Data-Flow and Pointer Aliasing

(Week 3)

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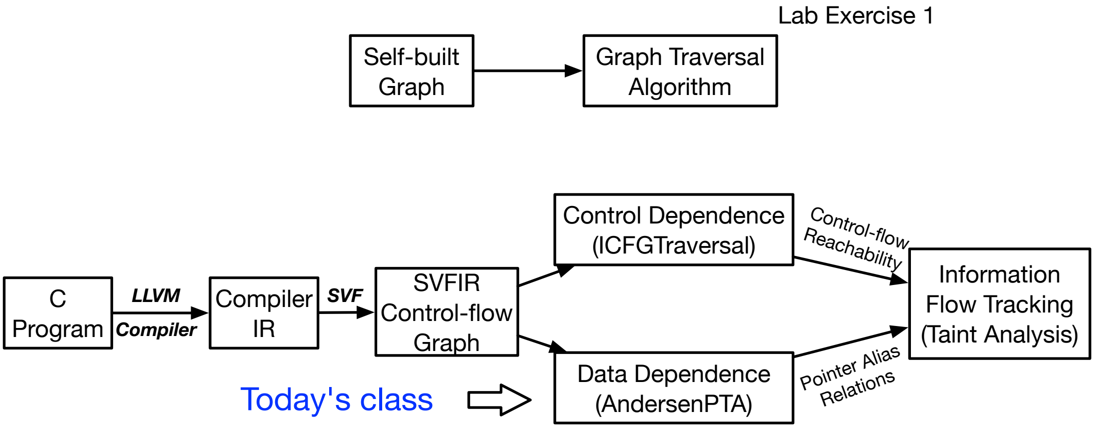
Today's class



Data-Dependence

Definition-use relations between variables. Two types of variables on LLVM IR:

- **Top-level variables**, whose addresses are not taken (`ValPN` in SVF)
  - Including stack virtual **registers** (symbols starting with "%") and **global** variables (symbols starting with "@") are explicit, i.e., directly accessed.

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  - **Def-use for top-level variables are directly available from LLVM’s SSA form**.
  - For example, def-use for %a1 from Instruction-1 to Instruction-2.
    - Instruction-1: `%a1 = alloca i8, align 1;`
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- **Address-taken variables** (abstract objects), accessed indirectly at load or store instructions via top-level variables (`ObjPN` in SVF)
  - A **stack object** created at an LLVM's 'alloca' instruction or a **heap object** created via (e.g., 'malloc' callsite) or a **global object**.

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  - **Def-use for address-taken variables are computed via pointer analysis**.
  - For example, there is a def-use for object `o` from Instruction-1 to Instruction-2 if pointers %a and %b both point to `o`.
    - Instruction-1: `store i8* %a1, i8** %a, align 8`
    - Instruction-2: `%c = load i8** %b, align 8`

Pointer analysis

- Points-to Analysis: aims to statically determine the possible runtime values of a pointer at compile-time.
  - Compute the *points-to set* (**a set of address-taken variables**) of each *pointer* (**top-level variable)**
  - For example, `p = &a; q = p;`
  - The resulting points-to sets of `p` and `q` are: `pts(p) = pts(q) =` $\{$`a`$\}$

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  - The resulting points-to sets of `p` and `q` are: `pts(p) = pts(q) =` $\{a\}$
- Alias Analysis: determine whether two pointer dereferences refer to the same memory location.
  - If the points-to sets of two pointers `p` and `q` have overlapping elements (i.e., `pts(p)` $\cap$ `pts(q) is not empty`) then `p` and `q` are aliases. The derereferences of `p` and `q` may refer to the same memory location.

Pointer analysis

Why shall we learn pointer analysis?

- Essential for building data-dependence relations between variables (memory objects).

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- Compiler optimizations and bug detection
  - Constant propagation
    - `*p = 1; x = *q;`
      `x` is a constant value and equals 1, if `p` and `q` are must-aliases (always point to the same memory location w.r.t every execution path).
    - `*p = 1; *q = r; x = *p;`
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    - `*p = 1; *q = r; x = *p;`
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  - Taint analysis
    - `*p = taintedInput; x = *q;`
      `x` is tainted if `p` and `q` are aliases.

