Control-Dependence and Control-Flow Reachability

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Control- and Data-Dependence

What are control- and data-dependence?

- **Control-dependence**
  - Execution order between two program statements/instructions.
  - Can program point B be reached from point A in the control-flow graph of a program?
  - Obtained through traversing the ICFG of a program
- **Data-dependence**
  - Definition-use relation between two program variables.
  - Will the definition of a variable X be used and passed to another variable Y?
  - Obtained through analyzing the SVFIR of a program
  - Combining SVFIR with ICFG to conduct symbolic execution (mimic the runtime path-based execution) of a program.

Control- and Data-Dependence

Why learn control- and data-dependence?

A program dependence relation by its nature is the reachability property on a graph, particularly useful in program understanding, optimizations and bug detection.

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- **Applications of control-dependence**
  - Dead code elimination: If a subgraph of an ICFG is not connected from the entry block of a program, that subgraph is possibly dead code.

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  - Identifying infinite loops: If the exit block is unreachable from the entry block, an infinite loop may exist.
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- **Applications of data-dependence**
  - Pointer alias analysis: statically determine possible runtime values of a pointer to detect memory errors, such as null pointer dereferences and use-after-frees.

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  - Identifying infinite loops: If the exit block is unreachable from the entry block, an infinite loop may exist.
  - ...
- **Applications of data-dependence**
  - Pointer alias analysis: statically determine possible runtime values of a pointer to detect memory errors, such as null pointer dereferences and use-after-frees.
  - Taint analysis: if two program variables v1 and v2 are aliases (e.g., representing the same memory location), if v1 is tainted by user inputs, then v2 is also tainted.
  - ...

Control-Dependence

We say that a program statement (ICFG node) `snk` is control-flow dependent on `src` if `src` can reach `snk` on the ICFG.

- Context-insensitive control-dependence
  - control-flow traversal without matching calls and returns.
  - fast but imprecise

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- Context-insensitive control-dependence
  - control-flow traversal without matching calls and returns.
  - fast but imprecise
- Context-sensitive control-dependence
  - control-flow traversal by matching calls and returns.
  - precise but maintains an extra abstract call stack (storing a sequence of callsite ID information) to mimic the runtime call stack.

Control-Dependence

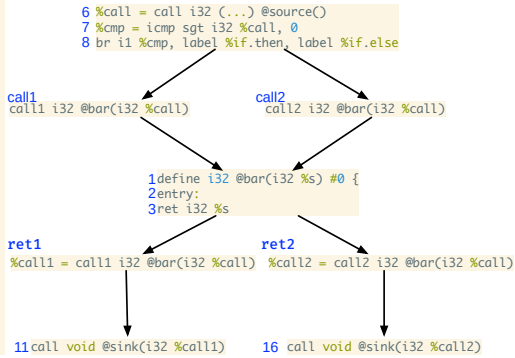
```
int bar(int s){
    return s;
}
int main(){
    int a = source();
    if (a > 0){
        int p = bar(a);
        sink(p);
    }else{
        int q = bar(a);
        sink(q);
    }
}
```

Control-Dependence

```
define i32 @bar(i32 %s) #0 {
entry:
ret i32 %s
}

define i32 @main() #0 {
entry:
%call = call i32 (...) @source()
%cmp = icmp sgt i32 %call, 0
br i1 %cmp, label %if.then, label %if.else

if.then:          ; preds = %entry
%call1 = call i32 @bar(i32 %call)
call void @sink(i32 %call1)
br label %if.end

if.else:          ; preds = %entry
%call2 = call i32 @bar(i32 %call)
call void @sink(i32 %call2)
br label %if.end

if.end:       ; preds = %if.else, %if.then
ret i32 0
}
```

Control-Dependence

```
1  define i32 @bar(i32 %s) #0 {
2  entry:
3  ret i32 %s
3  }

   define i32 @main() #0 {
4  entry:
5  %call = call i32 (...) @source()
6  %cmp = icmp sgt i32 %call, 0
7  br i1 %cmp, label %if.then, label %if.else
8
   if.then:          ; preds = %entry
9  %call1 = call i32 @bar(i32 %call)
10 call void @sink(i32 %call1)
11 br label %if.end
12
   if.else:          ; preds = %entry
13 %call2 = call i32 @bar(i32 %call)
14 call void @sink(i32 %call2)
15 br label %if.end
16
   if.end:       ; preds = %if.else, %if.then
17 ret i32 0
18 }
```



