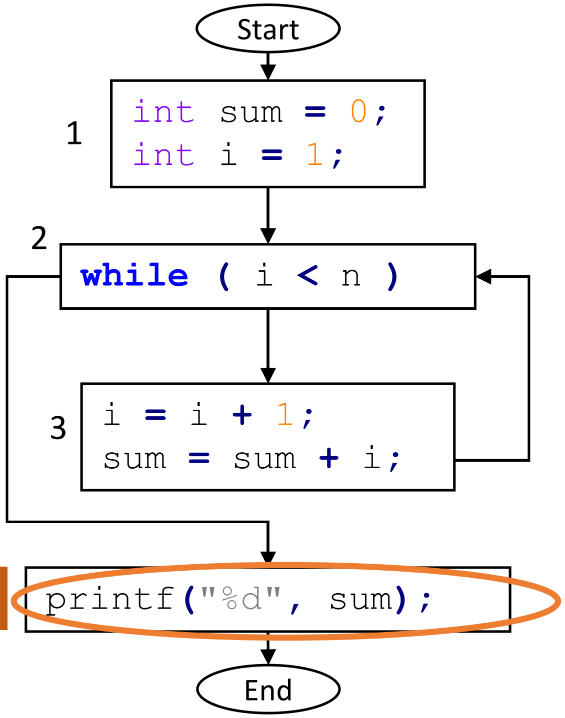
- We can look at a path and observe dependencies
  - “The value of power depends on the value of y”
  - “The execution of block 3 depends on the execution of block 1”
  - “The loop iteration depends on the value of power”
- These dependencies can be modeled so that an algorithm can analyze them
- Control Dependencies
  - Dominator
  - Post-dominator
  - Immediate Dominator/Post-dominator
- Data Dependencies



Dominator

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

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```

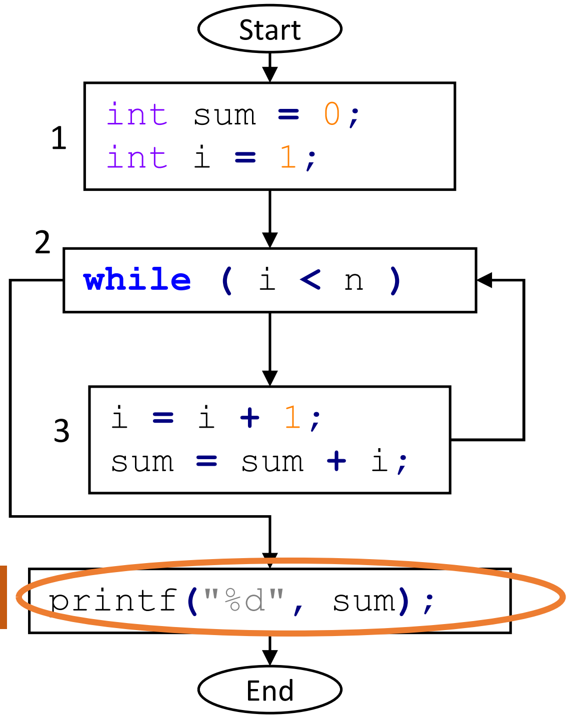


DOM(4) = {1, 2, 4}

Strict Dominator

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

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```



```
int sum = 0;
int i = 1;
```

```
while ( i < n )
```

```
i = i + 1;
sum = sum + i;
```

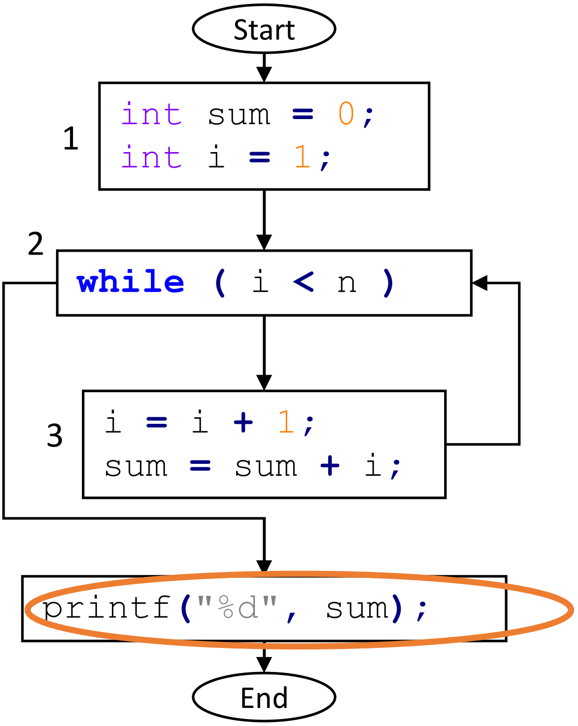
```
printf("%d", sum);
```

SDOM(4) = {1, 2}

Immediate Dominator

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

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```



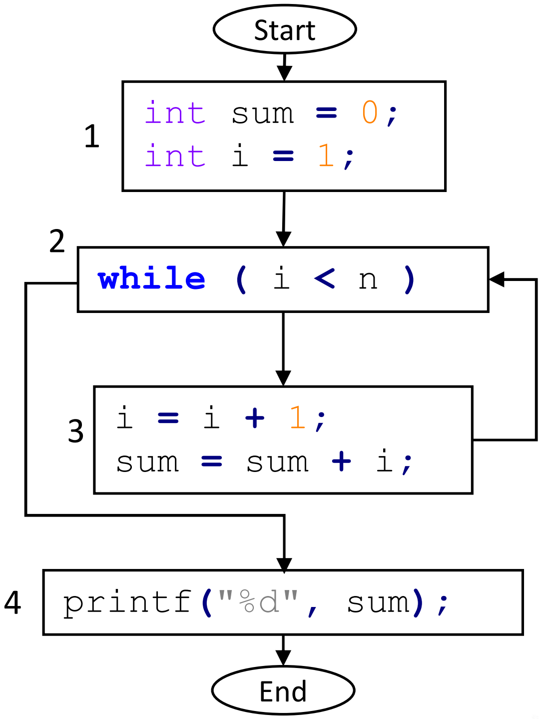
IDOM(4) = {2}

Dominators Allow for **Backward** Reasoning

- Dominators allow algorithms to determine backward control flow
- Put simply: “Who needs to execute for block X to execute?”

DOM(START) = {}
DOM(1) = {1}
DOM(2) = {1, 2}
DOM(3) = {1, 2, 3}
DOM(4) = {1, 2, 4}
DOM(END) = {1, 2, 4}

- Notice that Start and End are not true nodes!
- Notice that DOM(END) = Blocks executed for ANY input

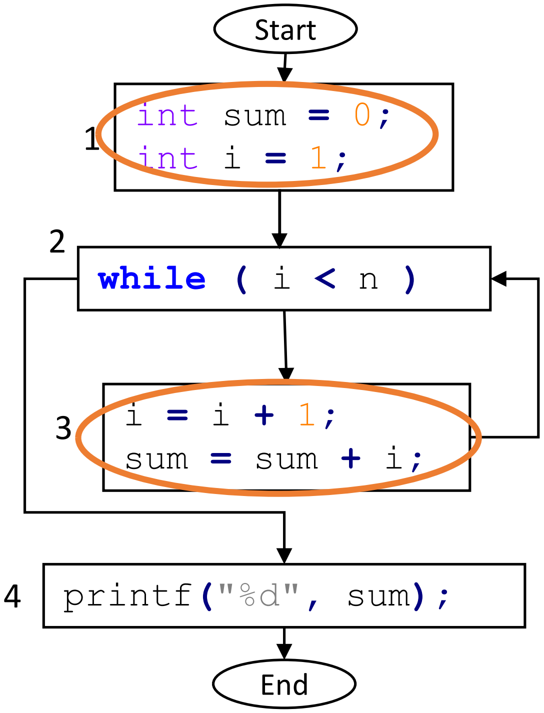


Post-Dominator

- X post-dominates Y if **every** possible program path from Y to End has to pass through X
  - Similar strict post-dominator & immediate post-dominator

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```

PDOM(3) = {2, 3, 4}
SPDOM(3) = {2, 4}
IPDOM(3) = {2}

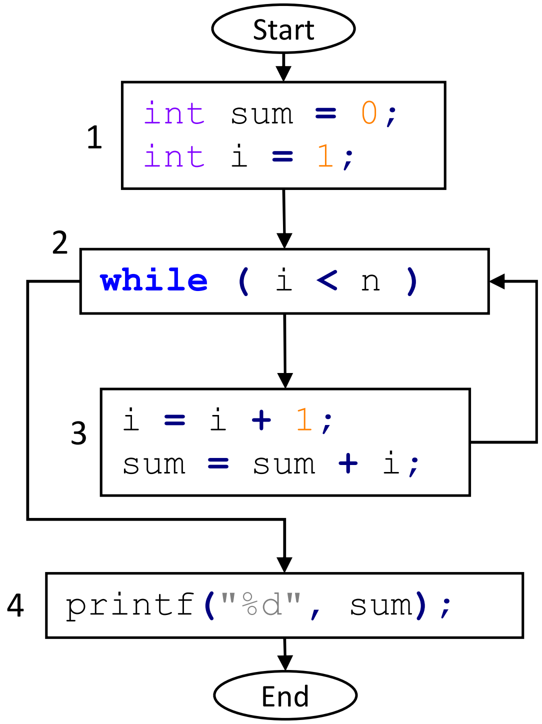


Post-Dominators Allow for **Forward** reasoning

- Post-dominators allow algorithms to determine forward control flow
- Put simply: "If block X executes, then who else must execute?"

PDOM(START) = {1, 2, 4}
PDOM(1) = {1, 2, 4}
PDOM(2) = {2, 4}
PDOM(3) = {2, 3, 4}
PDOM(4) = {4}
PDOM(END) = {}

- Notice that **PDOM(START) = DOM(END)**. Why??

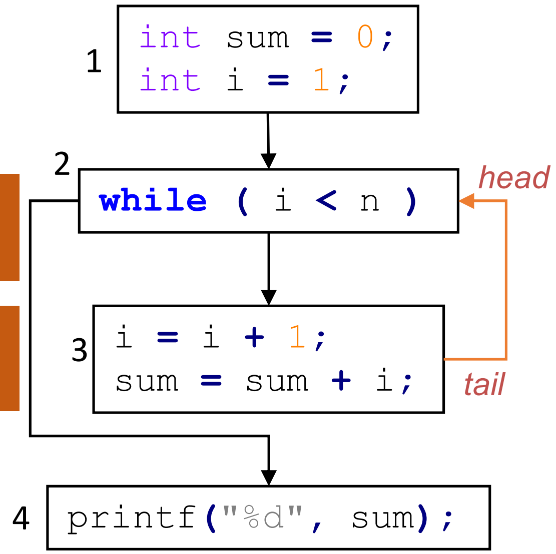


Back Edges

- Dominators/Post-dominators allow us to define characteristics of the CFG
- The **most common**: A back edge is an edge whose head dominates its tail
- A “**closed loop back edge**” is an edge whose head dominates AND post-dominates its tail
- What would be different if block 3 looked like this?