Precision Dimensions

Can be generally classified into the following precision dimensions at different levels of abstractions.

Flow-insensitive analysis:

- Ignores program execution order
- A single solution across whole program

Context-insensitive analysis:

- Merges all calling contexts when analysing a program method

Path-insensitive analysis:

- Merges all incoming path information at the join points of the control-flow graph

Flow-sensitive analysis:

- Respects the program execution order
- Separate solution at each program point

Context-sensitive analysis:

- Distinguishes between different calling contexts of a program method

Path-sensitive analysis:

- Computes a solution per (abstract) program path.

Precision Dimensions

Levels of Abstractions

Assume x is a tainted value

p = x

p = y

flow-sensitivity

at which

program point

p is tainted?

```
foo(x)      foo(y)
  call ↘   ↙ call
     foo(p){

     }
```

context-sensitivity

under which

calling context

p is tainted?

```
if(cond)
        p = x
else
        p = y
```

path-sensitivity

along which

program path

p is tainted?

Andersen's Pointer analysis

Flow-, context-, and path-insensitive analysis

In this subject, we will practice **Andersen's analysis**[1], a **flow-insensitive, context-insensitive and path-insensitive pointer analysis** through analyzing the **Constraint Graph** of a program.

- One of the most popular and widely used pointer analyses
- Constraint solving, i.e., inclusion-based constraint solving between program variables (`ConstraintNode` in SVF)

Andersen's Pointer Analysis

An inclusion-based analysis operating on top of the constraint graph of a program. SVF transforms each LLVM instruction into a constraint edge connecting two nodes

- `ConstraintNode` represents
  - A pointer: (top-level variable) or
  - An object: (address-taken variable, i.e., heap, stack, global or function object)
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SVF IR	C code	LLVM IR	Constraint rules
`AddrStmt`	$\%ptr = alloca_o$	$p = alloc$	$pts(p) = pts(p) \cup \{o\}$
`CopyStmt`	$\%p = bitcast\ \%q$	$p = q$	$pts(q) = pts(q) \cup pts(p)$
`LoadStmt`	$\%p = load\ \%q$	$p = *q$	$\forall o \in pts(p) : pts(q) = pts(o) \cup pts(q)$
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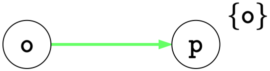

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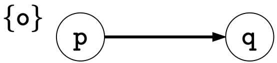

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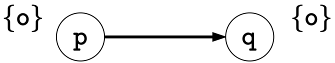

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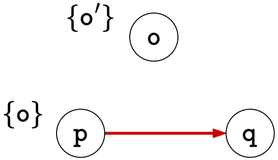

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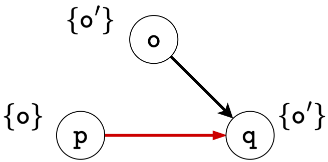

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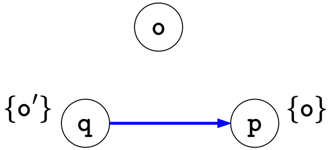

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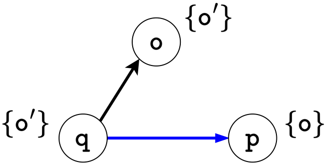

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Compiling a C Program to Its LLVM IR

```c
void swap(char **p, char **q){
  char* t = *p;
  *p = *q;
  *q = t;
}
int main(){
  char a1;
  char *a;
  char b1;
  char *b;
  a = &a1;
  b = &b1;
  swap(&a,&b);
}
```

swap.c

Compile

⇨

```llvm
define void @swap(ptr %p, ptr %q) #0 {
entry:
  %0 = load ptr, ptr %p, align 8
  %1 = load ptr, ptr %q, align 8
  store ptr %1, ptr %p, align 8
  store ptr %0, ptr %q, align 8
  ret void
}

define i32 @main() #0 {
entry:
  %a1 = alloca i8, align 1
  %a = alloca ptr, align 8
  %b1 = alloca i8, align 1
  %b = alloca ptr, align 8
  store ptr %a1, ptr %a, align 8
  store ptr %b1, ptr %b, align 8
  call void @swap(ptr %a, ptr %b)
  ret i32 0
}
```

swap.ll

*https://github.com/SVF-tools/Teaching-Software-Analysis/wiki/CodeGraph#2-llvm-ir-generation