ICFG

Control-Dependence

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2  entry:
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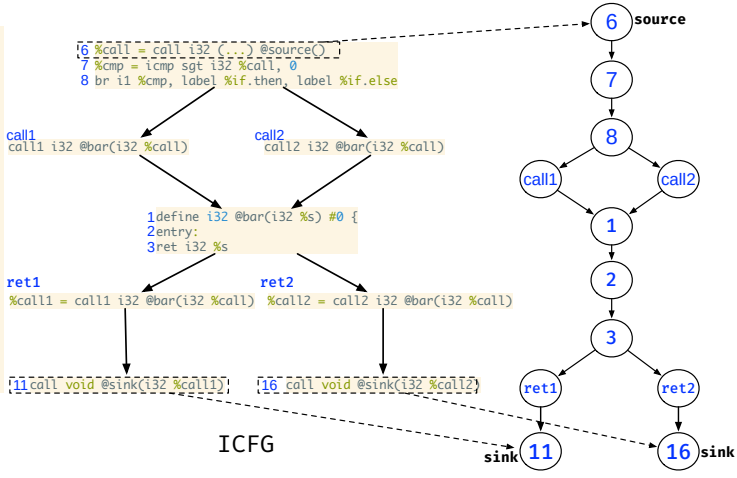
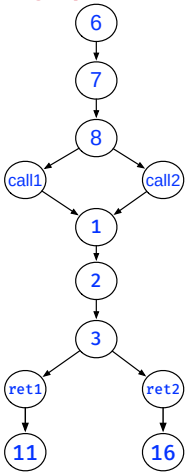


Context-Insensitive Control-Dependence

Obtaining a path from source to sink on ICFG



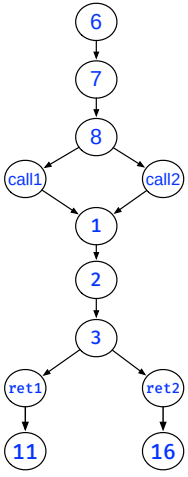
Basic DFS on ICFG: source → sink

```
visited: set<NodeID>
path: vector<NodeID>

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
           DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 11 on the ICFG



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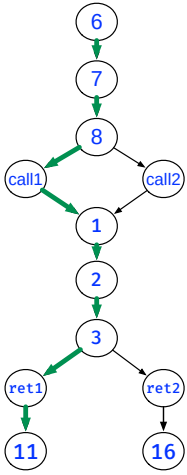
           DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

ICFG paths: node 6 → node 11

Path 1:
6→7→8→**call1**→1→2→3→**ret1**→11
Path 2:
6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Dependence

Feasible paths from node 6 to node 11



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   visited.erase(src);
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```

ICFG paths: node 6 → node 11

Path 1: **feasible path**

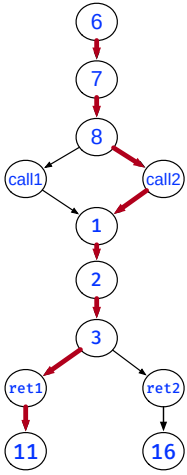
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:

6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Dependence

Infeasible path from node 6 to node 11



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```

ICFG paths: node 6 → node 11

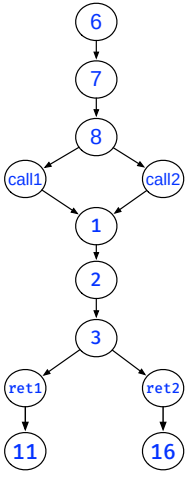
Path 1:
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:
6→7→8→**call2**→1→2→3→**ret1**→11

spurious path

Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 16 on ICFG



Basic DFS on ICFG: source → sink

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visited: set<NodeID>
path: vector<NodeID>

DFS(visited, path, src, dst)
   visited.insert(src);
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   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
           DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```
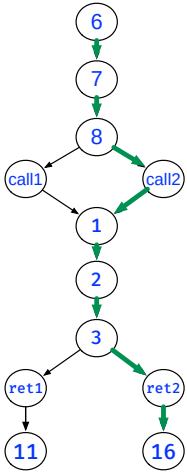

ICFG paths: node 6 → node 16

Path 3:
6→7→8→**call2**→1→2→3→**ret2**→16
Path 4:
6→7→8→**call1**→1→2→3→**ret2**→16

Context-Insensitive Control-Dependence

Feasible paths using from node 6 to node 16 on the ICFG



Basic DFS on ICFG: source → sink

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```

ICFG paths: node 6 → node 16

Path 3: **feasible path**

6→7→8→**call2**→1→2→3→**ret2**→16

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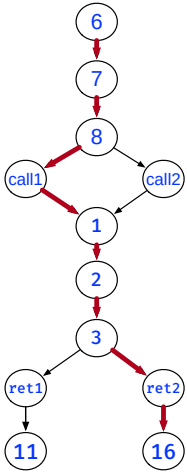
Context-Insensitive Control-Dependence

Infeasible paths using from node 6 to node 16 on the ICFG



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6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:
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spurious path

Context-Sensitive Control-Dependence

An extension of the context-insensitive algorithm by matching calls and returns.

- Get only feasible interprocedural paths and exclude infeasible ones
- Requires an extra callstack to store and mimic the runtime calling relations.

Context-Sensitive Control-Dependence (Algorithm)

Algorithm 1 Context sensitive control-flow reachability