DOM(2) = {1, 2}
DOM(3) = {1, 2, 3}

PDOM(2) = {2, 4}
PDOM(3) = {2, 3, 4}



```
int sum = 0;
int i = 1;
```

```
while ( i < n )
```

```
i = i + 1;
sum = sum + i;
```

```
printf("%d", sum);
```

3

```
i = i + 1;
sum = sum + i;
if(sum > 100)
    break;
```

Advanced Topics in Malware Analysis

Software Representation

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Control Dependencies

Control Dependence

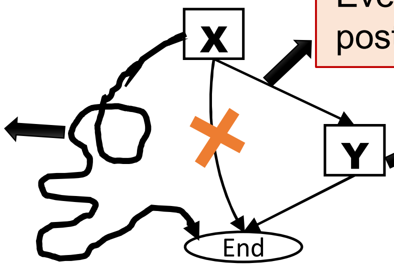
- Most importantly, Dominators & Post-dominators allow us to define **Control Dependence**
- Y is control dependent on X **iff** X directly determines whether Y executes
  - In general, statements inside each branch of a predicate are control dependent on the predicate
- Both criteria must hold:

1) X is not strictly post-dominated by Y

A path from X to End exists that does not pass Y or X==Y

2) There exists a path from X to Y such that every node on that path other than X is post-dominated by Y

& No such path exists for nodes in the path between X and Y



X is **not** strictly post-dominated by Y

Every node on this path **must be** post-dominated by Y

Then Y is control-dependent on X

Control Dependence - Example

- Y is control dependent on X **iff** X directly determines whether Y executes
  1) X is not strictly post-dominated by Y
  2) There exists a path from X to Y such that every node on that path other than X is post-dominated by Y

Tricky!! CD(2) = {2}

2->3->2'->4->End

X = 2, Y = 2' (2nd iteration)

SPDOM(2) = {4}

2' ∉ SPDOM(2) &

2->2' = {3, 2'}, and

2' ∈ PDOM(3)

2' ∈ PDOM(2')

X = 2, Y = 3

3 ∉ SPDOM(2) &

2->3 = {3}, 3 ∈ PDOM(3)

CD(3) = {2}

Why not CD(3) = {1, 2}?

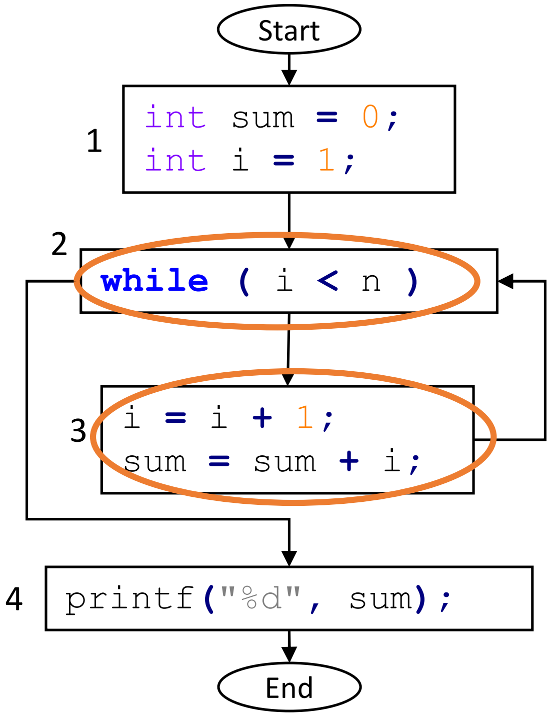
X = 1, Y = 3

3 ∉ SPDOM(1) &

1->3 = {2,3}, but

3 ∉ PDOM(2)

3 ∈ PDOM(3)



```
int sum = 0;
int i = 1;
```

```
while ( i < n )
```

```
i = i + 1;
sum = sum + i;
```

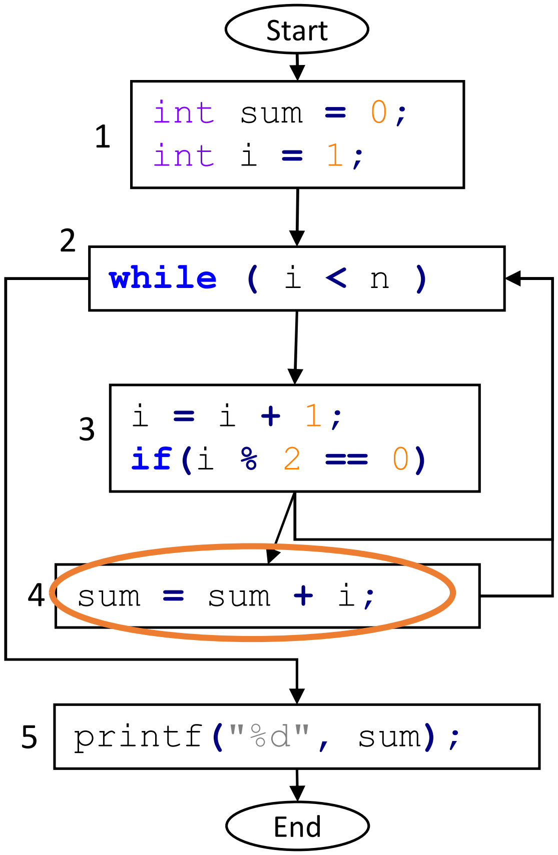
```
printf("%d", sum);
```

- May seem confusing, but this is really just the “unrolling” of the loop
- In fact, “**loop unrolling**” is the concrete term for “**loop induction**”
- Algorithm Analysis in Binary Analysis … Mind = Blown

Control Dependence is **not** Syntactically Explicit

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        if(i % 2 == 0)
            continue;
        sum = sum + i;
    }
    printf("%d", sum);
}
```

CD(4) = ?



Control Dependence is **not** Syntactically Explicit

- Y is control dependent on X **iff** X directly determines whether Y executes
  1) X is not strictly post-dominated by Y
  2) There exists a path from X to Y such that every node
     on that path other than X is post-dominated by Y

X = 3, Y = 4
SPDOM(3) = {2, 5}

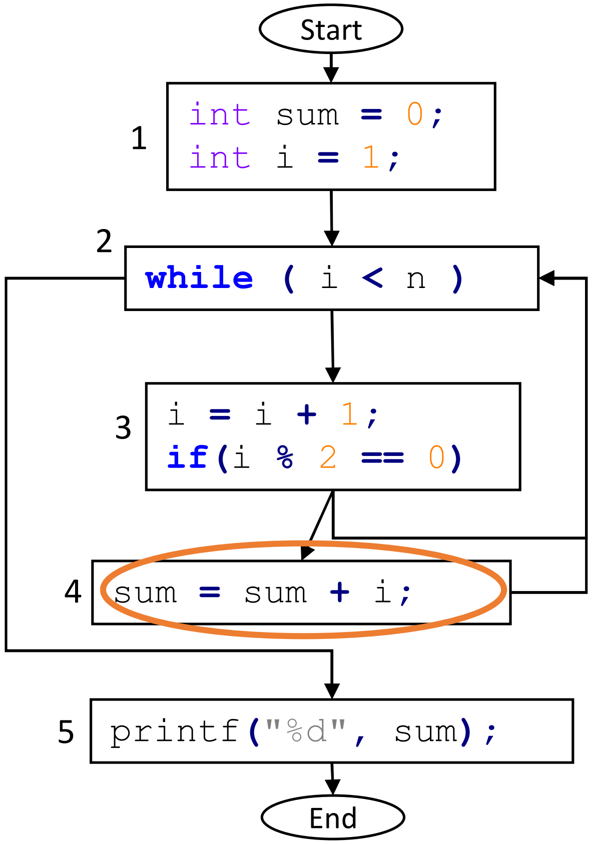
4 ∉ SPDOM(3) &
3->4 = {4}, 4 ∈ PDOM(4)

So CD(4) = {3}

X = 2, Y = 4
SPDOM(2) = {5}

4 ∉ SPDOM(2) &
2->4 = {3, 4}, but
4 ∉ PDOM(3)
4 ∈ PDOM(4)

So, 4 is **not** control dependent on 2!



```
int sum = 0;
int i = 1;
```

```
while ( i < n )
```

```
i = i + 1;
if(i % 2 == 0)
```

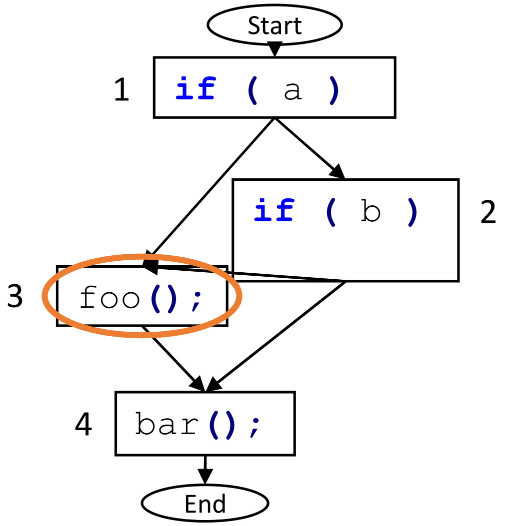
```
sum = sum + i;
```

```
printf("%d", sum);
```

Control Dependence is VERY Tricky!

- Y is control dependent on X **iff** X directly determines whether Y executes
  1) X is not strictly post-dominated by Y
  2) There exists a path from X to Y such that every node on that path other than X is post-dominated by Y
- Can one statement be control dependent on two predicates?

```
    cmp rax, 0
    jne .L2
    cmp rbx, 0
    je  .L3
.L2:
    call   foo
.L3:
    call   bar
```



