Advanced Topics in Malware Analysis

Program Slicing

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Slicing: Program Dependent Graphs

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Learning Objectives

- Locate the set of statements that compose a program slice
- Construct a program dependent graph
- Assemble dynamic slices using a program dependency graph

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What is Slicing?

- A **Slice** of variable **v** at statement **s** is the set of statements involved in computing the value of v at s. [Mark Weiser, 1982]

Control Dep.
Data Dep.

Slice(i @ 5) =

{1 (or START), 3, 4, 5}

- A slice is a **backwards traversal** of the Program Dependence Graph!

```
1. void sumUp(int n) {
2.     int sum = 0;
3.     int i = 1;
4.     while ( i < n ) {
5.         i = i + 1;
6.         sum = sum + i;
7.     }
8.     printf("%d", sum);
9. }
```

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Remember the Program Dependence Graph?

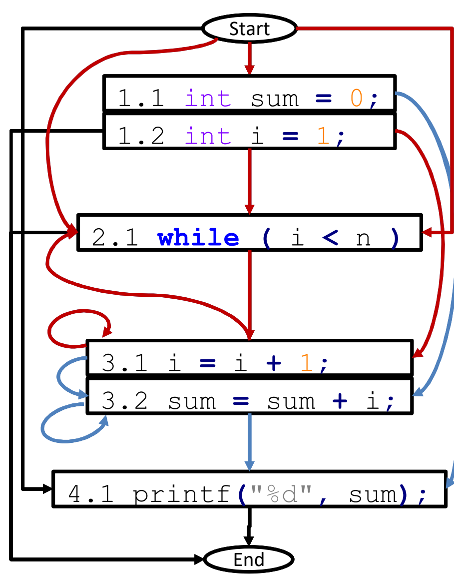
- A program dependence graph **PDG = (N, Ed, Ec)**
  - A finite set **N** of nodes which represent statements, possibly within basic blocks "**super-nodes**"
  - A finite set **Ed** of edges (**i, j**) representing that node $\mathbf{n_j}$ is data dependent on node n_i
  - A finite set **Ec** of edges (**i, j**) representing that (super-)node $\mathbf{n_j}$ is control dependent on node $\mathbf{n_i}$

Slice(i @ 3.1) =

{START, 1.2, 2.1, 3.1}

Slice

```
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.

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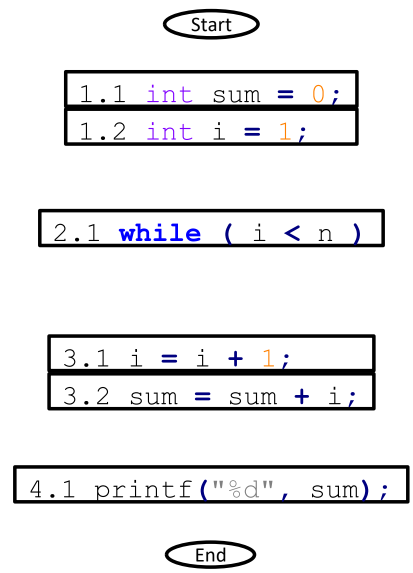
How To Compute A Slice Statically

- Build a **PDG = (N, Ed, Ec)**
  - A finite set **N** of nodes which represent 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);
}
```



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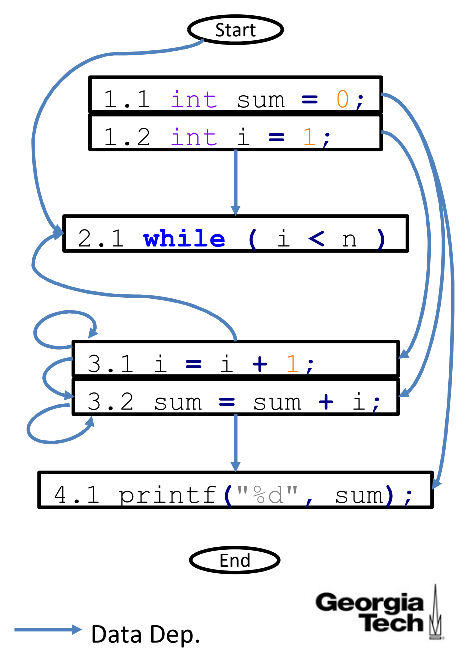
How To Compute A Slice Statically

- Build a **PDG = (N, Ed, Ec)**
  - A finite set N of nodes which represent 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