Construct a Constraint Graph from LLVM IR

```
define i32 @main() #0 {
entry:
  %a1 = alloca i8, align 1            // O1
  %a = alloca ptr, align 8            // O2
  %b1 = alloca i8, align 1            // O3
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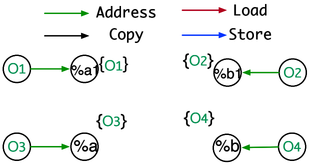

https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#5-pag

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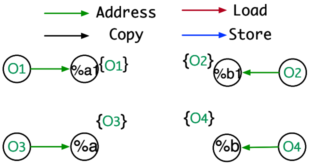


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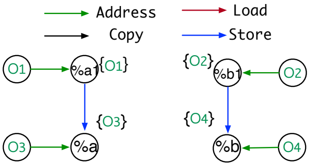

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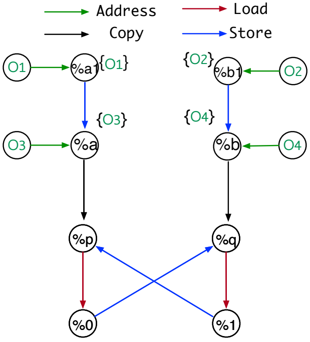

G = < V,E > // Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph
WorkList: a vector of nodes

foreach $o \xrightarrow{Address} p$ **do** // Address rule
    pts(p) = {o}
    pushIntoWorklist(p)
while WorkList ≠ ∅ do
  p <- popFromWorklist()
  foreach o ∈ pts(p) **do**
    foreach $q \xrightarrow{Store} p$ **do** // Store rule
      if $q \xrightarrow{Copy} o \notin E$ **then**
        $E \leftarrow E \cup \{ q \xrightarrow{Copy} o \}$ // Add copy edge
        pushIntoWorklist(q)
    foreach $p \xrightarrow{Load} r$ **do** // Load rule
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        pushIntoWorklist(o)
  foreach $p \xrightarrow{Copy} x \in E$ **do** // Copy rule
    pts(x) <- pts(x) ∪ pts(p)
    if pts(x) changed **then**
      pushIntoWorklist(x)

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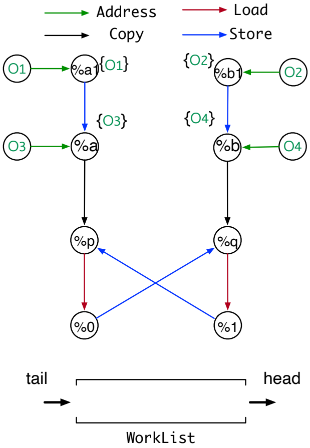

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        pushIntoWorklist(o)
  foreach p $\xrightarrow{\text{Copy}}$ x ∈ E **do** // Copy rule
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    if pts(x) changed **then**
      pushIntoWorklist(x)

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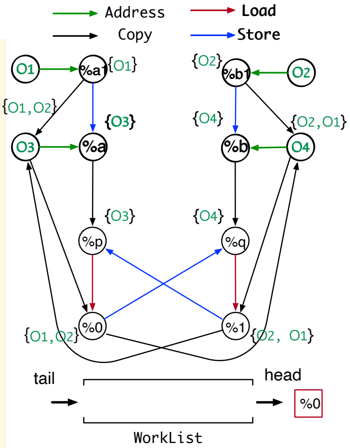
Andersen's Pointer Analysis

Algorithm