```
if ( a || b )
    foo();
bar();
```

X = 2, Y = 3
SPDOM(2) = {4}

3 ∉ SPDOM(2) &
2->3 = {3}, 3 ∈ PDOM(3)

So CD(3) = {2} ... but wait

You didn't think we were finished with assembly, did you??

X = 1, Y = 3
SPDOM(1) = {4}

3 ∉ SPDOM(1) &
1->3 = {3}, 3 ∈ PDOM(3)

So CD(3) = {1, 2}

Advanced Topics in Malware Analysis

Software Representation

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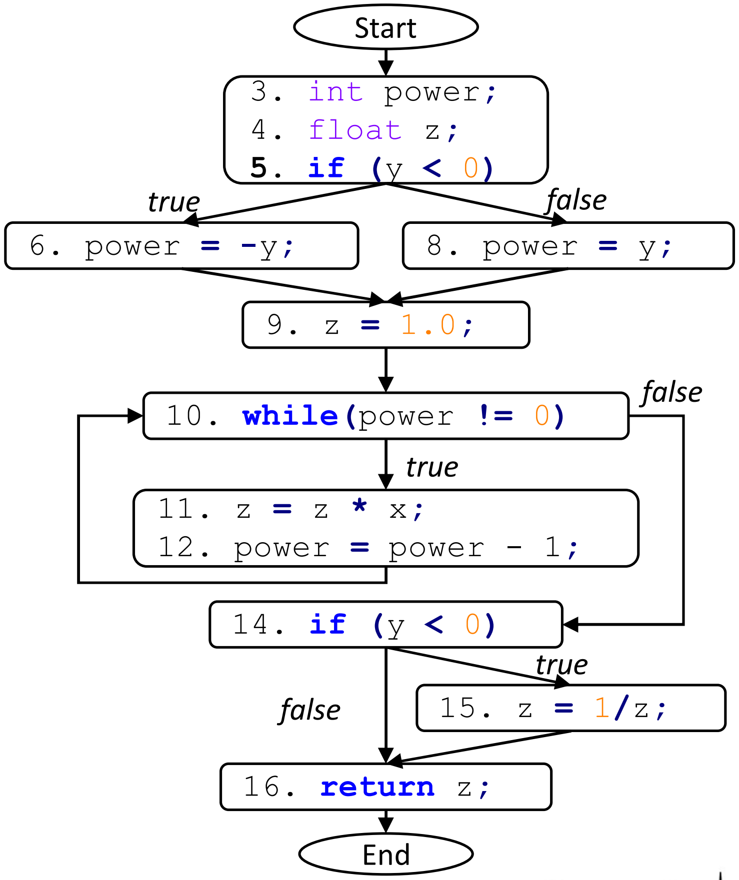
Data Dependencies

Data Dependence

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined
- Data dependence is calculated **per statement**
  - Rarely will results be aggregated per basic block

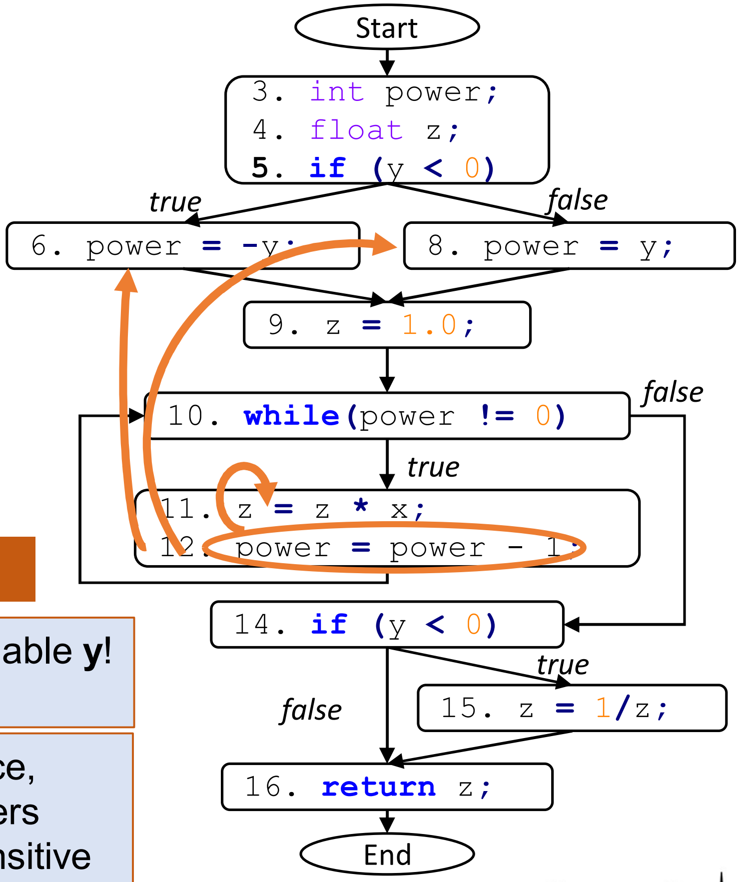
Data Dependence Example

```
1.  float pow(int x, int y)
2.  {
3.       int power;
4.       float z;
5.       if (y < 0)
6.           power = -y;
7.       else
8.           power = y;
9.       z = 1.0;
10.      while(power != 0) {
11.          z = z * x;
12.          power--;
13.      }
14.      if (y < 0)
15.          z = 1/z;
16.      return z;
17. }
```



Data Dependence Example

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined
- Data dependence is calculated **per statement**
  - Rarely will results be aggregated per basic block



DD(12) = {6, 8, 12}

But notice, NOT on the variable **y**! Why?

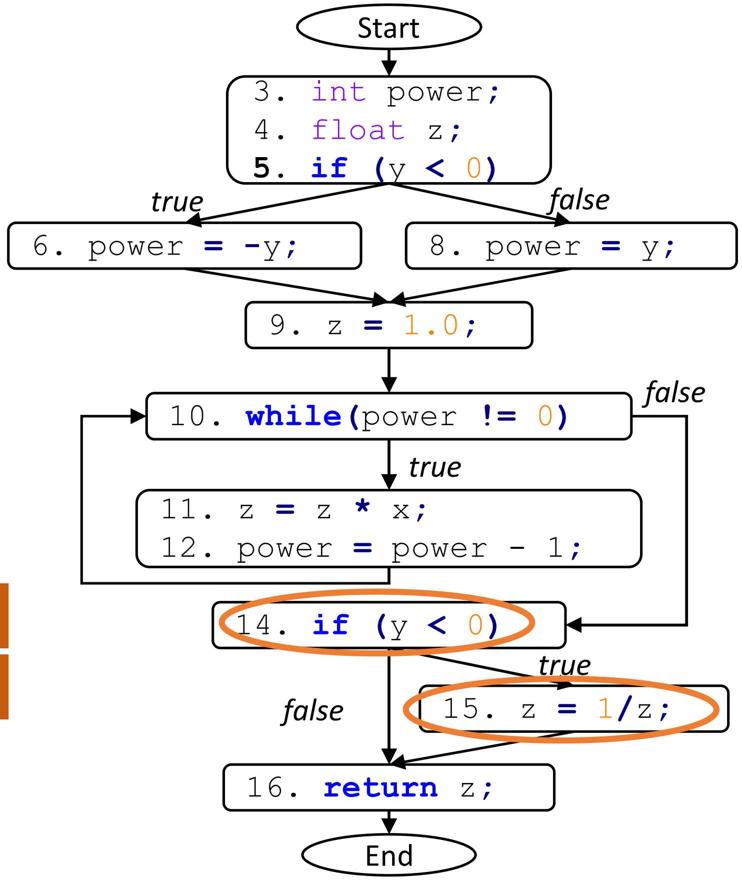
Just like control dependence, data dependence only covers direct dependence, not transitive dependence!

Data Dependence Example 2

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined
- Data dependence is calculated **per statement**
  - Rarely will results be aggregated per basic block

DD(14) = {Arg2}

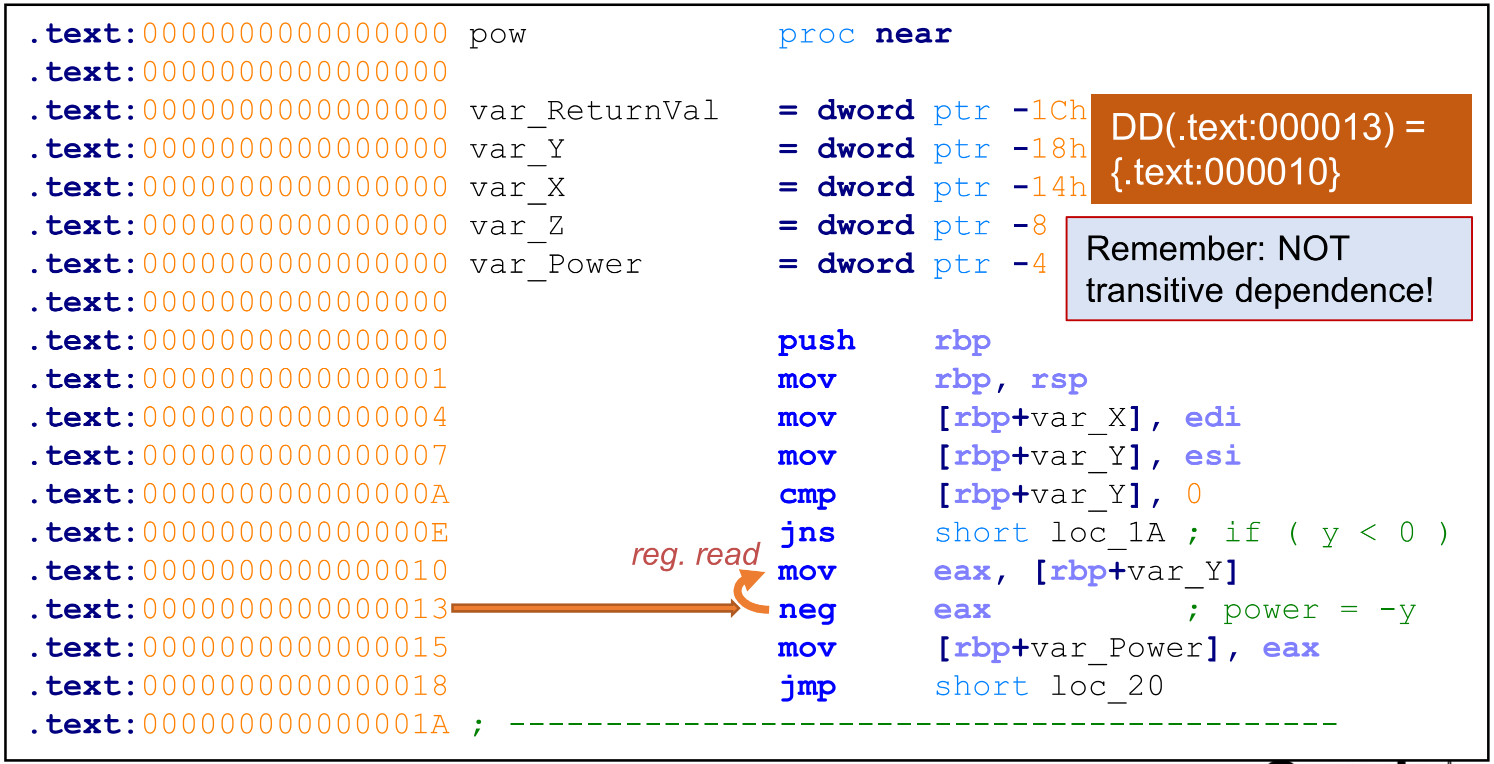
DD(15) = {9, 11}



```
3. int power;
4. float z;
5. if (y < 0)
6. power = -y;
8. power = y;
9. z = 1.0;
10. while(power != 0)
11. z = z * x;
12. power = power - 1;
14. if (y < 0)
15. z = 1/z;
16. return z;
```

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined