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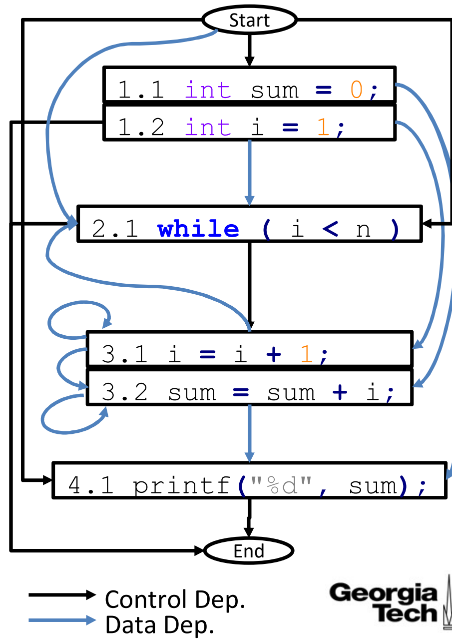
How To Compute A Slice Statically

- Build a PDG = (N, Ed, Ec)
  - A finite set N of nodes which represent 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
  - A finite set Ec of edges (i, j) representing that (super-)node n_j is control dependent on node 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



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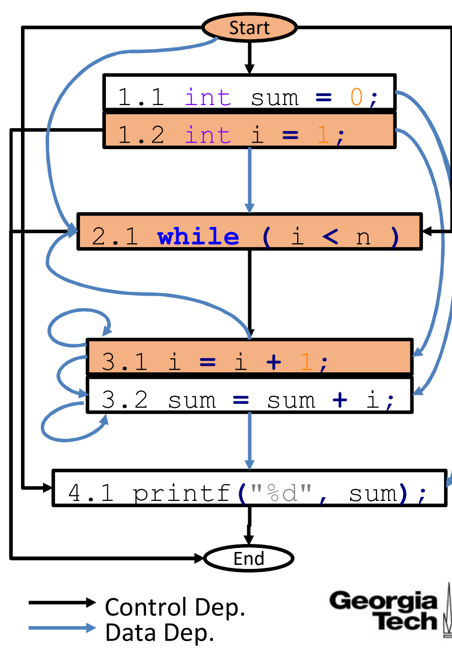
How To Compute A Slice Statically

- Build a 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
  - A finite set Ec of edges (i, j) representing that (super-)node n_j is control dependent on node n_i
- Given a slice criterion, i.e., the starting point, a slice is computed by traversing the set of **backward-reachable** nodes in the program dependence graph
- Slice (I @ 3.1) = {START, 1.2, 2.1, 3.1}



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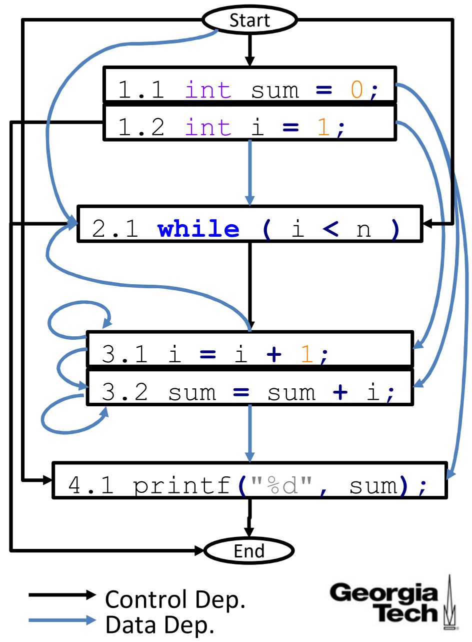
How To Compute A Slice Statically

- Build a 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
  - A finite set Ec of edges (i, j) representing that (super-)node n_j is control dependent on node n_i
- Given a slice criterion, i.e., the starting point, a slice is computed by traversing the set of **backward-reachable** nodes in the program dependence graph
- Slice (sum @ 4.1) = ?



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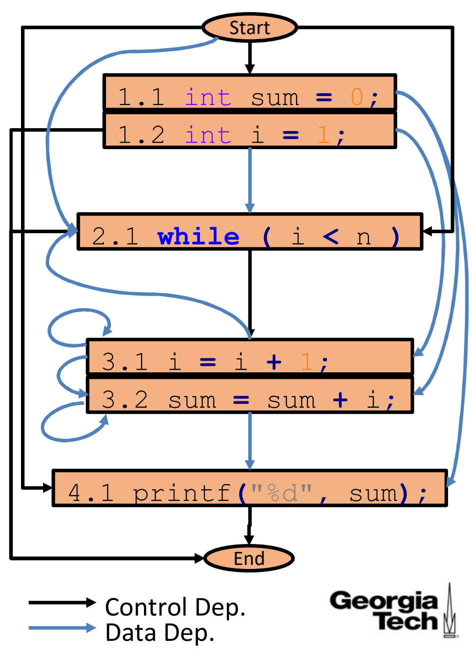
How To Compute A Slice Statically

