

# Control- and Data-Dependence

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# Control- and Data-Dependence

## What are control- and data-dependence?

- **Control-dependence**

- Execution order between two program statements/instructions.
- Whether program point A reaches point B along the control-flow graph of a program?
- Obtained through traversing on the ICFG of a program

- **Data-dependence**

- Definition-use relation between two program variables.
- Whether the definition of a variable X will be used and pass its value to another variable Y?
- Obtained through analyzing the PAG of a program
- Combining PAG with ICFG to yield more precise flow-sensitive and context-sensitive data-dependence.

# 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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- **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.
- 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 the possible runtime values of a pointer to detect memory errors, such as null pointers and use-after-frees.

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

- **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.
- 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 the possible runtime values of a pointer to detect memory errors, such as null pointers and use-after-frees.
- Taint analysis: if two program variables  $v_1$  and  $v_2$  are aliases (e.g., representing the same memory location), if  $v_1$  is tainted by user inputs, then  $v_2$  is also tainted.
- ...

# Control-Dependence

We say that a program statement (ICFG node)  $s_{nk}$  is control-flow dependent on  $s_{rc}$  if  $s_{rc}$  can reach  $s_{nk}$  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 maintaining 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 {  
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  
9 if.then:                ; preds = %entry  
9 %call1 = call i32 @bar(i32 %call)  
10 call void @sink(i32 %call1)  
11 br label %if.end  
12  
13 if.else:                ; preds = %entry  
13 %call2 = call i32 @bar(i32 %call)  
14 call void @sink(i32 %call2)  
15 br label %if.end  
16  
17 if.end:                ; preds = %if.else, %if.then  
17 ret i32 0  
18 }
```

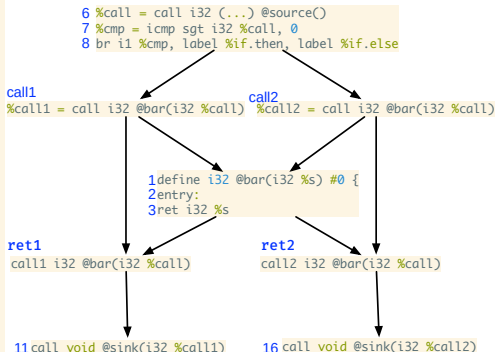
## Control-Dependence

```

1  define i32 @bar(i32 %s) #0 {
2  entry:
3  ret i32 %s
4  }
5
6  define i32 @main() #0 {
7  entry:
8  %call = call i32 (...) @source()
9  %cmp = icmp sgt i32 %call, 0
10 br i1 %cmp, label %if.then, label %if.else
11
12 if.then:
13 ; preds = %entry
14 %call1 = call i32 @bar(i32 %call)
15 call void @sink(i32 %call1)
16 br label %if.end
17
18 if.else:
19 ; preds = %entry
20 %call2 = call i32 @bar(i32 %call)
21 call void @sink(i32 %call2)
22 br label %if.end
23
24 if.end:
25 ; preds = %if.else, %if.then
26 ret i32 0
27 }

```

LLVM-IR

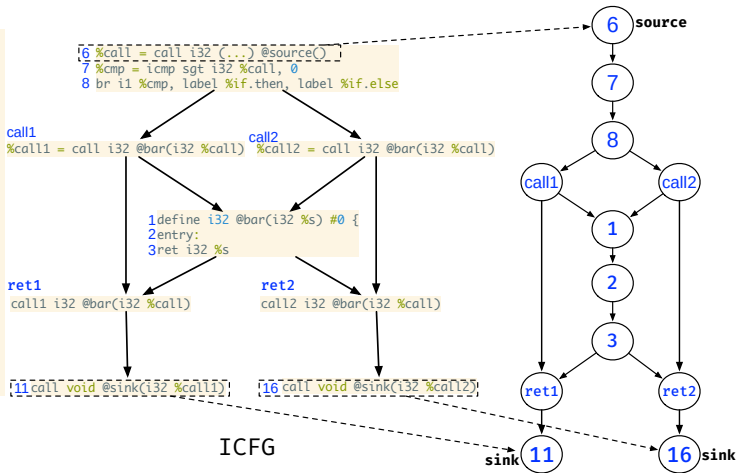


ICFG

# 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()  
6 %cmp = icmp sgt i32 %call, 0  
7 br i1 %cmp, label %if.then, label %if.else  
8  
9 if.then:                ; preds = %entry  
10 %call1 = call i32 @bar(i32 %call)  
11 call void @sink(i32 %call1)  
12  
13 if.else:                ; preds = %entry  
14 %call2 = call i32 @bar(i32 %call)  
15 call void @sink(i32 %call2)  
16 br label %if.end  
17  
18 if.end:                 ; preds = %if.else, %if.then  
19 ret i32 0  
20}
```

