Data-Flow and Pointer Aliasing

(Week 3)

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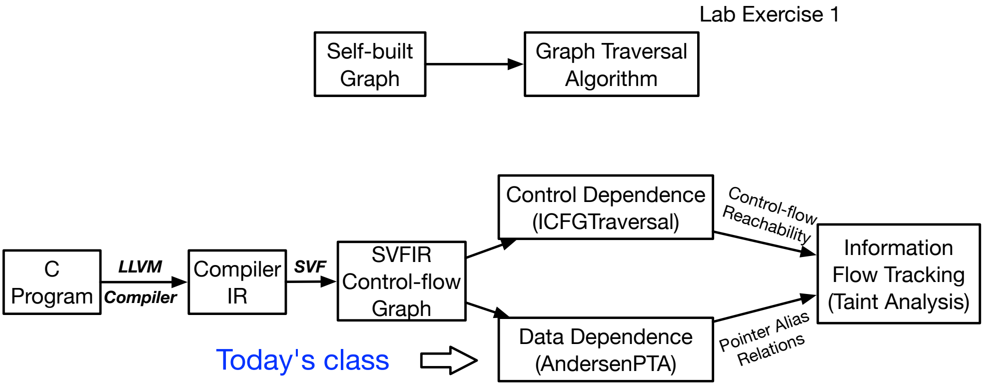
Today's class



Data-Flow and 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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  - 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)
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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 (Revisit Andersen's Analysis in Lab-Exercise-1)

A typical data-flow 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**: determines 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., $\mathtt{pts(p)} \cap \mathtt{pts(q)} \neq \emptyset$) 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?

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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;`
      `x` is a constant value and equals 1, if `p` and `q` do not alias with each other.
  - 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

A **flow-insensitive, context-insensitive and path-insensitive points-to analysis** to determine points-to set of a pointer by analyzing the **Constraint Graph** or **Program Assignment Graph (PAG)** of a program.

- Also called **inclusion-based points-to analysis**, the most popular and widely used pointer analysis.
- Constraint solving, i.e., inclusion-based constraint solving between `SVFVar`s in the form of `ConstraintNode`s.
- The analysis requires iterative constraint solving by (1) propagating points-to sets among constraint graph nodes, and (2) adding new edges until a fixed point is reached, i.e., no new edges are added. (**Lab-Exercise-1**)

Andersen, L. O. (1994). Program analysis and specialization for the C programming language (Doctoral dissertation, University of Cophenhagen).

Field-Sensitive Andersen's Pointer Analysis

The analysis operating upon a program's constraint graph which is a subgraph of PAG (program assignment graph).

- `ConstraintNode` represents
  - A pointer (`ValVar`): (top-level variable) or
  - An object (`ObjVar`): (address-taken objects, i.e., heap/stack/global/function objs)
- `ConstraintEdge` represents a constraint between two nodes

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Constraint Edge	LLVM IR	C code	Constraint rules
$\mathtt{p} \xleftarrow{\mathtt{Addr}} \mathtt{o}$	`%p = alloca`$_o$	$\mathtt{p} = \&\mathtt{o}$	$\mathtt{pts(p)} = \mathtt{pts(p)} \cup \{\mathtt{o}\}$
$\mathtt{q} \xleftarrow{\mathtt{Copy}} \mathtt{p}$	`%q = bitcast %p`	$\mathtt{q} = \mathtt{p}$	$\mathtt{pts(q)} = \mathtt{pts(q)} \cup \mathtt{pts(p)}$
$\mathtt{q} \xleftarrow{\mathtt{Load}} \mathtt{p}$	`%q = load %p`	$\mathtt{q} = *\mathtt{p}$	$\forall \mathtt{o} \in \mathtt{pts(p)}$: add edge $\mathtt{q} \xleftarrow{\mathtt{Copy}} \mathtt{o}$
$\mathtt{q} \xleftarrow{\mathtt{Store}} \mathtt{p}$	`store %p, %q`	$*\mathtt{q} = \mathtt{p}$	$\forall \mathtt{o} \in \mathtt{pts(q)}$: add edge $\mathtt{o} \xleftarrow{\mathtt{Copy}} \mathtt{p}$
$\mathtt{q} \xleftarrow{\mathtt{Gep,fld}} \mathtt{p}$	`%q = gep %p, fld`	$\mathtt{q} = \&\mathtt{p} \rightarrow \mathtt{fld}$	$\forall \mathtt{o} \in \mathtt{pts(p)} : \mathtt{pts(q)} = \mathtt{pts(q)} \cup \{\mathtt{o.fld}\}$