- Build a 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
  - A finite set Ec of edges (i, j) representing that (super-)node n_j is control dependent on node n_i
- Given a slice criterion, i.e., the starting point, a slice is computed by traversing the set of **backward-reachable** nodes in the program dependence graph
- Slice (sum @ 4.1) = {START, 1.1, 1.2, 2.1, 3.1, 3.2, 4.1}



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But I Thought We Were Done With Static Analysis??

- We are!
- Static slices are extremely imprecise
    1. Don't have dynamic control flow information
    2. Static alias analysis is very difficult (as you know)
- This makes the underlying Program Dependence Graph very imprecise
- So slicing is generally only performed dynamically

```
if (P)
  x=f(…);
else
  x=g(…);
…=x;
```

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

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Dynamic Slicing

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Static VS. Dynamic slicing Example

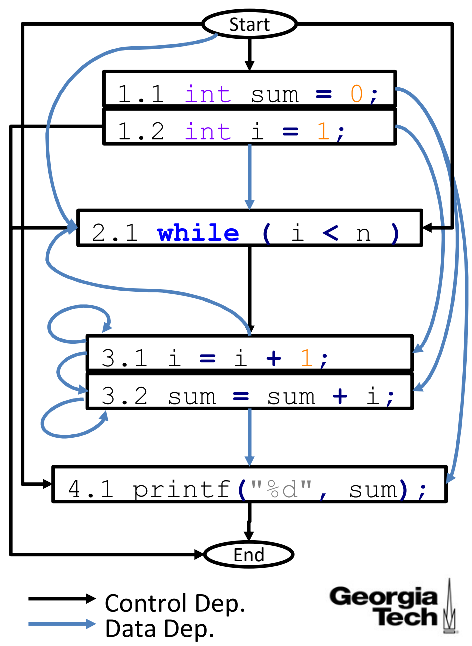
StaticSlice(sum @ 4.1) =
{START, 1.1, 1.2, 2.1, 3.1, 3.2, 4.1}

Execution Trace (n = 0)

```
1.1 int sum = 0;
1.2 int i = 1;
2.1 while ( i < n )
4.1 printf("%d", sum);
```

DynamicSlice(sum @ 4.1) = {1.1, 4.1}

- Much better right?
- Dynamic analysis concretizes many assumptions that restrict static analysis!



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Dynamic Slicing

- Korel and Laski, 1988
- Dynamic slicing makes use of all information about a particular execution of a program
- Dynamic slices are computed by constructing a Dynamic Program Dependence Graph
  - Each node is an **executed statement** (instruction)
  - An edge is **present** between two nodes **if there exists a data or control dependence**
  - A dynamic slice **criterion** is a **triple <Variable, Execution Point, Input>**
- The set of statements reachable in the DPDG from a criterion constitute the slice
- Dynamic slices are smaller, more precise, more helpful to the user (or malware analyst)

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Computing Dynamic Slices

- Data dependence
  - Do we still care about aliasing? No! ☺
  - A backward linear scan over the trace is able to recover **all** data dependences
  - We now only need to compute a dynamic Def/Use chain!
- Control Dependence
  - Recall that we need to find the predicate instance that a statement is control dependent on
  - Can we simply traverse backwards and find the closest predicate?
  - No! ☹
  - Recall our execution trace from before:
    - Is 4.1 control dependent on 2.1? No!
  - We need to define the notion of dynamic control dependence!

Execution Trace (n = 0)

```
1.1 int sum = 0;
1.2 int i = 1;
2.1 while ( i < n )
4.1 printf("%d", sum);
```

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Dynamic Data Dependence

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Dynamic Data Dependence

- Instrument the executable to log the Def/Use of each instruction
- At runtime, all memory locations will be resolved

```
.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                     printf(“00 D: rsp %d, U: rsp rbp”, rsp-4)
.text:01 mov   rbp, rsp                printf(“01 D: rbp, U: rsp”)
.text:04 mov   [rbp+var_X], edi        printf(“04 D: %d, U: rbp edi”, rbp+var_X)
.text:07 mov   [rbp+var_Y], esi        printf(“07 D: %d, U: rbp esi”, rbp+var_Y)
.text:0A cmp   [rbp+var_Y], 0          printf(“0A D: rflags, U: rbp %d”, rbp+var_Y)
.text:0E jns   short loc_1A            printf(“0E D: U: rflags”)
.text:10 mov   eax, [rbp+var_Y]        printf(“10 D: eax, U: rbp %d”, rbp+var_Y)
.text:13 neg   eax                     printf(“13 D: eax, U: eax”)
.text:15 mov   [rbp+var_Power], eax    printf(“15 D: %d U: rbp eax”, rbp+var_Power)
.text:18 jmp   short loc_20            printf(“18 D: U:”)
```