```
Input : src : ICFGNode   dst : ICFGNode
        path : vector⟨ICFGNode⟩   visited : set⟨ICFGNode⟩;
1  dfs(path, src, dst)
2    visited.insert(src)
3    path.push_back(src)
4    if src == dst then
5      print path
6    foreach edge ∈ src.getOutEdges() do
7      if edge.dst ∉ visited then
8        if edge.isIntraCFGEdge() then
9          if handleIntra(edge) then
10           dfs(path, edge.dst, dst)
11       else if edge.isCallCFGEdge() then
12         if handleCall(edge) then
13           dfs(path, edge.dst, dst)
14       else if edge.isRetCFGEdge() then
15         if handleRet(edge) then
16           dfs(path, edge.dst, dst)
17   visited.erase(src)
18   path.pop_back(src)
```

Algorithm 2 Handle intra ICFGEdge

```
1  handleIntra(intraEdge)
2    return true
```

Algorithm 3 Handle call ICFGEdge

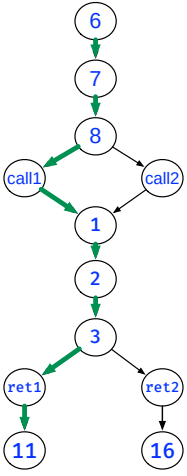
```
1  handleCall(callEdge)
2    callNode ← getSrcNode(callEdge)
3    callstack.push_back(callNode)
4    return true
```

Algorithm 4 Handle return ICFGEdge

```
1  handleRet(retEdge)
2    retNode ← getDstNode(retEdge)
3    if callstack ≠ ∅ then
4      if callstack.back() == getCallICFGNode(retNode) then
5        callstack.pop()
6        return true
7      else
8        return false
9    return true
```

Context-Sensitive Control-Dependence (Example)

call1 matches with ret1



Algorithm 1 Context sensitive control-flow reachability

Input : src : ICFGNode dst : ICFGNode
path : vector⟨ICFGNode⟩ visited : set⟨ICFGNode⟩;

```
1  dfs(path, src, dst)
2    visited.insert(src)
3    path.push_back(src)
4    if src == dst then
5      print path
6    foreach edge ∈ src.getOutEdges() do
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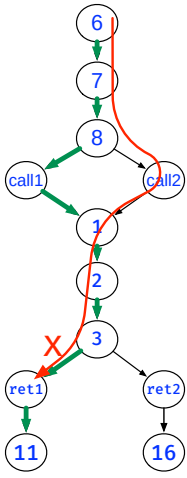
18   path.pop_back(src)
```

Context-Sensitive Control-Dependence (Example)

call2 does not match with ret1



Algorithm 1 Context sensitive control-flow reachability

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path : vector⟨ICFGNode⟩ visited : set⟨ICFGNode⟩;

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17   visited.erase(src)
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```

What's next?

- (1) Understand control-flow reachability in this slides
- (2) Finish the quizzes of Assignment 2 on Canvas
- (3) Implement a context-sensitive ICFG traversal, i.e., coding task in Assignment 2
  - Refer to 'Assignment-2.pdf' on Canvas to know more.