```
define i32 @main() #0 {
entry:
   %a1 = alloca i8, align 1          // O1
   %a = alloca ptr, align 8          // O2
   %b1 = alloca i8, align 1          // O3
   %b = alloca ptr, align 8          // O4
   store ptr %a1, ptr %a, align 8
   store ptr %b1, ptr %b, align 8
   call void @swap(ptr %a, ptr %b)
   ret i32 0
}

define void @swap(ptr %p, ptr %q) #0 {
entry:
   %0 = load ptr, ptr %p, align 8
   %1 = load ptr, ptr %q, align 8
   store ptr %1, ptr %p, align 8
   store ptr %0, ptr %q, align 8
   ret void
}
```




```
G = < V,E >  // Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph
WorkList: a vector of nodes
foreach o --Address--> p do                     // Address rule
    pts(p) = {o}
    pushIntoWorklist(p)
while WorkList ≠ ∅ do
  p <- popFromWorklist()
  foreach o ∈ pts(p) do
    foreach q --Store--> p do                   // Store rule
      if q --Copy--> o ∉ E then
        E <- E ∪ { q --Copy--> o }              // Add copy edge
        pushIntoWorklist(q)
    foreach p --Load--> r do                    // Load rule
      if o --Copy--> r ∉ E then
        E <- E ∪ { o --Copy--> r }              // Add copy edge
        pushIntoWorklist(o)
  foreach p --Copy--> x ∈ E do                  // Copy rule
    pts(x) <- pts(x) ∪ pts(p)
    if pts(x) changed then
      pushIntoWorklist(x)
```

Andersen's Pointer Analysis

Constraint solving Algorithm

- A worklist holds a list of constraint graph nodes for processing
- Pop a node `p` from the worklist.
- Handle each incoming `store` edge and each outgoing `load` edge of node `p` by adding `copy` edges.
- Handle each outgoing `copy` edge of `p` by propagating points-to information.
- The constraint solving stops when no points-to set of a pointer is changed.

APIs for Implementing Andersen's analysis

SVF :: AndersenBase

```
::getPts(NodeID ptr)                  //get points-to set of ptr
::addPts(NodeID ptr, NodeID obj)      // add obj to point-to set of object ptr
::unionPts(NodeID ptr, NodeID ptr)    // union two point-to sets
::pushIntoWorklist(NodeID id)         // push the node to worklist
::popFromWorklist()                   // pop a node from the worklist
::isInWorklist(NodeID id)             // return true if the node in the worklist
::isWorklistEmpty()                   // return true if the worklist is empty
```

SVF :: AndersenPTA (derived from SVF :: AndersenBase)

```
::addCopyEdge(NodeID src, NodeID dst) // add a copy edge from src to dst
```

SVF :: ConstraintGraph

```
::getConstraintNode(nodeId id)        //get the node based on its id
::dump()                              // dump the ConsG
```

SVF :: ConstraintNode

```
::getStoreInEdge()                    // get incoming store edges of the node
::getStoreOutEdge()                   //get outgoing store edges of the node
::getDirectOutEdge()                  // get outgoing copy edges of the node
::getDirectInEdge()                   // get incoming copy edges of the node
```

https://github.com/SVF-tools/Teaching-Software-Analysis/wiki/SVF-CPP-API#worklist-operations
https://github.com/SVF-tools/Teaching-Software-Analysis/wiki/SVF-CPP-API#points-to-set-operations
https://github.com/SVF-tools/Teaching-Software-Analysis/wiki/SVF-CPP-API#constraintgraph-constraintnode-and-constraintedge

Andersen's Pointer Analysis

Constraint graph before the while loop worklist solving