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Dynamic Data Dependence

- A backward linear scan over the trace is able to recover **all** data dependences

Trace Output (assume: RSP=0x460020)

00 D: rsp 0x46001c, U: rsp rbp

01 D: rbp, U: rsp

04 D: 0x460008, U: rbp edi

07 D: 0x460004, U: rbp esi

0A D: rflags, U: rbp 0x460004

0E D: U: rflags

10 D: eax, U: rbp 0x460004

13 D: eax, U: eax

15 D: 0x460018 U: rbp eax

18 D: U:

```
.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
.text:01 mov      rbp, rsp
.text:04 mov      [rbp+var_X], edi
.text:07 mov      [rbp+var_Y], esi
.text:0A cmp      [rbp+var_Y], 0
.text:0E jns      short loc_1A
.text:10 mov      eax, [rbp+var_Y]
.text:13 neg      eax
.text:15 mov      [rbp+var_Power], eax
.text:18 jmp      short loc_20
```

DD(01) = ?

DD(01) = {00}

DD(07) = ?

DD(07) = {START, 01}

DD(10) = ?

DD(10) = {01, 07}

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Dynamic Control Dependence (DCD)

- Computing control dependence from only a dynamic trace is challenging
- Linear scan will not work
  - This is because an execution trace has no notion of the "curly bracket" i.e., **{ }**

Execution Trace (n = 0)

```
1.1 int sum = 0;
1.2 int i = 1;
2.1 while ( i < n )
4.1 printf("%d", sum);
```

VS.

Execution Trace (n = 0)

```
1.1 int sum = 0;
1.2 int i = 1;
2.1 while ( i < n ) {
    }
4.1 printf("%d", sum);
```

- Can we just fall back to our previous static control dependence??
  - Maybe …

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DCD - Offline TRACE Analysis

1. Assume there are no recursive functions
2. Assume we have already built a dictionary **CD(i) = {$\mathbf{cdi_1}$, $\mathbf{cdi_2}$, … $\mathbf{cdi_n}$}** which maps any instruction i to the set of **static control dependencies** for **i**, say **$\mathbf{cdi_1}$**, **$\mathbf{cdi_2}$, … $\mathbf{cdi_n}$**
3. Collect a dynamic control flow trace
4. To find the control dependence of any instruction **j** in that trace: Traverse backward starting from **j** & find the closest **x, s.t. x** is in **CD(j)**
5. **j** is therefore dynamically control dependent on **x** *(Cont'd)*

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DCD - Offline TRACE Analysis (Cont'd)

5. **j** is therefore dynamically control dependent on **x**
   - VERY problematic in the presence of recursion
   - Notice that each instruction in the trace can only be dynamically control dependent on a single instruction!
     - Recall that one instruction could be statically control dependent on two!
     - This is because within a concrete trace you can only arrive at that instruction via a single path!

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Are We Done Yet?

- No
- The previously mentioned algorithms are essentially offline graph construction
  - This implies offline traversals of (extremely) long data reference and control flow traces
- Can we do better?
- Yes
- Efficient online algorithms:
  - Online data dependence detection
  - Online control dependence detection
- The output of our dynamic dependence detection tool will only be the dependencies of each instruction and not a full trace

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Dynamic Data Dependence Detection

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Efficient Dynamic Data Dependence Detection

- Full Shadow Registers & Memory
- **Basic idea:** Store metadata in a structure which models every real data location
- This enables **online def/use tracking**!
- For each data location that an instruction can define, keep a "**shadow**" **copy** to mark the **last instruction** which defined it
- Implemented **via a dictionary** (or similar data structure) which maps data locations (i.e., registers or memory) to the last instruction which defined them

```
.text:00 push    rbp printf("00 D: rsp %d, U: rsp rbp", rsp-4)
```

```
.text:00 push    rbp   printf("00 DD: %s, %s", shadow_regs[rsp], shadow_regs[rbp]);
                       shadow_regs[rsp]=".text:00"; shadow_mem[&[rsp]]=".text:00";
```

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Efficient Dynamic Data Dependence Detection

- Update shadows before or after instruction executes?
  - E.g., **`shadow_mem[&[rsp]]="…"`** vs. **`shadow_mem[&[rsp]-4]="…"`**
- Also, granularity considerations:
  - Shadow each flag? Shadow memory in 1,4,8 bytes?