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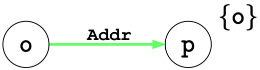

pts(p) = {o}

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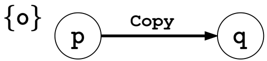

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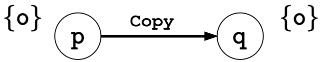

`pts(p) = {o}`
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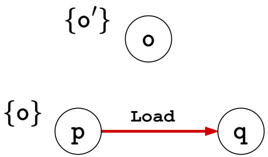

$\texttt{pts(p)} = \{o\}$
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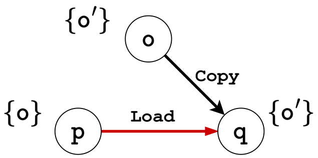

`pts(p) = {o}`
`pts(o) = {o′}`
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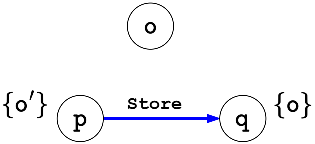

$pts(p) = \{o'\}$
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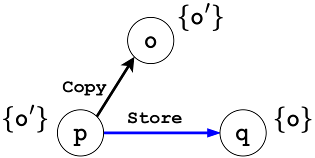

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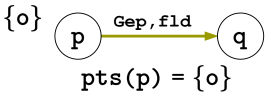

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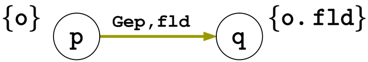

pts(p) = {o}

pts(q) = {o.fld}

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/Software-Security-Analysis/wiki/SVFIR#2-llvm-ir-generation

Construct the 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
    %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:
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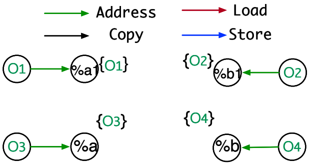

https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#5-pag

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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
}
```
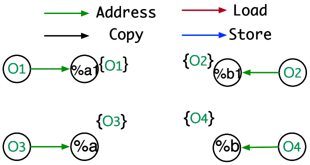
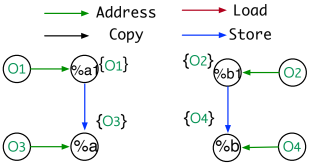



*https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#5-pag

Construct the Constraint Graph from LLVM IR

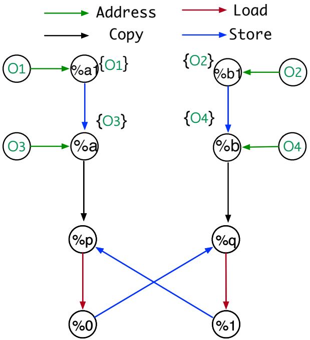
```
define i32 @main() #0 {
entry:
   %a1 = alloca i8, align 1          // O1
   %a = alloca ptr, align 8          // O2
   %b1 = alloca i8, align 1          // O3
   %b = alloca ptr, align 8          // O4
   store ptr %a1, ptr %a, align 8
   store ptr %b1, ptr %b, align 8
   call void @swap(ptr %a,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



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

Construct the 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
  %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
}
```



Algorithm 1: 1 Anderson's Pointer Analysis

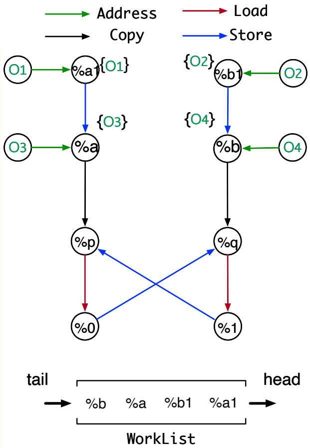
Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do              // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};          // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                    // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

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

Andersen's Pointer Analysis