```
define i32 @main() #0 {
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   %a1 = alloca i8, align 1          // O1
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   %b1 = alloca i8, align 1          // O3
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   store ptr %a1, ptr %a, align 8
   store ptr %b1, ptr %b, align 8
   call void @swap(ptr %a, ptr %b)
   ret i32 0
}

define void @swap(ptr %p, ptr %q) #0 {
entry:
   %0 = load ptr, ptr %p, align 8
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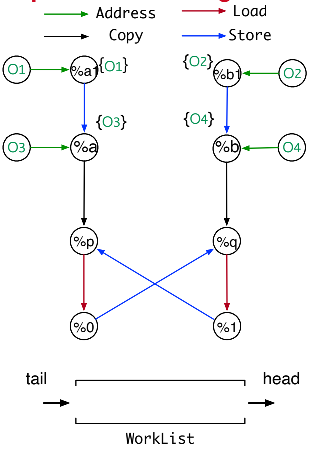
   store ptr %1, ptr %p, align 8
   store ptr %0, ptr %q, align 8
   ret void
}
```

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         if  q --Copy--> o  ∉ E then
            E <- E ∪ { q --Copy--> o }                // Add copy edge
            pushIntoWorklist(q)
      foreach  p --Load--> r  do                      // Load rule
         if o --Copy--> r  ∉ E then
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            pushIntoWorklist(o)
   foreach p --Copy--> x  ∈ E do                      // Copy rule
      pts(x) <- pts(x) ∪ pts(p)
      if pts(x) changed then
         pushIntoWorklist(x)
```