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Efficient Dynamic Data Dependence Detection

```
.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    printf("00 DD: %s, %s", shadow_regs[rsp], shadow_regs[rbp]);
                        shadow_regs[rsp]=".text:00"; shadow_mem[&[rsp]]=".text:00";
.text:01 mov     rbp, rsp    printf("01 DD: %s", shadow_regs[rsp]);
                             shadow_regs[rbp]=".text:01";
.text:04 mov     [rbp+var_X], edi
                printf("04 DD: %s, %s", shadow_regs[rbp], shadow_regs[edi]);
                shadow_mem[&[rbp+var_X]]=".text:04";
.text:07 mov     [rbp+var_Y], esi
                printf("07 DD: %s, %s", shadow_regs[rbp], shadow_regs[esi]);
                shadow_mem[&[rbp+var_Y]]=".text:07";
.text:0A cmp     [rbp+var_Y], 0
                printf("0A DD: %s, %s", shadow_regs[rbp], shadow_mem[&[rbp+var_Y]]);
                shadow_regs[rflags]=".text:0A";
.text:0E jns     short loc_1A      printf("0E DD: %s", shadow_regs[rflags]);
.text:10 mov     eax, [rbp+var_Y]
                printf("10 DD: %s, %s", shadow_regs[rbp], shadow_mem[&[rbp+var_Y]]);
                shadow_regs[eax]=".text:10";
.text:13 neg     eax         printf("13 DD: %s", shadow_regs[eax]);
                             shadow_regs[eax]=".text:13";
.text:15 mov     [rbp+var_Power], eax
                printf("15 DD: %s, %s", shadow_regs[rbp], shadow_regs[eax]);
                shadow_mem[&[rbp+var_Power]]=".text:15";
.text:18 jmp     short loc_20
```

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Efficient Dynamic Data Dependence Detection

- Beware of space constraints!
  - You cannot pre-allocate **4 bytes** of metadata for every byte of **RAM**!
- Implementation tradeoffs are everywhere!
  - Time vs space, packed vs unpacked data, …
- Read:
  - Nethercote, N. & Seward, J. (2007). How to shadow every byte of memory used by a program. *Proceedings of the 3rd International Conference on Virtual Execution Environments*. (yes, the valgrind author).
- Shadow data is also used to implement taint tracking
  - **Example**: Mark the initial input as "tainted" (1 bit shadow metadata) & taint everywhere the data flows during execution
  - **Application**: Can this program leak sensitive data?

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Efficient Dynamic Control Dependence Detection

- We can perform a similar online tracking of dynamic control dependence
- Recall our definition of control dependence:
- Y is control-dependent on X iff
  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
- We can watch for these conditions at runtime & determine control dependence from
  the final execution trace
  - **Benefits**: 1) **May** not require ahead-of-time static control dependence analysis
    2) Does not require logging the huge dynamic control flow trace
  - **Problems**: Not as straightforward as the offline approach

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Regions

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Dynamic "Regions"

- In order to monitor the execution for our control dependence conditions, we need to introduce the concept of an execution "**region**"
- **Region**: The set of executed statements between a predicate instance and its immediate post-dominator
- We can then say that each statement instance $\mathbf{x}_i$ is dynamically control dependent on the predicate instance leading $\mathbf{x}_i$'s nearest enclosing region
- Thanks to our definition of immediate post-dominated, regions are either nested or disjoint, but can never overlap!
- Read:
  - Xin, B. & Zhang, X. (2007). Efficient online detection of dynamic control dependence. *Proceedings of the 2007 International Symposium on Software Testing and Analysis*.

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Region Examples

- **Region**: The set of executed statements between a **predicate instance** and its immediate **post-dominator**
- We can then say that each statement instance $\mathbf{x_i}$ is dynamically **control dependent** on the predicate instance leading $\mathbf{x_i}$**'s nearest enclosing region**
- Regions are either **nested** or **disjoint**, but can **never overlap**!