```
.text:0000000000000000 pow                proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal      = dword ptr -1Ch
.text:0000000000000000 var_Y              = dword ptr -18h
.text:0000000000000000 var_X              = dword ptr -14h
.text:0000000000000000 var_Z              = dword ptr -8
.text:0000000000000000 var_Power          = dword ptr -4
.text:0000000000000000
.text:0000000000000000                    push    rbp
.text:0000000000000001                    mov     rbp, rsp
.text:0000000000000004                    mov     [rbp+var_X], edi
.text:0000000000000007                    mov     [rbp+var_Y], esi
.text:000000000000000A                    cmp     [rbp+var_Y], 0
.text:000000000000000E                    jns     short loc_1A ; if ( y < 0 )
.text:0000000000000010                    mov     eax, [rbp+var_Y]
.text:0000000000000013                    neg     eax          ; power = -y
.text:0000000000000015                    mov     [rbp+var_Power], eax
.text:0000000000000018                    jmp     short loc_20
.text:000000000000001A ; ------------------------------------------
```

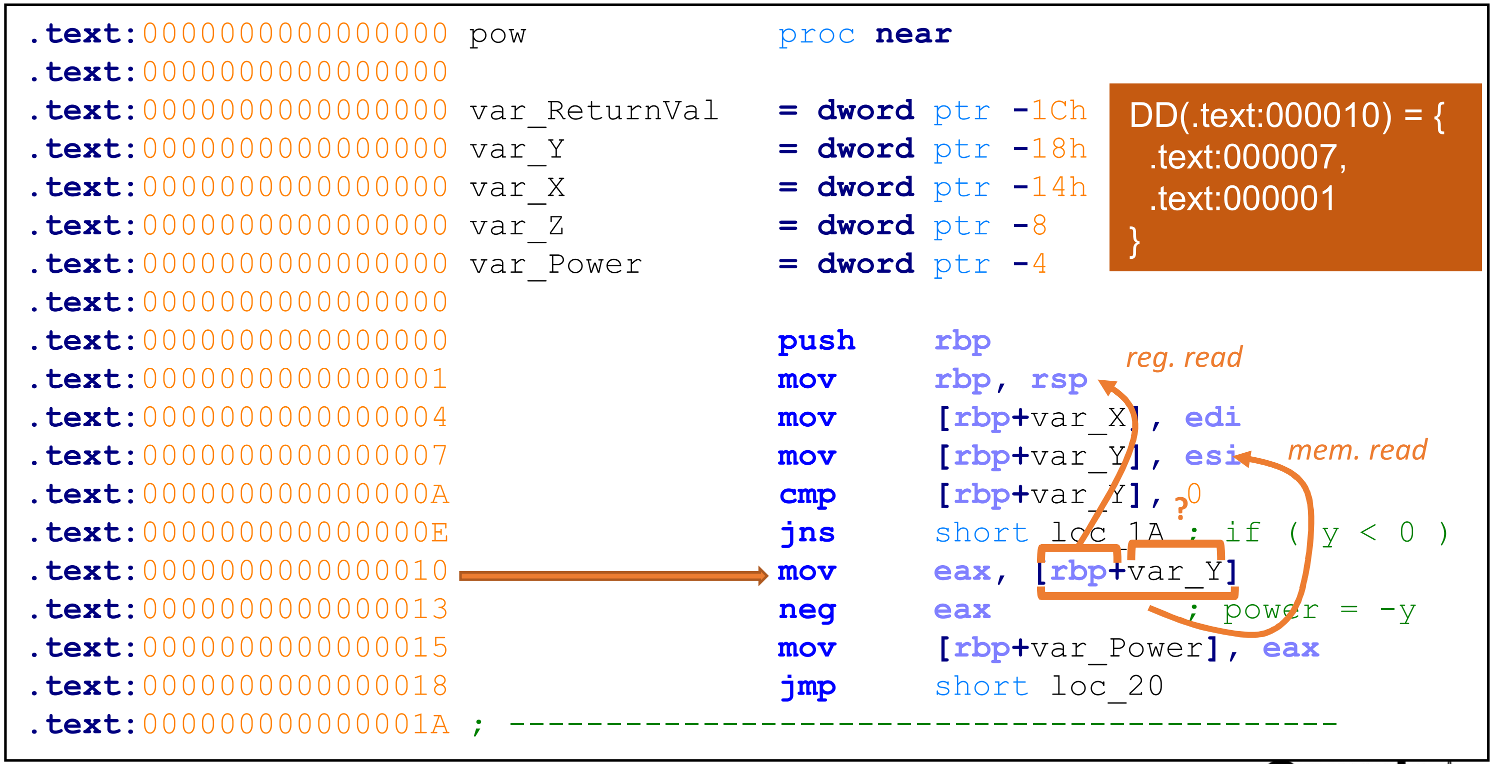
reg. read

DD(.text:000013) = {.text:000010}

Remember: NOT transitive dependence!

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

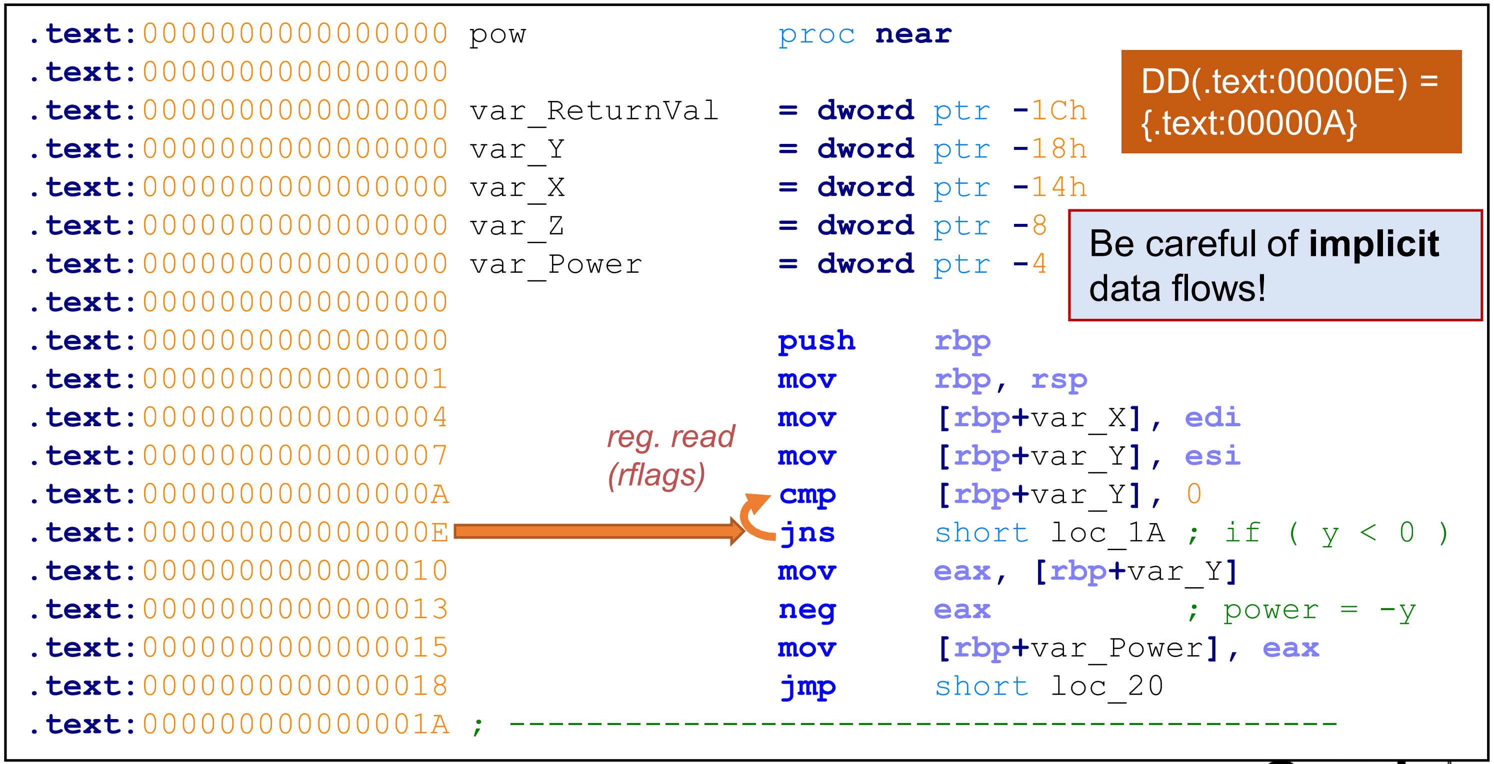


```
.text:0000000000000000 pow             proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal   = dword ptr -1Ch
.text:0000000000000000 var_Y           = dword ptr -18h
.text:0000000000000000 var_X           = dword ptr -14h
.text:0000000000000000 var_Z           = dword ptr -8
.text:0000000000000000 var_Power       = dword ptr -4
.text:0000000000000000
.text:0000000000000000                 push    rbp
.text:0000000000000001                 mov     rbp, rsp
.text:0000000000000004                 mov     [rbp+var_X], edi
.text:0000000000000007                 mov     [rbp+var_Y], esi
.text:000000000000000A                 cmp     [rbp+var_Y], 0
.text:000000000000000E                 jns     short loc_1A ; if ( y < 0 )
.text:0000000000000010                 mov     eax, [rbp+var_Y]
.text:0000000000000013                 neg     eax       ; power = -y
.text:0000000000000015                 mov     [rbp+var_Power], eax
.text:0000000000000018                 jmp     short loc_20
.text:000000000000001A ; -------------------------------------------
```

DD(.text:000010) = {
.text:000007,
.text:000001
}

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined



```
.text:0000000000000000 pow             proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal   = dword ptr -1Ch
.text:0000000000000000 var_Y           = dword ptr -18h
.text:0000000000000000 var_X           = dword ptr -14h
.text:0000000000000000 var_Z           = dword ptr -8
.text:0000000000000000 var_Power       = dword ptr -4
.text:0000000000000000
.text:0000000000000000                 push    rbp
.text:0000000000000001                 mov     rbp, rsp
.text:0000000000000004                 mov     [rbp+var_X], edi
.text:0000000000000007                 mov     [rbp+var_Y], esi
.text:000000000000000A                 cmp     [rbp+var_Y], 0
.text:000000000000000E                 jns     short loc_1A ; if ( y < 0 )
.text:0000000000000010                 mov     eax, [rbp+var_Y]
.text:0000000000000013                 neg     eax             ; power = -y
.text:0000000000000015                 mov     [rbp+var_Power], eax
.text:0000000000000018                 jmp     short loc_20
.text:000000000000001A ; -------------------------------------------
```

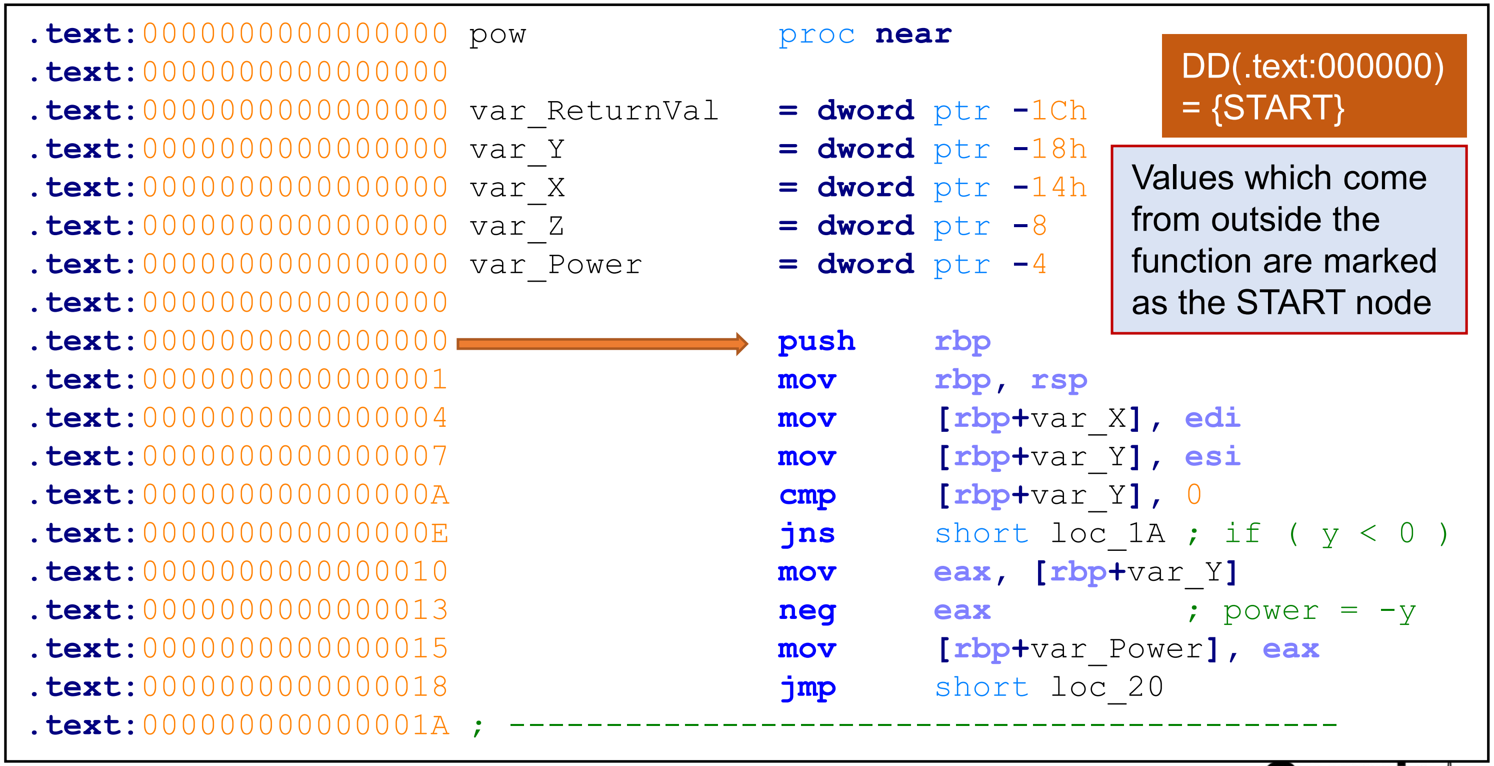
DD(.text:00000E) = {.text:00000A}

Be careful of **implicit** data flows!

reg. read (rflags)

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined



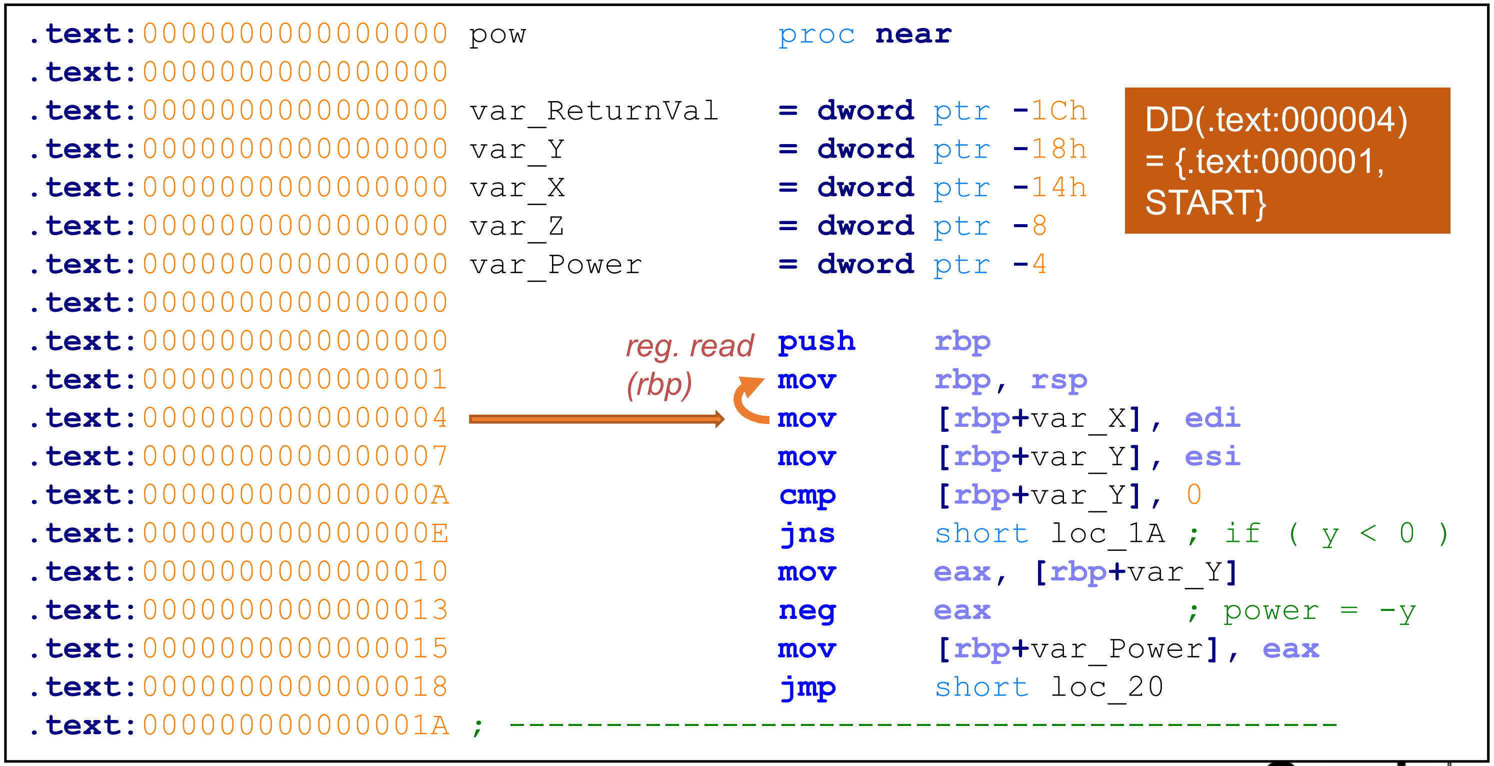
```
.text:0000000000000000 pow             proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal   = dword ptr -1Ch
.text:0000000000000000 var_Y           = dword ptr -18h
.text:0000000000000000 var_X           = dword ptr -14h
.text:0000000000000000 var_Z           = dword ptr -8
.text:0000000000000000 var_Power       = dword ptr -4
.text:0000000000000000
.text:0000000000000000                 push    rbp
.text:0000000000000001                 mov     rbp, rsp
.text:0000000000000004                 mov     [rbp+var_X], edi
.text:0000000000000007                 mov     [rbp+var_Y], esi
.text:000000000000000A                 cmp     [rbp+var_Y], 0
.text:000000000000000E                 jns     short loc_1A ; if ( y < 0 )
.text:0000000000000010                 mov     eax, [rbp+var_Y]
.text:0000000000000013                 neg     eax             ; power = -y
.text:0000000000000015                 mov     [rbp+var_Power], eax
.text:0000000000000018                 jmp     short loc_20
.text:000000000000001A ; -------------------------------------------
```

DD(.text:000000) = {START}

Values which come from outside the function are marked as the START node

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined



```
.text:0000000000000000 pow                proc near
.text:0000000000000000
.text:0000000000000000 var_ReturnVal      = dword ptr -1Ch
.text:0000000000000000 var_Y              = dword ptr -18h
.text:0000000000000000 var_X              = dword ptr -14h
.text:0000000000000000 var_Z              = dword ptr -8
.text:0000000000000000 var_Power          = dword ptr -4
.text:0000000000000000
.text:0000000000000000                    push    rbp
.text:0000000000000001                    mov     rbp, rsp
.text:0000000000000004                    mov     [rbp+var_X], edi
.text:0000000000000007                    mov     [rbp+var_Y], esi
.text:000000000000000A                    cmp     [rbp+var_Y], 0
.text:000000000000000E                    jns     short loc_1A ; if ( y < 0 )
.text:0000000000000010                    mov     eax, [rbp+var_Y]
.text:0000000000000013                    neg     eax         ; power = -y
.text:0000000000000015                    mov     [rbp+var_Power], eax
.text:0000000000000018                    jmp     short loc_20
.text:000000000000001A ; -------------------------------------------
```

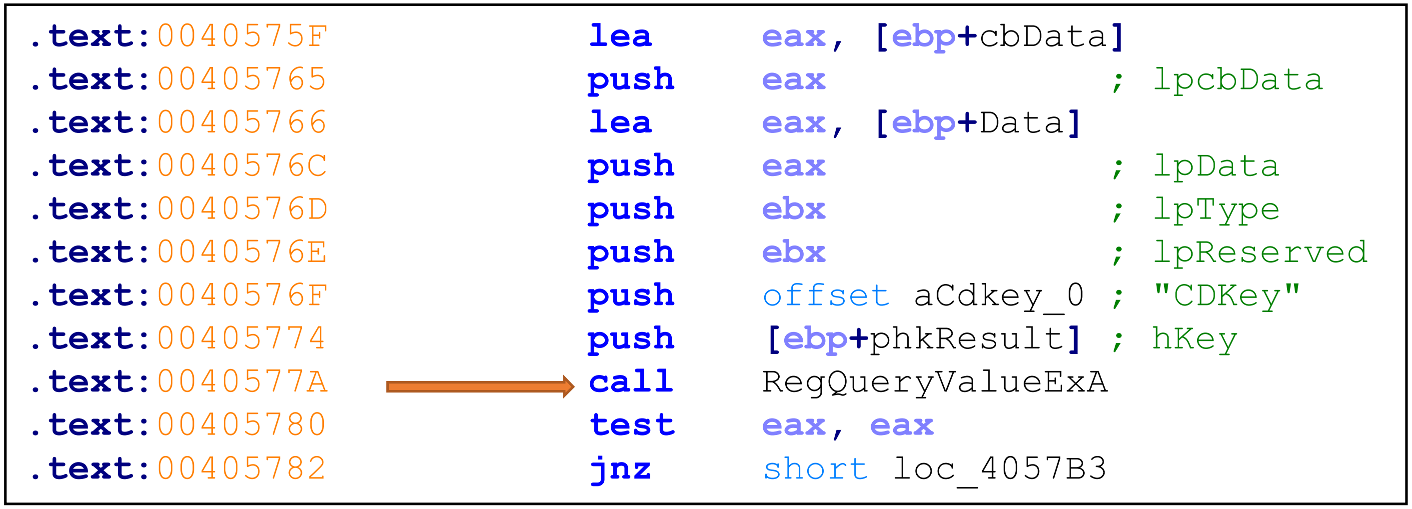
reg. read (rbp)

DD(.text:000004) = {.text:000001, START}

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

DD(.text:0040577A) = { }



```
.text:0040575F                lea     eax, [ebp+cbData]
.text:00405765                push    eax             ; lpcbData
.text:00405766                lea     eax, [ebp+Data]
.text:0040576C                push    eax             ; lpData
.text:0040576D                push    ebx             ; lpType
.text:0040576E                push    ebx             ; lpReserved
.text:0040576F                push    offset aCdkey_0 ; "CDKey"
.text:00405774                push    [ebp+phkResult] ; hKey
.text:0040577A                call    RegQueryValueExA
.text:00405780                test    eax, eax
.text:00405782                jnz     short loc_4057B3
```

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

DD(.text:00405780) = {.text:0040577A}

Don't forget about implicit flows!!
Calls redefine the RAX/EAX register!