```
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
}
```



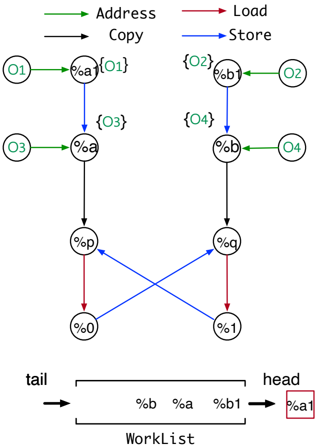
Algorithm 2: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                          // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```

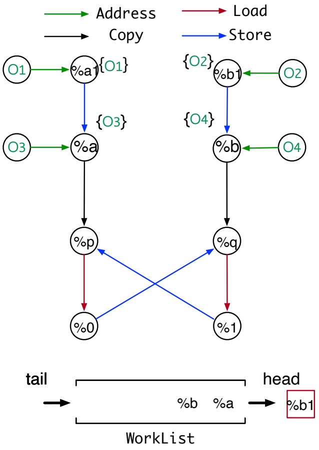


Algorithm 3: 1 Anderson's Pointer Analysis

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

Andersen’s Pointer Analysis

```
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
}
```



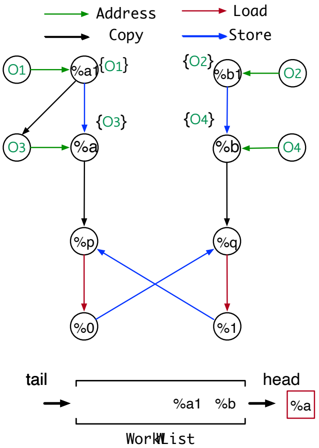
Algorithm 4: 1 Anderson’s Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                         // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do              // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};          // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                    // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



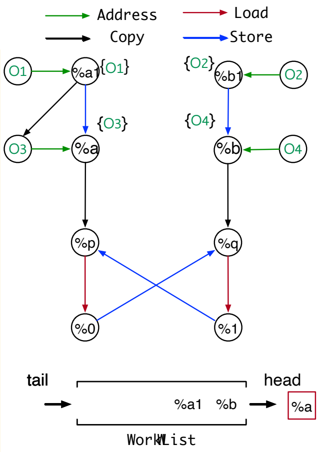
Algorithm 5: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                      // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do            // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};         // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                  // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



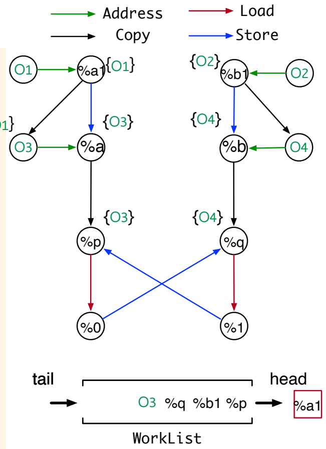
Algorithm 6: 1 Anderson's Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                          // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do                 // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};             // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                       // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



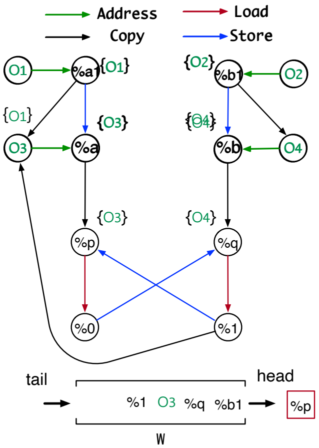
Algorithm 7: 1 Anderson's Pointer Analysis

Input : $G = \langle V, E \rangle$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

WorkList := an empty vector of nodes;
foreach $o \xrightarrow{Address} p$ **do** // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ ∅ **do**
    p := popFromWorklist();
    foreach $o \in pts(p)$ **do**
        foreach $q \xrightarrow{Store} p \in E$ **do** // Store rule
            if $q \xrightarrow{Copy} o \notin E$ **then**
                $E := E \cup \{q \xrightarrow{Copy} o\}$; // Add copy edge
                pushIntoWorklist(q);
        foreach $p \xrightarrow{Load} r \in E$ **do** // Load rule
            if $o \xrightarrow{Copy} r \notin E$ **then**
                $E := E \cup \{o \xrightarrow{Copy} r\}$; // Add copy edge
                pushIntoWorklist(o);
    foreach $p \xrightarrow{Copy} x \in E$ **do** // Copy rule
        $pts(x) := pts(x) \cup pts(p)$;
        if *pts(x) changed* **then**
            pushIntoWorklist(x);
    foreach $p \xrightarrow{Gep} x \in E$ **do** // Gep rule
        foreach $o \in pts(p)$ **do**
            $pts(x) := pts(x) \cup \{o.fld\}$;
        if *pts(x) changed* **then**
            pushIntoWorklist(x);

Andersen's Pointer Analysis