Execution Trace

```
1_1. for(i=0; i<N, i++)
2_1. if(i%2 == 0)
3_1. p = &a[i];
4_1. foo(p);
…
1_2. for(i=0; i<N, i++)
2_2. if(i%2 == 0)
4_2. foo(p);
…
1_3. for(i=0; i<N, i++)
6_1. a = a+1;
```

Program

```
1. for(i=0; i<N, i++) {
2.     if(i%2 == 0)
3.         p = &a[i];
4.     foo(p);
5. }
6. a = a+1;
```

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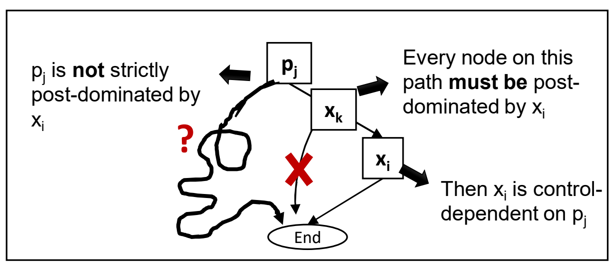
Regions: Property One

Each statement instance x_i is dynamically control dependent on the predicate instance leading x_i's nearest enclosing region



- **Proof**: Let the predicate instance be p_j and assume x_i is not control dependent on p_j
- Therefore, either:

1. No path exists from p_j to exit which that does not pass through x_i. This would indicate that x_i is a post-dominator of p_j, contradicting the condition that x_i is in the region delimited by p_j and its immediate post-dominator; OR
2. There is a node x_k in between p_j and x_i such that x_k has a path to exit that does not pass x_i. Since p_j's immediate post-dominator is also a post-dominator of x_k, x_k and p_j's post-dominator form a smaller region that includes x_i, contradicting that pj leads the enclosing region of xi

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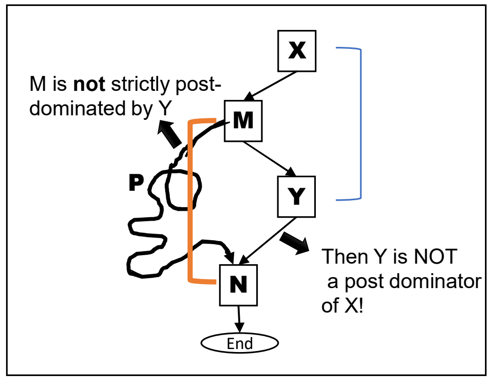
Regions: Property Two

- Regions are either nested or disjoint, but can never overlap!
- Proof: Assume there are two regions (x, y) and (m, n) that overlap
- Let m reside in (x, y). Thus, y resides in (m, n)
- This implies there is a path P from m to exit without passing y
- Therefore, the path from x to m and P constitute a path from x to exit without passing y, contradicting the condition that y is a post-dominator of x



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Detecting Regions At Runtime

- **Observation**: During execution, Regions follow the LIFO pattern
  - Otherwise, some regions must overlap
- **Implication**: The current sequence of nested regions for the current execution point can be maintained by a stack, called a control dependence stack (CDS)
- Each region is nested within the region immediately preceding it in the stack
- The enclosing region for the current execution point is always the top entry in the stack
  - Therefore any execution point is control dependent on the predicate that leads the top entry
- An entry is pushed onto CDS if a branching instruction (predicated jump) is executed
- The current entry is popped if the immediate post-dominator of the branching point is executed, denoting the end of the current region

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Algorithms

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“Idealistic” Algorithm

```
Branch (xi)
{
     CDS.push(<xi, IPD(xi)>);
}

Merge (tj)
{
      while (CDS.top( ).second == tj)
          CDS.pop( );
}

GetCurrentCD ( )
{
     return CDS.top( ).first;
}
```

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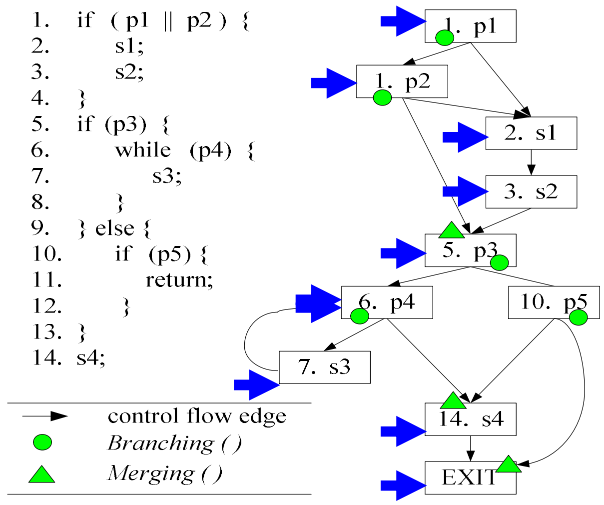
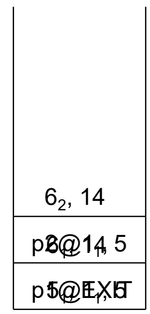
"Idealistic" Algorithm Example