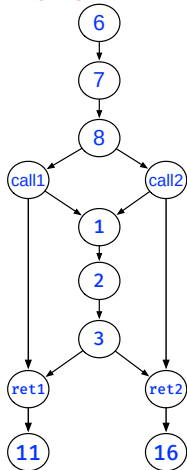
LLVM-IR



ICFG

# Context-Insensitive Control-Dependence

Obtaining a path from source to sink on ICFG



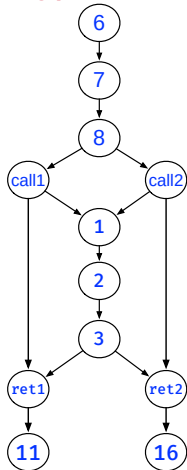
Basic DFS on ICFG: source  $\rightarrow$  sink

```
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  $\in$  outEdges(src) do  
        if (e.dst  $\notin$  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



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 11

Path 1:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  ret1  $\rightarrow$  11

Path 2:

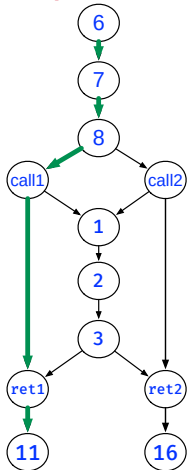
6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11

Path 3:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11

# Context-Insensitive Control-Dependence

Feasible paths from node 6 to node 11



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 11

Path 1: **feasible path**

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  ret1  $\rightarrow$  11

Path 2:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11

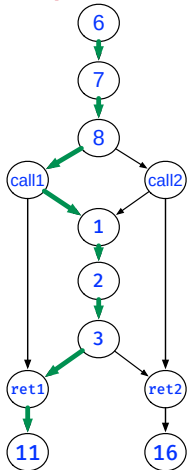
Path 3:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11



# Context-Insensitive Control-Dependence

Feasible paths from node 6 to node 11



Basic DFS on ICFG: source  $\rightarrow$  sink

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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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 11

Path 1:

6 $\rightarrow$ 7 $\rightarrow$ 8 $\rightarrow$ call1 $\rightarrow$ ret1 $\rightarrow$ 11

Path 2: **feasible path**

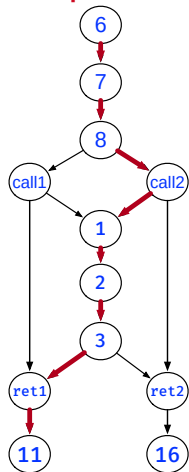
6 $\rightarrow$ 7 $\rightarrow$ 8 $\rightarrow$ call1 $\rightarrow$ 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ ret1 $\rightarrow$ 11

Path 3:

6 $\rightarrow$ 7 $\rightarrow$ 8 $\rightarrow$ call2 $\rightarrow$ 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ ret1 $\rightarrow$ 11

# Context-Insensitive Control-Dependence

Infeasible path from node 6 to node 11



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 11

Path 1:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  ret1  $\rightarrow$  11

Path 2:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11

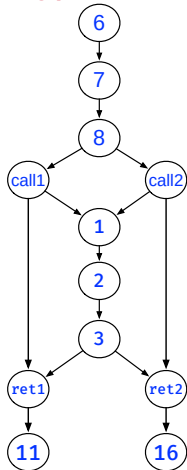
Path 3:

**spurious path**

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret1  $\rightarrow$  11

# Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 16 on ICFG



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 16

Path 4:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  ret2  $\rightarrow$  16

Path 5:

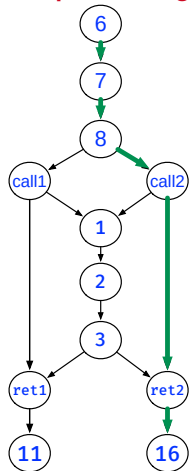
6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

Path 6:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

# Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 16

Path 4: **feasible path**

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  ret2  $\rightarrow$  16

Path 5:

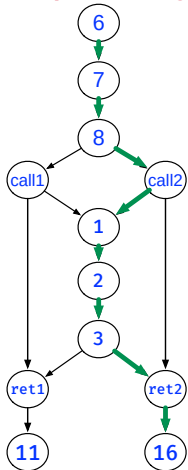
6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

Path 6:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

# Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 16

Path 4:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  ret2  $\rightarrow$  16

Path 5: **feasible path**

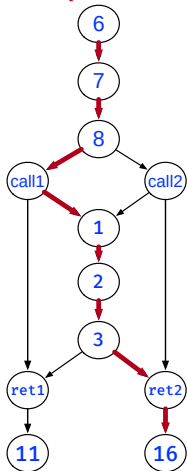
6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

Path 6:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

# Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source  $\rightarrow$  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  $\in$  outEdges(src) do
    if (e.dst  $\notin$  visited)
      DFS(visited, path, e.dst, dst);
  visited.erase(src);
  path.pop_back();
```