Andersen's Pointer Analysis

Constraint graph after the while loop worklist solving

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   store ptr %a1, ptr %a, align 8
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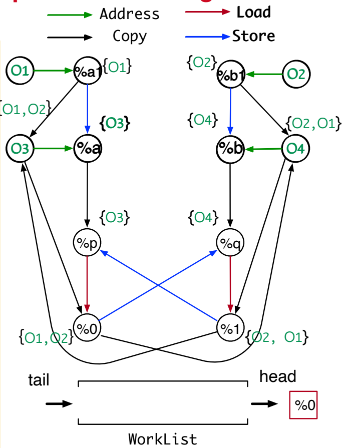
   store ptr %0, ptr %q, align 8
   ret void
}
```



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      if o $\xrightarrow{Copy}$ r ∉ E **then**
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  foreach p $\xrightarrow{Copy}$ x ∈ E **do** // Copy rule
    pts(x) <- pts(x) ∪ pts(p)
    if pts(x) changed **then**
      pushIntoWorklist(x)

What’s next?

- (1) Understand data-dependence in today’s slides
- (2) Finish the quiz for Assignment-3
- (3) Implement Andersen’s pointer analysis, i.e., coding task in Assignment 3
  - Refer to ‘Assignment-3.pdf‘ on Canvas to know more about Assignment 3.

Information Flow Tracking

(Week 3)

Yulei Sui

School of Computer Science and Engineering

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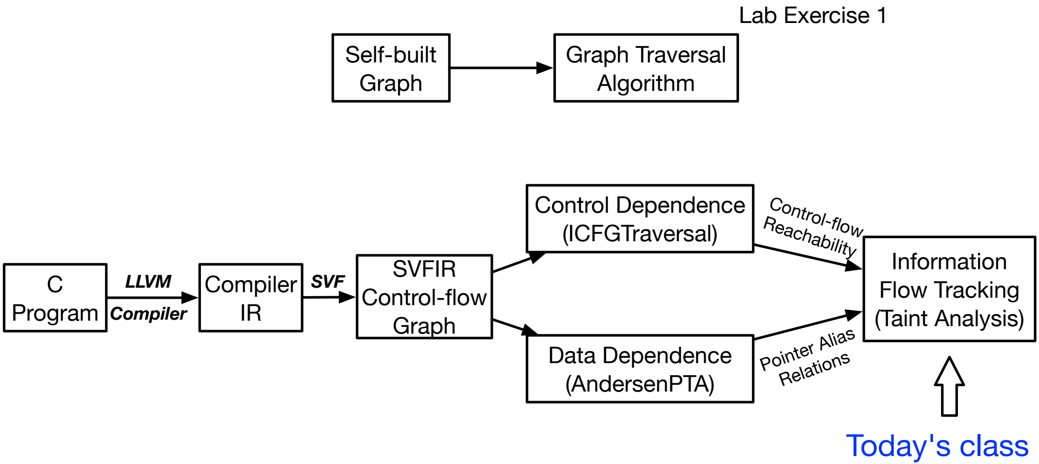
Today's Class



What is Taint Analysis?

- Taint analysis aims to reason about the control and data dependence from a source (statement/node) to a sink (statement/node).
- Taint analysis can also be seen as information flow tracking analysis.
  - Static taint analysis: taint tracking at compile time (**this subject**)
  - Dynamic taint analysis: taint tracking during runtime.

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- Taint analysis can also be seen as information flow tracking analysis.
  - Static taint analysis: taint tracking at compile time (**this subject**)
  - Dynamic taint analysis: taint tracking during runtime.

Why learn Taint Analysis?

- Detect information leakage
  - sensitive data stored in a heap object and manipulated by pointers can be passed around and stored to an unchecked memory (untrusted third-party APIs)
- Detect code vulnerability
  - There is a vulnerability if an unchecked tainted **source** (e.g., return value from an untrusted third party function) flows into one of the following **sinks**, where the tainted variable being used as
    - a parameter passed to a sensitive function or
    - a bound access (array index) or
    - a termination condition (loop condition)
    - ...

How to Perform Static Taint Analysis?

Let us use what we have learned about control- and data-dependence to develop an information flow checker to validate tainted flows from a source to a sink.

- A **source** $\mathbf{v_{src}}$@$\mathbf{s_{src}}$ is a tuple consisting of a variable $\mathbf{v_{src}}$ and a statement $\mathbf{s_{src}}$ where $\mathbf{v_{src}}$ is defined.
- A **sink** $\mathbf{v_{snk}}$@$\mathbf{s_{snk}}$ is also a tuple consisting of a variable $\mathbf{v_{snk}}$ and a statement $\mathbf{s_{snk}}$ where $\mathbf{v_{snk}}$ is used.
- In SVF, variables $\mathbf{v_{src}}$ and $\mathbf{v_{snk}}$ are `PAGNodes`. Statements $\mathbf{s_{src}}$ and $\mathbf{s_{snk}}$ are `ICFGNodes`.

How to Perform Static Taint Analysis?

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- In SVF, variables $\mathbf{v_{src}}$ and $\mathbf{v_{snk}}$ are `PAGNodes`. Statements $\mathbf{s_{src}}$ and $\mathbf{s_{snk}}$ are `ICFGNodes`.
- Given a **tainted** source $\mathbf{v_{src}}$@$\mathbf{s_{src}}$, we say that a sink $\mathbf{v_{snk}}$@$\mathbf{s_{snk}}$ is also **tainted** if both of the following two conditions satisfy:
  - (1) $\mathbf{s_{src}}$ reaches $\mathbf{s_{snk}}$ on the ICFG (**Assignment 2**), and
  - (2) $\mathbf{v_{src}}$ is aliased with $\mathbf{v_{snk}}$, i.e., $pts(v_{src}) \cap pts(v_{snk}) \neq \varnothing$ (**Assignment 3**)

Taint Analysis

Example 1

```
int main(){
    char* secretToken = tgetstr();   // source
    char* a = secretToken;
    char* b = a;
    broadcast(b);                    // sink
}
```

What is the tainted flow?

Taint Analysis

Example 1

```
1 int main(){
2     char* secretToken = tgetstr();    // source
3     char* a = secretToken;
4     char* b = a;
5     broadcast(b);                     // sink
6 }
```

What is the tainted flow?

- Line 2 reaches Line 5 along the ICFG (control-dependence holds) `secretToken` and `b` are aliases (data-dependence holds)
- Both control-dependence and data-dependence hold. Therefore, `secretToken`@Line 2 flows to `b`@Line 5.

Taint Analysis

Example 2

```
int main(){
    char* secretToken = tgetstr(...);    // source
    char* a = secretToken;
    char* b = a;
    char* publicToken = "hello";
    broadcast(publicToken);          // sink
}
```

Do we have a tainted flow from source to sink?

Taint Analysis

Example 2