```
.text:0040575F              lea     eax, [ebp+cbData]
.text:00405765              push    eax                 ; lpcbData
.text:00405766              lea     eax, [ebp+Data]
.text:0040576C              push    eax                 ; lpData
.text:0040576D              push    ebx                 ; lpType
.text:0040576E              push    ebx                 ; lpReserved
.text:0040576F              push    offset aCdkey_0 ; "CDKey"
.text:00405774  reg. read   push    [ebp+phkResult] ; hKey
.text:0040577A  (eax)       call    RegQueryValueExA
.text:00405780              test    eax, eax
.text:00405782              jnz     short loc_4057B3
```

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

DD(.text:004010BB) = { }

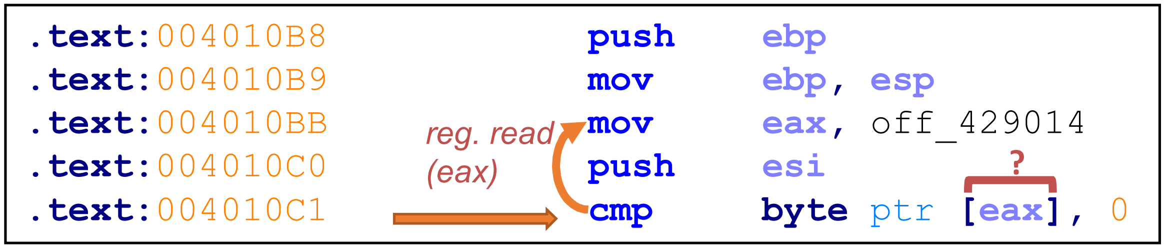
Constant offset value! Just like “mov eax, 0x1234”

```
.text:004010B8                 push    ebp
.text:004010B9                 mov     ebp, esp
.text:004010BB                 mov     eax, off_429014
.text:004010C0                 push    esi
.text:004010C1                 cmp     byte ptr [eax], 0
```

Data Dependence On Binaries

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

DD(.text:004010C1) = {.text:004010BB, ?? }



```
.text:004010B8                push    ebp
.text:004010B9                mov     ebp, esp
.text:004010BB                mov     eax, off_429014
.text:004010C0                push    esi
.text:004010C1                cmp     byte ptr [eax], 0
```

- Handling global data dependence is implementation specific!
- **Options:**
  1) Only track global data globally
  2) Track all data globally
  3) Note global dependencies at the START node & patch later

Advanced Topics in Malware Analysis

Software Representation

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Def-Use Chains

Data Dep. Modelling with DU Chains

- DU chains (Def-Use chains) link the definition of a variable and the use of the variable
- **Pro**: Very fast to collect data dependencies, easy to program (table data structure)
- **Con**: Must compute & store every variable, cannot omit unused variables

```
float pow(int x, int y)    // D: x, y
{
    int power;
    float z;
    if (y < 0)             // U: y
        power = -y;        // D: power    U: y
    else
        power = y;         // D: power    U: y
    z = 1.0;               // D: z
    while(power != 0) {    // U: power
        z = z * x;         // D: z    U: x, z
        power--;           // D: power    U: power
    }
    if (y < 0)             // U: y
        z = 1/z;           // D: z    U: z
    return z;              // U: z
}
```

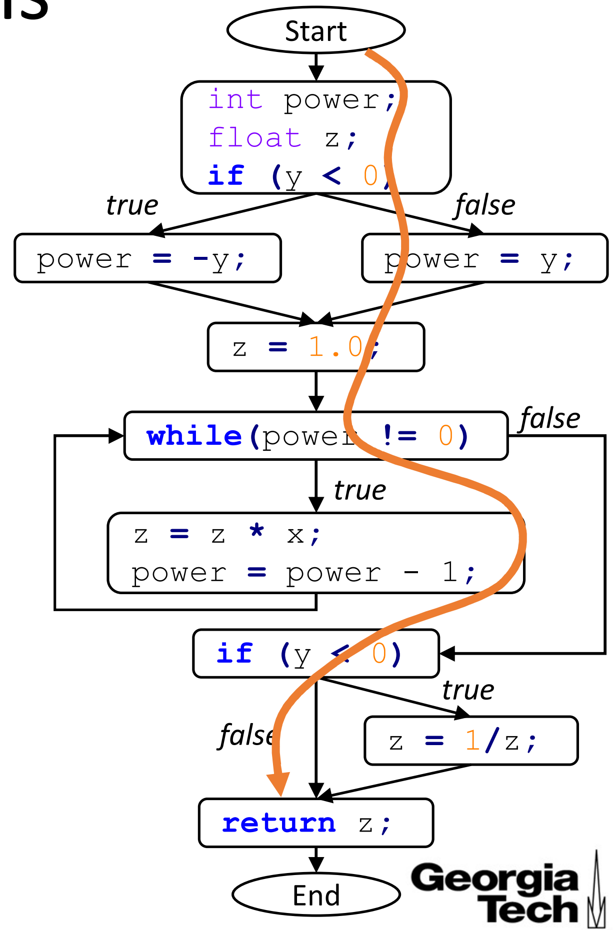
Data Dep. Modelling with DU Chains

- X is data dependent on Y **iff**
  1) There is a variable **V** that is defined at **Y** and used at **X**
  2) There exists a path of nonzero length from **Y** to **X** along which **V** is not re-defined

```
1.  float pow(int x, int y)    // D: x, y
2.  {
3.      int power;
4.      float z;
5.      if (y < 0)             // U: y
6.          power = -y;        // D: power    U: y
7.      else
8.          power = y;         // D: power    U: y
9.      z = 1.0;               // D: z
10.     while(power != 0) {    // U: power
11.         z = z * x;         // D: z     U: x, z
12.         power--;           // D: power    U: power
13.     }
14.     if (y < 0)             // U: y
15.         z = 1/z;           // D: z     U: z
16.     return z;              // U: z
17. }
```

DD(16) = {9}

DD(16) = ?



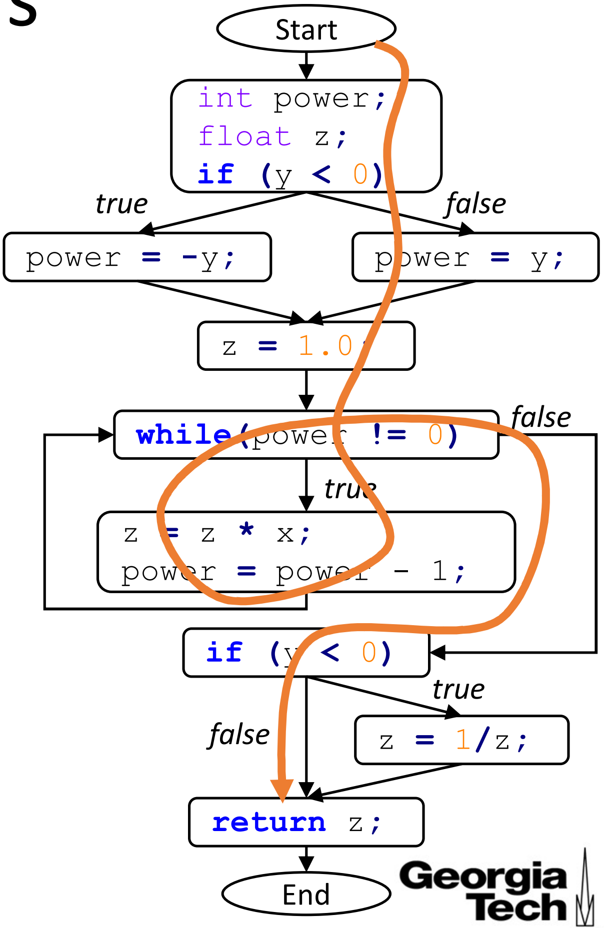
Data Dep. Modelling with DU Chains

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

```
1.  float pow(int x, int y)    // D: x, y
2.  {
3.      int power;
4.      float z;
5.      if (y < 0)             // U: y
6.          power = -y;        // D: power     U: y
7.      else
8.          power = y;         // D: power     U: y
9.      z = 1.0;               // D: z
10.     while(power != 0) {    // U: power
11.         z = z * x;         // D: z     U: x, z
12.         power--;           // D: power     U: power
13.     }
14.     if (y < 0)             // U: y
15.         z = 1/z;           // D: z     U: z
16.     return z;              // U: z
17. }
```

DD(16) = {9}

DD(16) = {9, 11}



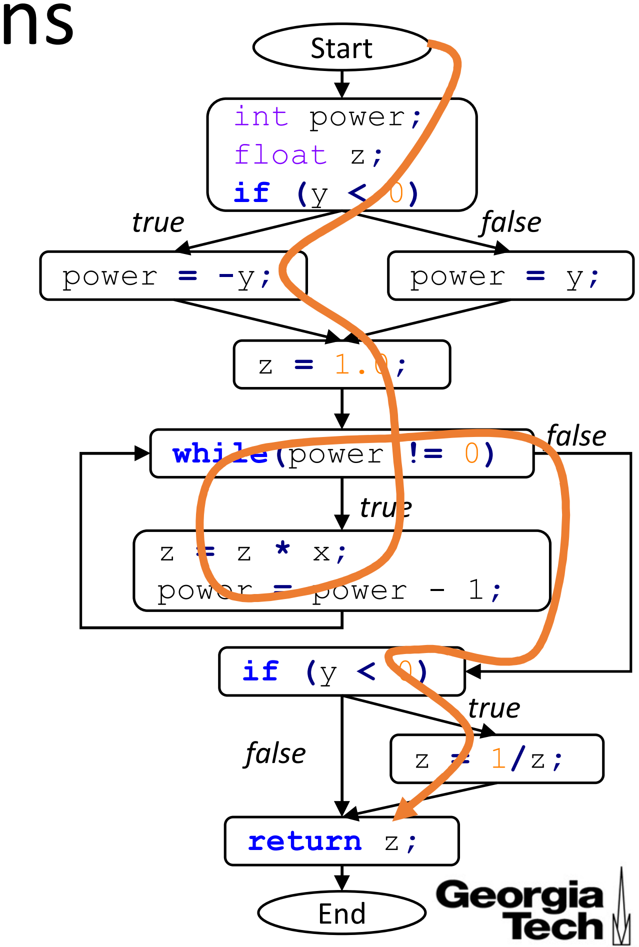
Data Dep. Modelling with DU Chains

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined

```
1.  float pow(int x, int y)    // D: x, y
2.  {
3.      int power;
4.      float z;
5.      if (y < 0)             // U: y
6.          power = -y;        // D: power    U: y
7.      else
8.          power = y;         // D: power    U: y
9.      z = 1.0;               // D: z
10.     while(power != 0) {    // U: power
11.         z = z * x;         // D: z    U: x, z
12.         power--;           // D: power    U: power
13.     }
14.     if (y < 0)             // U: y
15.         z = 1/z;           // D: z    U: z
16.     return z;              // U: z
17. }
```

DD(16) = {9, 11}

DD(16) = {9, 11, 15}



DU Chains on Binaries

- Def-Use chains link the definition of a data location and the use of the data location
  - Registers or memory!