```
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
}
```



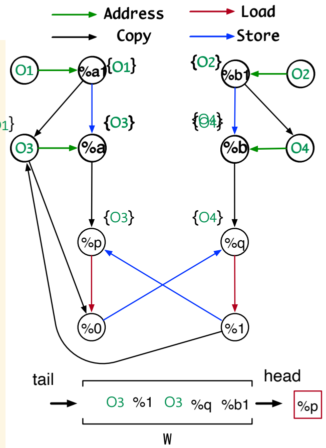
Algorithm 8: 1 Anderson's Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

WorkList := an empty vector of nodes;
foreach $o \xrightarrow{Address} p$ **do** // Address rule
  pts(p) := pts(p) ∪ {o};
  pushIntoWorklist(p);
while WorkList ≠ **do**
  p := popFromWorklist();
  foreach $o \in pts(p)$ **do**
    foreach $q \xrightarrow{Store} p \in E$ **do** // Store rule
      if $q \xrightarrow{Copy} o \notin E$ **then**
        $E := E \cup \{q \xrightarrow{Copy} o\}$; // Add copy edge
        pushIntoWorklist(q);
    foreach $p \xrightarrow{Load} r \in E$ **do** // Load rule
      if $o \xrightarrow{Copy} r \notin E$ **then**
        $E := E \cup \{o \xrightarrow{Copy} r\}$; // Add copy edge
        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);
  foreach $p \xrightarrow{Gep} x \in E$ **do** // Gep rule
    foreach $o \in pts(p)$ **do**
      pts(x) := pts(x) ∪ {o.fld};
    if *pts(x) changed* **then**
      pushIntoWorklist(x);

Andersen's Pointer Analysis