```
1 int main(){
2     char* secretToken = tgetstr(...);   // source
3     char* a = secretToken;
4     char* b = a;
5     char* publicToken = "hello";
6     broadcast(publicToken);             // sink
7 }
```

Do we have a tainted flow from source to sink?

- Line 2 reaches Line 6 along the ICFG (control-dependence holds),
- `secretToken` and `publicToken` are not aliases (data-dependence does not hold),
- `secretToken`@Line 2 does not flow to `publicToken`@Line 6.

Taint Analysis

Example 3

```
char* foo(char* token){ return token; }
int main(){
    if(condition){
        char*  secretToken = tgetstr(...);     // source
        char* b = foo(secretToken);
    }
    else{
        char* publicToken = "hello";
        char* a = foo(publicToken);
        broadcast(a);                        // sink
    }
}
```

Do we have a tainted flow from source to sink?

Taint Analysis

Example 3

```
1  char* foo(char* token){ return token; }
2  int main(){
3      if(condition){
4          char*  secretToken = tgetstr(...);     // source
5          char* b = foo(secretToken);
6      }
7      else{
8          char* publicToken = "hello";
9          char* a = foo(publicToken);
10         broadcast(a);                         // sink
11     }
12 }
```

Do we have a tainted flow from source to sink?

- `secretToken` and `a` are aliases due to callee `foo` (data-dependence holds),
- Line 4 does not reach Line 10 on ICFG (control-dependence does not hold),
- `secretToken`@Line 4 does not flow to `a`@Line 10.

Taint Analysis

Example 4

```
int main(){
    char* secretToken = tgetstr(...);                    // source
    while(loopCondition){
        if(BranchCondition){
            char* a = secretToken;
            broadcast(a);                                // sink
        }
        else{
            char* b = "hello";
        }
    }
}
```

How many tainted flows from source to sink?

Taint Analysis

Example 4

```
1  int main(){
2      char* secretToken = tgetstr(...);                       // source
3      while(loopCondition){
4          if(BranchCondition){
5              char* a = secretToken;
6              broadcast(a);                                   // sink
7          }
8          else{
9              char* b = "hello";
10         }
11     }
12 }
```

How many tainted flows from source to sink?

- (At least) two paths from Line 2 to Line 6 on ICFG (control-dependence holds),
- `secretToken` and `a` are aliases (data-dependence holds),
- `secretToken`@Line 2 has two tainted paths flowing to `a`@Line 6.

Configuring Sources and Sinks for Taint Analysis

Aim: enable different taint tracking patterns by defining/configuring sources and sinks.

- Given a source $\mathbf{v_{src}@s_{src}}$ and a sink $\mathbf{v_{snk}@s_{snk}}$, in this class, we are interested in the case that $\mathbf{s_{src}}$ and $\mathbf{s_{snk}}$ are both API calls, i.e., `CallBlockNode` in SVF.

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- $\mathbf{v_{src}}$ is a return value from the call statement $\mathbf{s_{src}}$.
- $\mathbf{v_{snk}}$ is a parameter being passed to a call statement $\mathbf{s_{snk}}$.

Configuring Sources and Sinks for Taint Analysis

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- Given a source $\mathbf{v_{src}}@\mathbf{s_{src}}$ and a sink $\mathbf{v_{snk}}@\mathbf{s_{snk}}$, in this class, we are interested in the case that $\mathbf{s_{src}}$ and $\mathbf{s_{snk}}$ are both API calls, i.e., `CallBlockNode` in SVF.
- $\mathbf{v_{src}}$ is a return value from the call statement $\mathbf{s_{src}}$.
- $\mathbf{v_{snk}}$ is a parameter being passed to a call statement $\mathbf{s_{snk}}$.
- We can identify $\mathbf{s_{src}}$ and $\mathbf{s_{snk}}$ according to different APIs, so as to configure sources and sinks.
- In our Example 1, variable `secretToken` is $\mathbf{v_{src}}$ and `b` is $\mathbf{v_{snk}}$. The call statement `tgetstr(..)` represents $\mathbf{s_{src}}$ and `broadcast(..)` are used for $\mathbf{s_{snk}}$.