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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  - 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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  - 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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  - 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.
  - 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

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
- 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

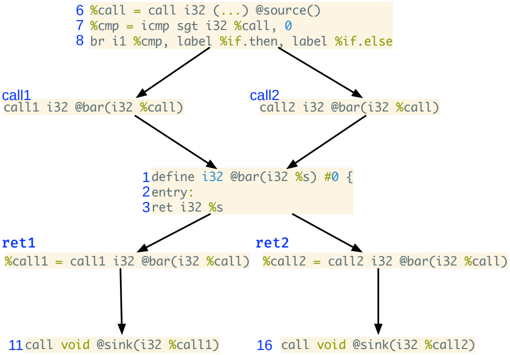
```c
int bar(int s){
    return s;
}
int main(){
    int a = source();
    if (a > 0){
        int p = bar(a);
        sink(p);
    }else{
        int q = bar(a);
        sink(q);
    }
}
```

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

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

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

   define i32 @main() #0 {
4  entry:
5  %call = call i32 (...) @source()
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15 br label %if.end
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```
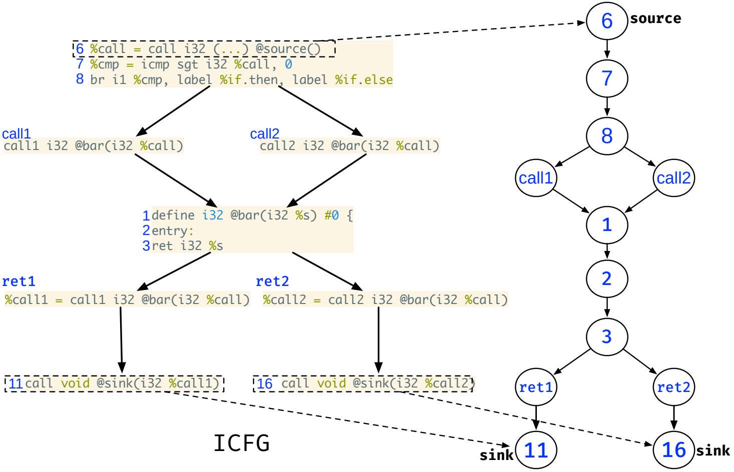
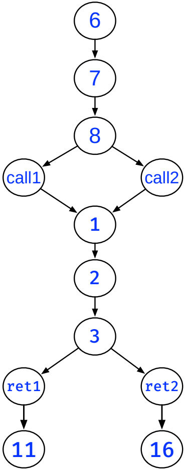



Context-Insensitive Control-Dependence

Obtaining a path from source to sink on ICFG

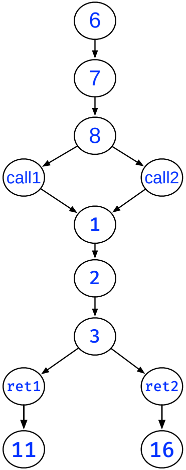


Basic DFS on ICFG: source → sink

```
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();
```

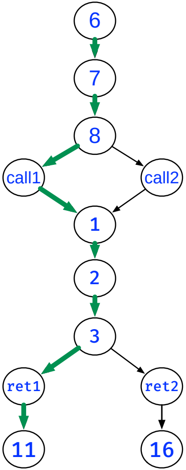
ICFG paths: node 6 → node 11

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



Basic DFS on ICFG: source → sink

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

ICFG paths: node 6 → node 11

Path 1: **feasible path**

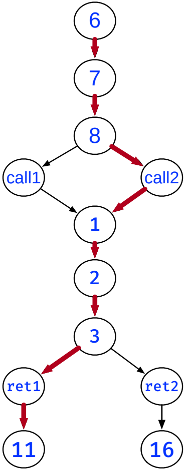
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:

6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Dependence

Infeasible path from node 6 to node 11



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
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   if src == dst then
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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

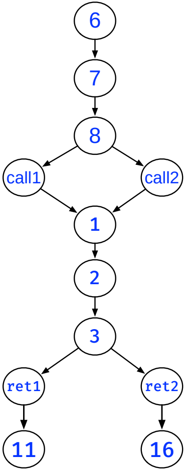
Path 2:

6→7→8→**call2**→1→2→3→**ret1**→11

spurious path

Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 16 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();
```

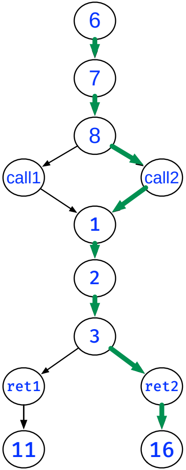
ICFG paths: node 6 → node 16

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