```
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
}
```



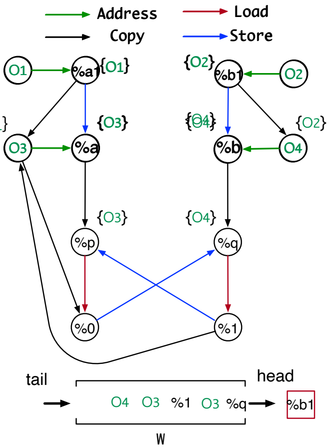
Algorithm 9: 1 Anderson's Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
  V: a set of nodes in graph
  E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                          // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



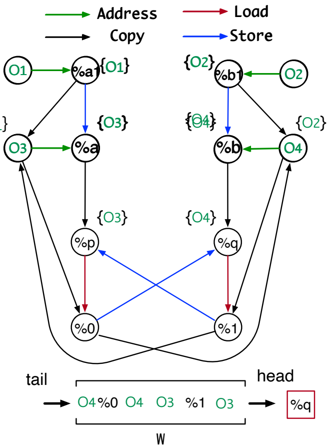
Algorithm 10: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                          // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



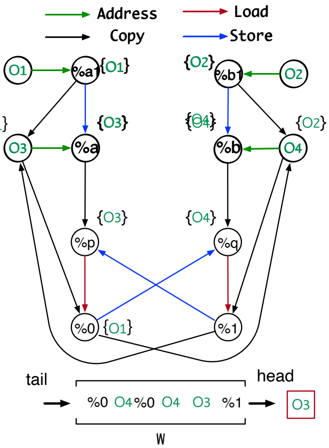
Algorithm 11: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                        // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do              // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};          // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                    // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



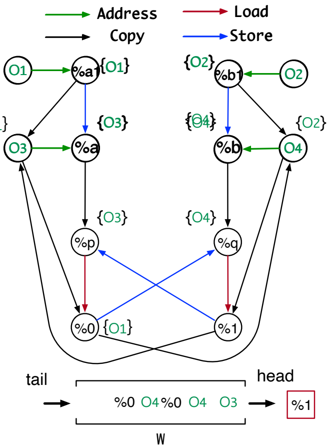
Algorithm 12: 1 Anderson's Pointer Analysis

Input : $G = < V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                      // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ ∅ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do            // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};        // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                  // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```

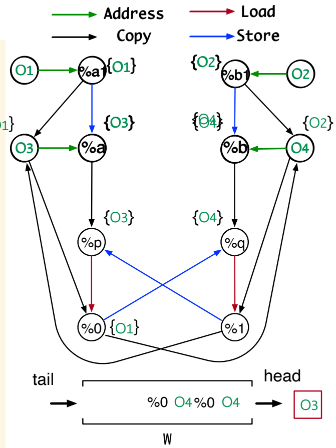


Algorithm 13: 1 Anderson's Pointer Analysis

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

Andersen's Pointer Analysis

```
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
}
```



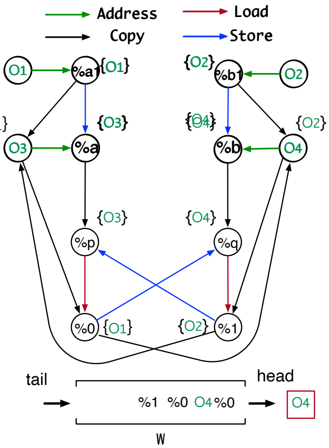
Algorithm 14: 1 Anderson's Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                          // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};             // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



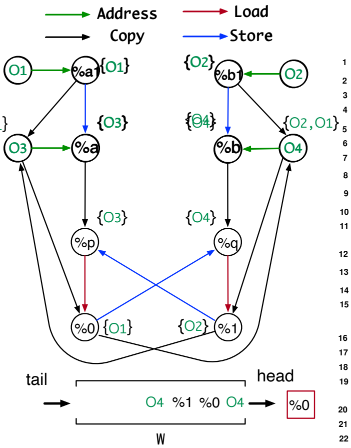
Algorithm 15: 1 Anderson's Pointer Analysis

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

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                         // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do               // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};           // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                     // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



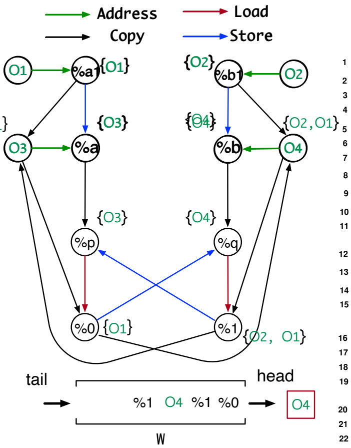
Algorithm 16: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

WorkList := an empty vector of nodes;
foreach $o \xrightarrow{Address} p$ **do** // Address rule
  pts(p) := pts(p) ∪ {o};
  pushIntoWorklist(p);
while WorkList ≠ **do**
  p := popFromWorklist();
  foreach $o \in pts(p)$ **do**
    foreach $q \xrightarrow{Store} p \in E$ **do** // Store rule
      if $q \xrightarrow{Copy} o \notin E$ **then**
        $E := E \cup \{q \xrightarrow{Copy} o\}$; // Add copy edge
        pushIntoWorklist(q);
    foreach $p \xrightarrow{Load} r \in E$ **do** // Load rule
      if $o \xrightarrow{Copy} r \notin E$ **then**
        $E := E \cup \{o \xrightarrow{Copy} r\}$; // Add copy edge
        pushIntoWorklist(o);
  foreach $p \xrightarrow{Copy} x \in E$ **do** // Copy rule
    $pts(x) := pts(x) \cup pts(p)$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);
  foreach $p \xrightarrow{Gep} x \in E$ **do** // Gep rule
    foreach $o \in pts(p)$ **do**
      $pts(x) := pts(x) \cup \{o.fld\}$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);

Andersen's Pointer Analysis