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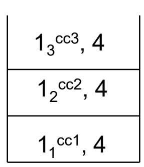
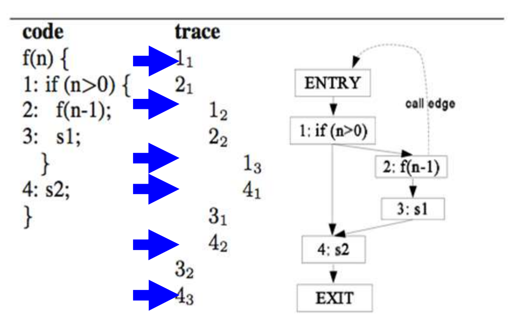
Even Handles Recursion!

- Annotate CDS entries with calling context
- Consider this recursive code and execution trace





Source: B. Xin, X. Zhang. Efficient Online Detection of Dynamic Control Dependence, International Symposium on Software Testing and Analysis, 2007.

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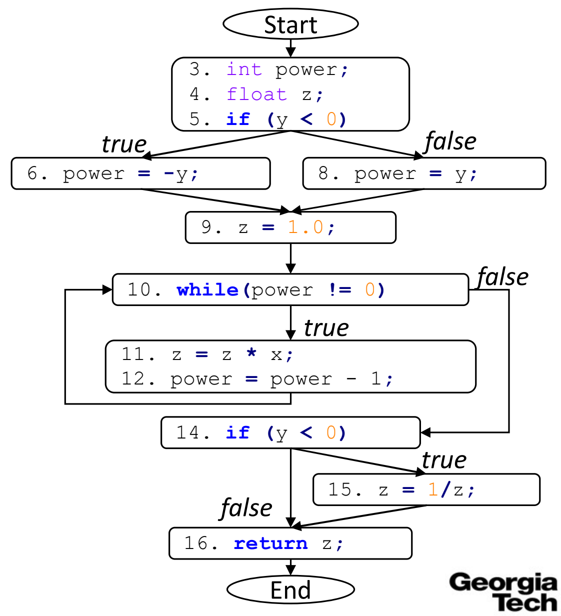
Challenges in Practice

1. You may not know the immediate post-dominator ahead of time!
   - This requires first collecting the control flow trace, then computing the IPDs, then updating the control dependence



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Challenges in Practice

2. If you only have execution traces, then it is not clear what is a branch until you execute both paths!
   - In general, implementations use a hybrid of offline and online analyses to compute control dependence

Execution Trace (x=0, y=0)

```
3.  int power;
4.  float z;
5.  if (y < 0)
8.  power = y;
9.  z = 1.0;
10. while(power != 0)
14. if (y < 0)
16. return z;
```

Execution Trace (x=1, y=1)

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

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Advanced Topics in Malware Analysis

Program Slicing

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Dynamic Slice Concepts

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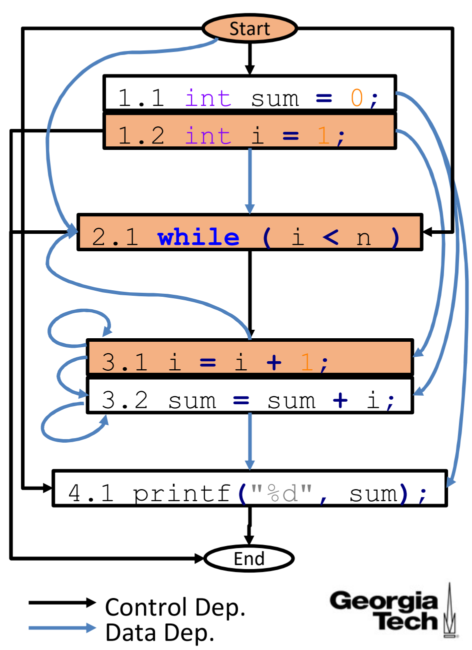
Wrap up of Dynamic Slice Concepts

- We have introduced the concept of slicing, slice criterions, and dynamic slicing
- We have seen **two** approaches to computing a dynamic slice:
  1. **Offline dynamic slicing algorithms** based on backwards traversal over traces is not efficient
  2. **Online algorithms** that detect dependences are efficient but control dependence can be complex/limited
- In fact, this form of slicing is called **Backward Slicing**
- Slice (I @ 3.1) = {START, 1.2, 2.1, 3.1}