```
.text:00 pow             proc near
.text:00
.text:00 var_ReturnVal   = dword ptr -1Ch
.text:00 var_Y           = dword ptr -18h
.text:00 var_X           = dword ptr -14h
.text:00 var_Z           = dword ptr -8
.text:00 var_Power       = dword ptr -4
.text:00
.text:00 push    rbp               ; D: rsp, [rsp] U: rsp, rbp
.text:01 mov     rbp, rsp          ; D: rbp U: rsp
.text:04 mov     [rbp+var_X], edi ; D: [rbp+var_X] U: rbp, edi
.text:07 mov     [rbp+var_Y], esi ; D: [rbp+var_Y] U: rbp, esi
.text:0A cmp     [rbp+var_Y], 0    ; D: rflags, U: rbp, [rbp+var_Y]
.text:0E jns     short loc_1A      ; D: U: rflags
.text:10 mov     eax, [rbp+var_Y] ; D: eax U: rbp, [rbp+var_Y]
.text:13 neg     eax               ; D: eax U: eax
.text:15 mov     [rbp+var_Power], eax ; D: [rbp+var_Power] U: rbp, eax
.text:18 jmp     short loc_20      ; D: U:
```

Data Dep. Modelling on Binaries

- Be careful! Data dependence in terms of source lines is easy to see
  - Because our brains naturally follow the control flow!!
- Consider:
  - The if statement (line 4) is dependent on the argument (line 1)
  - The **x += 1** (line 7) is dependent on the initialization of **x** (line 3)
  - The return is dependent on both paths of the if statement (lines 5 and 7), since either are possible

```
1. int func(int y)
2. {
3.     int x = 1;
4.     if (y == 1):
5.         x = 2;
6.     else:
7.         x += 1;
8.     return x;
9. }
```

Data Dep. Modelling on Binaries with DU Chains

- Data Dep. **must consider the CFG** of the basic blocks traversed before the current block!
- For example: A **linear parse of the DU Chain (not following the CFG)** would incorrectly say:
  - The **add esi,** 1 is data dependent on **mov esi,** 2
  - The **mov eax, esi** is only data dependent on **add esi,** 1
- When computing data dep, you MUST follow the possible paths in the CFG!

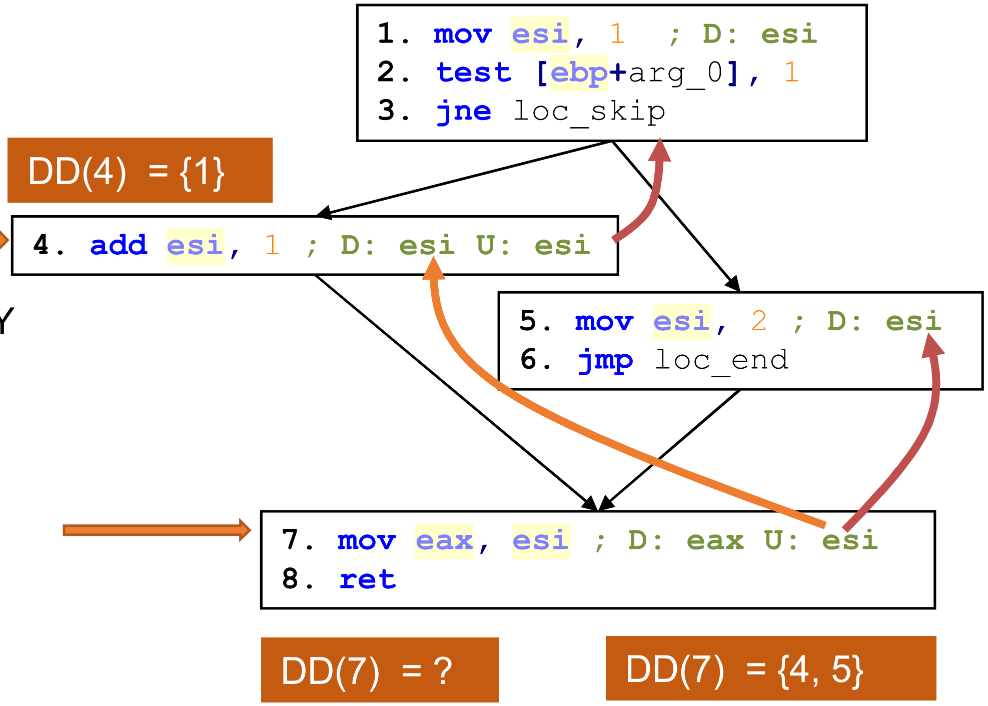
```
int func(int y)
{
     int x = 1;
     if (y == 1):
          x = 2;
     else:
          x += 1;
     return x;
}
```

```
loc_start:
     ; stack setup
     mov esi, 1          ; D: esi
     test [ebp+arg_0], 1
     jne loc_skip
     mov esi, 2          ; D: esi
     jmp loc_end

loc_skip:
     add esi, 1     ; D: esi U: esi

loc_end:
     mov eax, esi  ; D: eax U: esi
     ; clean up stack
     ret
```

Data Dep. Modelling on Binaries with DU Chains

Data Dep. **must consider the CFG** of the basic blocks traversed before the current block!

- X is data dependent on Y **iff**
  1) There is a variable V that is defined at Y and used at X
  2) There exists a path of nonzero length from Y to X along which V is not re-defined



```
1. mov esi, 1   ; D: esi
2. test [ebp+arg_0], 1
3. jne loc_skip
```

```
4. add esi, 1  ; D: esi U: esi
```

```
5. mov esi, 2 ; D: esi
6. jmp loc_end
```

```
7. mov eax, esi  ; D: eax U: esi
8. ret
```

DD(4) = {1}

DD(7) = ?

DD(7) = {4, 5}

Advanced Topics in Malware Analysis

Software Representation

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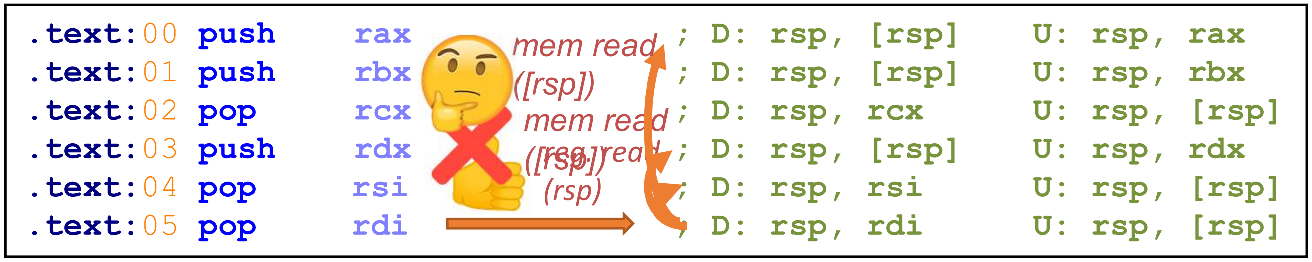
School of Electrical and Computer Engineering

Value Tracking

Keeping Pushes and Pops Straight!

- Problem: Pushes and Pops Def and Use the same stuff!!



```
.text:00 push    rax      ; D: rsp, [rsp]    U: rsp, rax
.text:01 push    rbx      ; D: rsp, [rsp]    U: rsp, rbx
.text:02 pop     rcx      ; D: rsp, rcx      U: rsp, [rsp]
.text:03 push    rdx      ; D: rsp, [rsp]    U: rsp, rdx
.text:04 pop     rsi      ; D: rsp, rsi      U: rsp, [rsp]
.text:05 pop     rdi      ; D: rsp, rdi      U: rsp, [rsp]
```

- Bigger Problem: **Linear parse of the DU Chain (even following the CFG) will be incorrect**
- **Solution:** Create a “Shadow Stack” --- A model stack which tracks who pushed what!

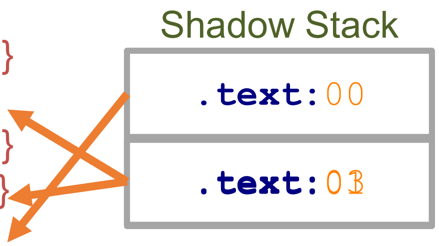
Keeping Pushes and Pops Straight!

- Problem: Pushes and Pops Def and Use the same stuff!!

```
.text:00 push    rax      ; D: rsp, [rsp]     U: rsp, rax
.text:01 push    rbx      ; D: rsp, [rsp]     U: rsp, rbx
.text:02 pop     rcx      ; D: rsp, rcx       U: rsp, [rsp]
.text:03 push    rdx      ; D: rsp, [rsp]     U: rsp, rdx
.text:04 pop     rsi      ; D: rsp, rsi       U: rsp, [rsp]
.text:05 pop     rdi      ; D: rsp, rdi       U: rsp, [rsp]
```

- Bigger Problem: **Linear parse of the DU Chain (even following the CFG) will be incorrect**
- **Solution:** Create a “Shadow Stack” --- A model stack which tracks who pushed what!

DD(.text:00) = { prior rax, rsp }
DD(.text:01) = { .text:00, prior rbx }
DD(.text:02) = { .text:01, .text:01 }
DD(.text:03) = { .text:02, prior rdx }
DD(.text:04) = { .text:03, .text:03 }
DD(.text:05) = { .text:04, .text:00 }



Computing Data Dependence is Hard in General

- Aliasing --- the kryptonite to the data dependence superhero!
  - Alias: A variable which can refer to multiple memory locations/objects

C loves aliases

```
int x, y,
z;
int * p;
x = 5;
y = 10;
z = 8;
p = &x;
p = p + z;
z = *p;
```

What is the value of z?

Assembly loves aliases

```
push    rbp
mov     rbp, rsp
push    rdi
sub     rsp, 16
...
cmp     QWORD PTR [rbp], 0
...
mov     rax, QWORD PTR
[rsp+24]
```

What is being moved into RAX?

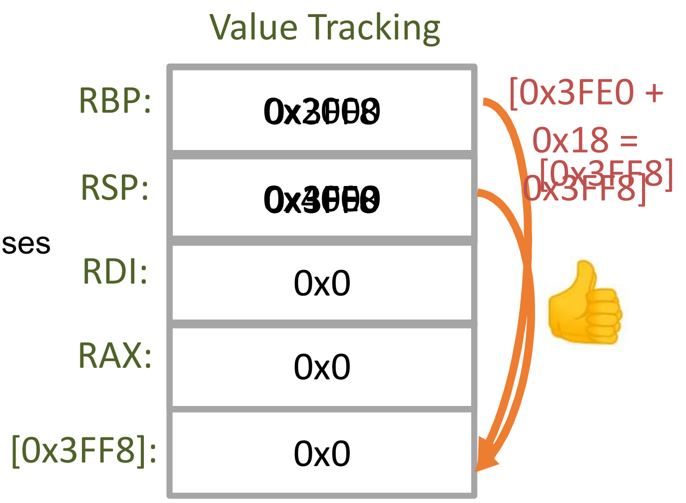
```
void func(int d) {
    int b;
    int c;
    if ( d == 0 )
        ...
    int a = d;
}
```

The original code had no aliases!

Static Value Tracking