```
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();
```

ICFG paths: node 6 → node 16

Path 3: **feasible path**

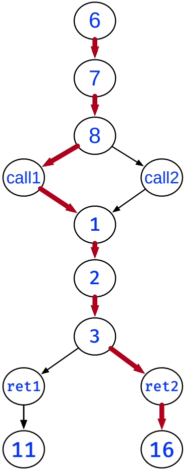
6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:

6→7→8→**call1**→1→2→3→**ret2**→16

Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source → sink

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DFS(visited, path, src, dst)
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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

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.

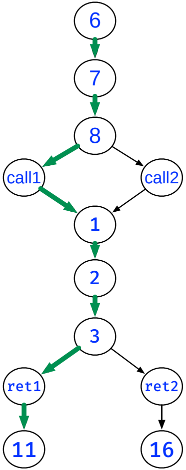
Context-Sensitive Control-Dependence (Algorithm)

Algorithm 1 Context sensitive control-flow reachability

```
Input : curEdge : ICFGEdge   dst : ICFGNode path : vector⟨ICFGEdge⟩   visited : set⟨ICFGEdge, callstack⟩;
dfs(path, curEdge, dst)
  curItem ← ⟨curEdge, callstack⟩
  visited.insert(curItem)
  path.push_back(curEdge)
  if src == dst then
    printICFGPath(path)
  foreach edge ∈ curEdge.dst.getOutEdges() do
    if edge.dst ∉ visited then
      if edge.isIntraCFGEdge() then
        dfs(path, edge, dst)
      else if edge.isCallCFGEdge() then
        callNode ← getSrcNode(edge)
        callstack.push_back(callNode)
        dfs(path, edge, dst)
      else if edge.isRetCFGEdge() then
        if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
          callstack.pop()
          dfs(path, edge, dst)
        else if callstack == ∅ then
          dfs(path, edge, dst)
  visited.erase(curItem)
  path.pop_back()
```

Context-Sensitive Control-Dependence (Example)

call1 matches with ret1



Algorithm 1 Context sensitive control-flow reachability

```
Input : curEdge : ICFGEdge   dst : ICFGNode path : vector⟨ICFGEdge⟩   visited : set⟨ICFGEdge, callstack⟩;
dfs(curEdge, dst)
  curItem ← ⟨curEdge, callstack⟩
  visited.insert(curItem)
  path.push_back(curEdge)
  if src == dst then
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  foreach edge ∈ curEdge.dst.getOutEdges() do
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      if edge.isIntraCFGEdge() then
        dfs(path, edge, dst)
      else if edge.isCallCFGEdge() then
        callNode ← getSrcNode(edge)
        callstack.push_back(callNode)
        dfs(path, edge, dst)
      else if edge.isRetCFGEdge() then
        if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
          callstack.pop()
          dfs(path, edge, dst)
        else if callstack == ∅ then
          dfs(path, edge, dst)
  visited.erase(curItem)
  path.pop_back()
```
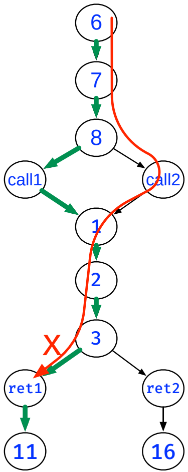

Context-Sensitive Control-Dependence (Example)

call2 does not match with ret1



Algorithm 1 Context sensitive control-flow reachability

Input : curEdge : ICFGEdge dst : ICFGNode path : vector⟨ICFGEdge⟩ visited : set⟨ICFGEdge, callstack⟩;

```
dfs(curEdge, dst)
  curItem ← ⟨curEdge, callstack⟩
  visited.insert(curItem)
  path.push_back(curEdge)
  if src == dst then
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  foreach edge ∈ curEdge.dst.getOutEdges() do
    if edge.dst ∉ visited then
      if edge.isIntraCFGEdge() then
        dfs(path, edge, dst)
      else if edge.isCallCFGEdge() then
        callNode ← getSrcNode(edge)
        callstack.push_back(callNode)
        dfs(path, edge, dst)
      else if edge.isRetCFGEdge() then
        if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
          callstack.pop()
          dfs(path, edge, dst)
        else if callstack == ∅ then
          dfs(path, edge, dst)
  visited.erase(curItem)
  path.pop_back()
```

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.