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Forward Dynamic Slice Computation

- The approaches we have discussed so far are for backward slicing
  - Dependence graphs are traversed **backwards** from a slicing criterion
  - The space complexity is O(execution length)

- There is an orthogonal concept of Forward Slice Computation
- A forward slice of a program with respect to a program point p and variable v consists of all statements and predicates in the program that may be affected by the value of v at p
- Given a slice criterion, i.e., the starting point, a forward slice is computed by traversing the set of **forward-reachable** nodes in the program dependence graph

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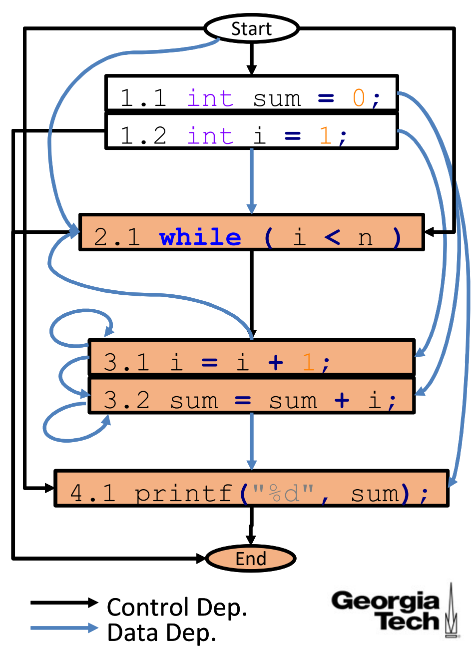
Forward Slice Computation

- **Step 1:** Build a PDG (as discussed previously)

- **Step 2:** Traverse the **forward-reachable** nodes in the PDG from the slice criterion

ForwardStaticSlice (I @ 3.1) =
{2.1, 3.1, 3.2, 4.1, END}



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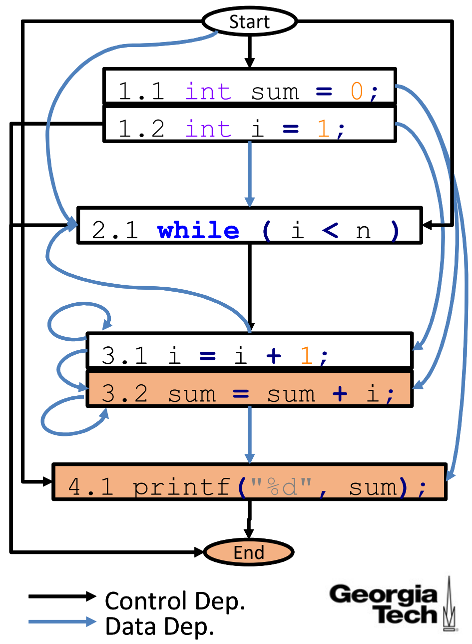
Forward Slice Computation

- **Step 1:** Build a PDG (as discussed previously)
- **Step 2:** Traverse the **forward-reachable** nodes in the PDG from the slice criterion

ForwardStaticSlice (I @ 3.1) =
{2.1, 3.1, 3.2, 4.1, END}

ForwardStaticSlice (sum @ 3.2) =
{3.2, 4.1, END}



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The Importance of Forward Slicing

- Slicing is by far the **most commonly** employed dynamic analysis
- Answer the question: "*What program components might be affected by a particular computation?*"
- Useful in determining **which statements** in a program can be **affected** by changes in the value of **v** at statement **s**

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The Importance of Forward Slicing: Example 1

- As software is maintained, modifications to parts of the program can lead to unforeseen side effects. When part of a program is changed, the effect of the change “ripples” through the program. Forward slicing exposes these effects.

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The Importance of Forward Slicing: Example 2

- When analyzing malware, we want to focus on only the most important payloads (and not waste time on others). When the malware receives an input or checks a condition, that value will only affect some payloads. Forward slicing can give you foresight into what values will be important later in the execution.

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Finally: Chopping

- Given a source criterion S and a target criterion T, determine what statements transmit the effects of S to T
- Simply the intersection of forward and backward slices

- **Step 1:** Compute a backward slice from the target criterion T
  - Recall: This is the set of all prior statements involved in computing the value of T.v at T.s
- **Step 2:** Compute a forward slice from the source criterion S
  - Recall: This is the set of all future statements affected by the value of S.v at S.s
- **Step 3:** Compute the intersection of the two graphs

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Lesson Summary

- Locate the set of statements that compose a program slice
- Construct a program dependent graph
- Assemble dynamic slices using a program dependency graph

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