```
push    rbp
mov     rbp, rsp
push    rdi
sub     rsp, 16
...
cmp     QWORD PTR [rbp], 0
...
mov     rax, QWORD PTR
[rsp+24]
```

Assembly loves aliases



Value Tracking

RBP: 0x2008 / 0x3FE0

RSP: 0x4000 / 0x3FF8 / 0x3FE0 / 0x3FD0

RDI: 0x0

RAX: 0x0

[0x3FF8]: 0x0

[0x3FE0 + 0x18 = 0x3FF8]

[0x3FF8]

RAX = 0x0!

What is being moved into RAX?

- Similar to Shadow Stack tracking, but now you track specific values of registers/memory
- You may have to assume “initial values” at function or program start
- As you step through the code, parse the instructions and update the tracked values
- When you need to know a value, hopefully you have tracked it!

Advanced Topics in Malware Analysis

Software Representation

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Assistant Professor

School of Electrical and Computer Engineering

Program Dependence Graphs

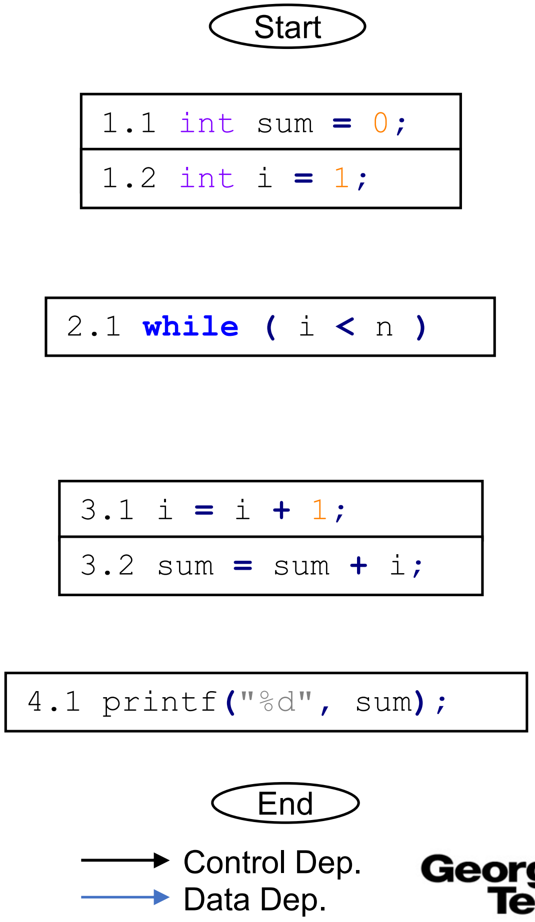
Program Dependence Graph (PDG)

- The second most widely used program representation
- Represents the union of the two types of dependences
  - Data dependence
  - Control dependence
- Optional (but valuable) reading:
  - Ferrante, J., Ottenstein, K. J., & Warren, J. D. (1987). The program dependence graph and its use in optimization. *ACM Transactions on Programming Languages and Systems*, *9*(3), 319–349.
  - Horwitz, S., Reps, T., & Binkley, D. (1990). Interprocedural slicing using dependence graphs. *ACM Transactions on Programming Languages and Systems*, *12*(1), 26–60.

Program Dependence Graph

- A program dependence graph **PDG = (N, Ed, Ec)**
  - A finite set **N** of nodes which represents statements, possibly within basic blocks “super-nodes”

```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```



Start

```
1.1 int sum = 0;
1.2 int i = 1;
```

```
2.1 while ( i < n )
```

```
3.1 i = i + 1;
3.2 sum = sum + i;
```

```
4.1 printf("%d", sum);
```

End

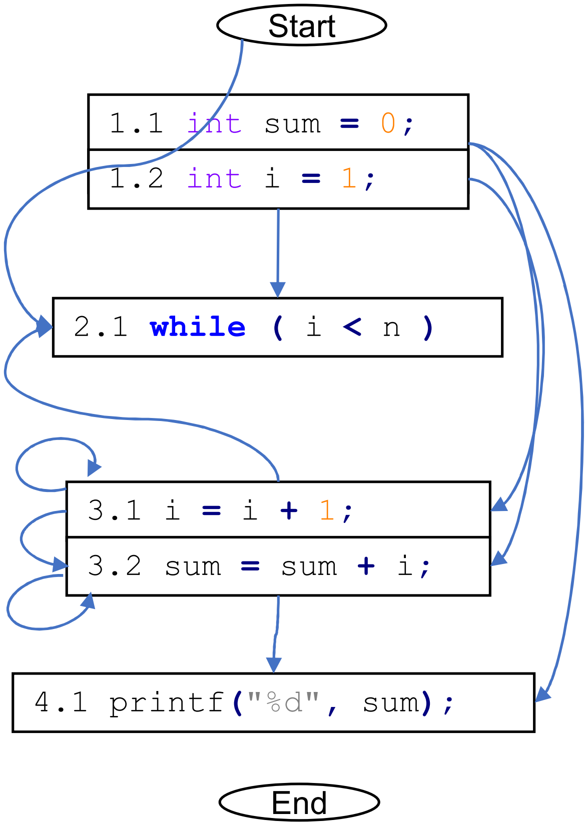
Control Dep.

Data Dep.

Program Dependence Graph

- A program dependence graph **PDG = (N, Ed, Ec)**
  - A finite set N of nodes which represents statements, possibly within basic blocks "super-nodes"
  - A finite set Ed of edges **(i, j)** representing that node **n_j** is data dependent on node **n_i**
  - Recall: **X** is data dependent on **Y** iff
    (1) There exists a variable **v** that is defined at **Y** and used at **X**
    (2) There exists a path of nonzero length from **Y** to **X** along which v is not re-defined

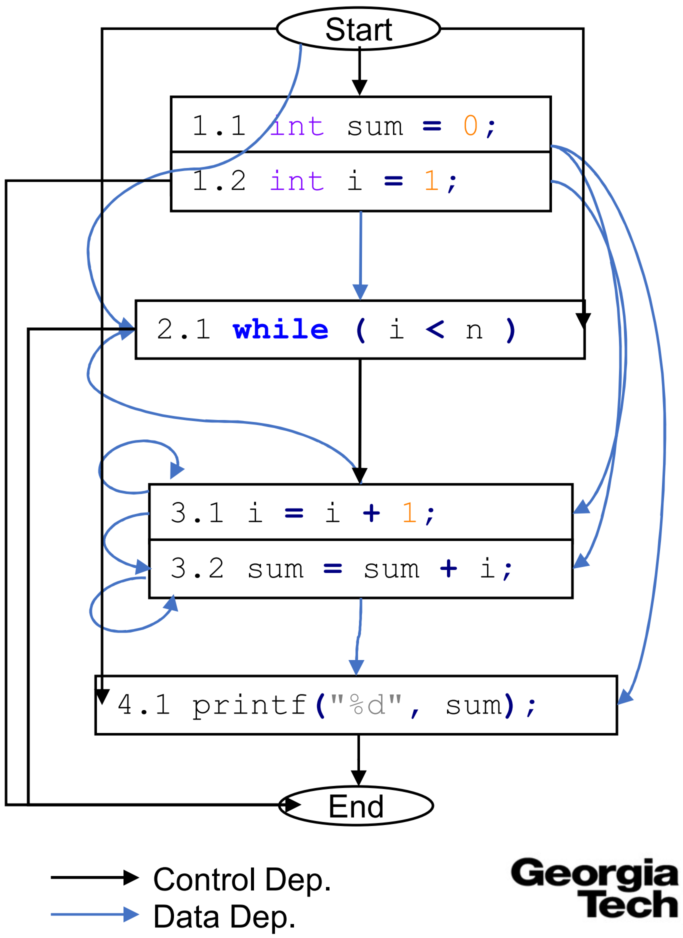
```
void sumUp(int n) {
    int sum = 0;
    int i = 1;
    while ( i < n ) {
        i = i + 1;
        sum = sum + i;
    }
    printf("%d", sum);
}
```



→ Control Dep.
→ Data Dep.

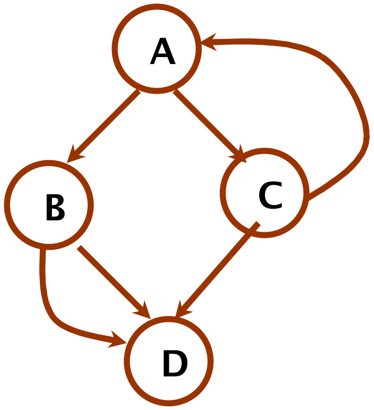
Program Dependence Graph

- A program dependence graph **PDG = (N, Ed, Ec)**
  - A finite set **N** of nodes which represents statements, possibly within basic blocks “**super-nodes**”
  - A finite set **Ed** of edges **(i, j)** representing that node $\mathbf{n_j}$ is data dependent on node $\mathbf{n_i}$
  - A finite set **Ec** of edges **(i, j)** representing that (super-) node $\mathbf{n_j}$ is control dependent on node $\mathbf{n_i}$
  - Recall: **Y** is control-dependent on **X** iff **X** directly determines whether **Y** executes:
    (1) **X** is not strictly post-dominated by **Y**
    (2) 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
- Used to represent the set of all program statements involved in reaching any single execution point



Call Graph (CG)

- **Simplest Case**: Nodes represent functions; each edge represents a function invocation
- Used to perform higher-level Intraprocedural Analysis



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

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

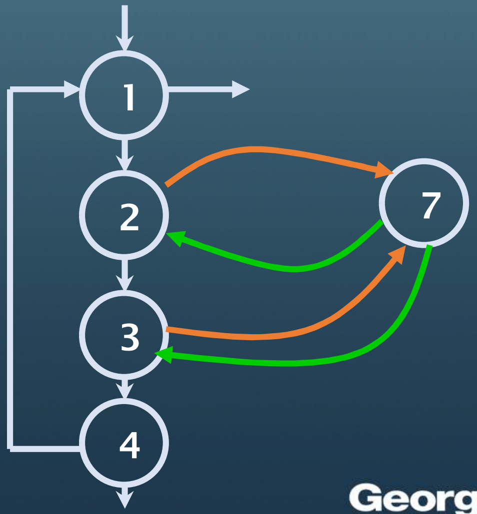
```
void B( ) {
L1:   D( );
L2:   D( );
}

void D ( ) {
}
```

Super Control Flow Graph (SCFG)

- Interprocedural control flow graph
  - Additional edges are added connecting each call site to the beginning of the procedure it calls
  - The return statement links back to the call site

- Rarely used in static analysis due to path explosion!
- Sometimes used in dynamic analysis due to ambiguity of function calls
  - JMP to some far away code? Fetch a return address and JMP to it?
  - JMP to a new function entry (no return address push) & then do a “double” return at RET?

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



Interprocedural Analysis

- Interprocedural analysis is a very deep rabbit hole!
- Excellent material:

  Chong, S. (2010). Interprocedural Analysis. Harvard University School of Engineering and Applied Sciences (https://www.seas.harvard.edu/courses/cs252/2011sp/slides/Lec05-Interprocedural.pdf)
- Interprocedural analysis can provide VERY precise static analysis
- But path explosion makes global reasoning nearly impossible!
- For this class, we will selectively cover interprocedural analysis as it applies to dynamic analysis
- As we will see, dynamic analysis cannot reason locally (due to limited knowledge)
- Therefore, everything is global until we realize it is local! ☺

Lesson Summary

- Describe software representation
- Describe basic blocks of software
- Reconstruct control flow graph
- Describe various types of paths
- Utilize paths to observe dependencies