ICFG paths: node 6  $\rightarrow$  node 16

Path 4:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  ret2  $\rightarrow$  16

Path 5:

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call2  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

Path 6:

**spurious path**

6  $\rightarrow$  7  $\rightarrow$  8  $\rightarrow$  call1  $\rightarrow$  1  $\rightarrow$  2  $\rightarrow$  3  $\rightarrow$  ret2  $\rightarrow$  16

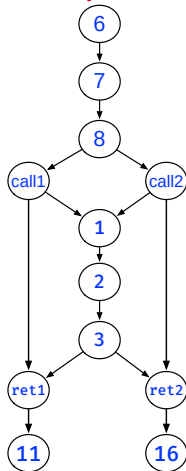
# Context-Sensitive Control-Dependence

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

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

# Context-Sensitive Control-Dependence

Obtaining feasible paths from a source node to sink node on ICFG

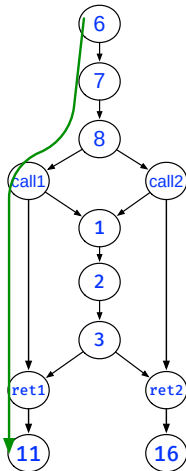


```
visited: set<NodeID>
path: vector<NodeID>
callstack: stack<callsite> //A stack of LLVM call instructions
DFS(visited, path, callstack, src, dst)
1  visited.insert(src)
2  path.push_back(src)
3  if src == dst then
4    Print path
5  foreach edge e ∈ outEdges(src) do
6    if e.dst ∉ visited then
7      if e.isIntraCFGEde() then
8        DFS(visited, path, callstack, e.dst, dst)
9      else if e.isCallCFGEde() then
10         callstack.push(e.getCallsite())
11         DFS(visited, path, callstack, e.dst, dst)
12      else if e.isRetCFGEde() then
13         if !callstack.empty() && callstack.top() == e.getCallsite() then
14           callstack.pop()
15           DFS(visited, path, callstack, e.dst, dst)
16  visited.erase(src);
17  path.pop_back();
```



# Context-Sensitive Control-Dependence

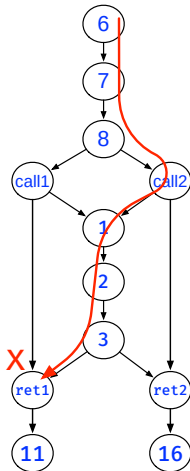
call1 matches with ret1



```
visited: set<NodeID>
path: vector<NodeID>
callstack: stack<callsite> //A stack of LLVM call instructions
DFS(visited, path, callstack, src, dst)
1  visited.insert(src)
2  path.push_back(src)
3  if src == dst then
4    Print path
5  foreach edge e ∈ outEdges(src) do
6    if e.dst ∉ visited then
7      if e.isIntraCFGEde() then
8        DFS(visited, path, callstack, e.dst, dst)
9      else if e.isCallCFGEde() then
10         callstack.push(e.getCallsite())
11         DFS(visited, path, callstack, e.dst, dst)
12      else if e.isRetCFGEde() then
13         if !callstack.empty() && callstack.top() == e.getCallsite() then
14             callstack.pop()
15             DFS(visited, path, callstack, e.dst, dst)
16  visited.erase(src);
17  path.pop_back();
```

# Context-Sensitive Control-Dependence

call2 does not match with ret1



```
visited: set<NodeID>
path: vector<NodeID>
callstack: stack<callsite> //A stack of LLVM call instructions
DFS(visited, path, callstack, src, dst)
1  visited.insert(src)
2  path.push_back(src)
3  if src == dst then
4    Print path
5  foreach edge e ∈ outEdges(src) do
6    if e.dst ∉ visited then
7      if e.isIntraCFGEde() then
8        DFS(visited, path, callstack, e.dst, dst)
9      else if e.isCallCFGEde() then
10         callstack.push(e.getCallsite())
11         DFS(visited, path, callstack, e.dst, dst)
12      else if e.isRetCFGEde() then
13         if !callstack.empty() && callstack.top() == e.getCallsite() then
14             callstack.pop()
15             DFS(visited, path, callstack, e.dst, dst)
16  visited.erase(src);
17  path.pop_back();
```

# What's next?

- (1) Understand control-dependence in this slides
- (2) Implement a context-insensitive ICFG traversal (Migrate the algorithm you have implemented in Assignment 1)
- (3) Implement a context-sensitive ICFG traversal, i.e., Task in Assignment 2
  - Refer to 'Assignment-2.pdf' on Canvas to know more about Assignment 2.