```
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
}
```



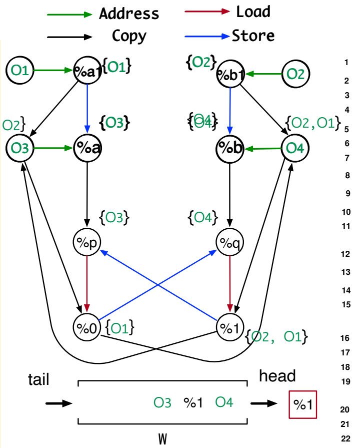
Algorithm 17: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty vector of nodes;
foreach o --Address--> p do                         // Address rule
    pts(p) := pts(p) ∪ {o};
    pushIntoWorklist(p);
while WorkList ≠ do
    p := popFromWorklist();
    foreach o ∈ pts(p) do
        foreach q --Store--> p ∈ E do               // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};           // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                     // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

```
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
}
```



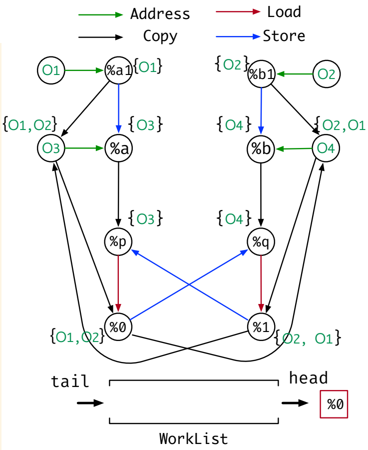
Algorithm 18: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

WorkList := an empty vector of nodes;
foreach $o \xrightarrow{Address} p$ **do** // Address rule
  pts(p) := pts(p) ∪ {o};
  pushIntoWorklist(p);
while WorkList ≠ **do**
  p := popFromWorklist();
  foreach o ∈ pts(p) **do**
    foreach $q \xrightarrow{Store} p \in E$ **do** // Store rule
      if $q \xrightarrow{Copy} o \notin E$ **then**
        $E := E \cup \{q \xrightarrow{Copy} o\}$; // Add copy edge
        pushIntoWorklist(q);
    foreach $p \xrightarrow{Load} r \in E$ **do** // Load rule
      if $o \xrightarrow{Copy} r \notin E$ **then**
        $E := E \cup \{o \xrightarrow{Copy} r\}$; // Add copy edge
        pushIntoWorklist(o);
  foreach $p \xrightarrow{Copy} x \in E$ **do** // Copy rule
    $pts(x) := pts(x) \cup pts(p)$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);
  foreach $p \xrightarrow{Gep} x \in E$ **do** // Gep rule
    foreach o ∈ pts(p) **do**
      $pts(x) := pts(x) \cup \{o.fld\}$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);

Andersen's Pointer Analysis

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



Algorithm 19: 1 Anderson's Pointer Analysis

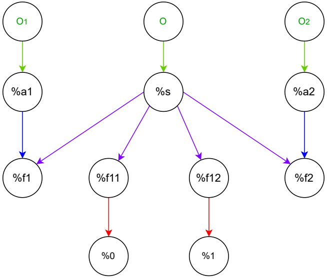
Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

WorkList := an empty vector of nodes;
foreach $o \xrightarrow{\text{Address}} p$ **do** // Address rule
  pts(p) := pts(p) ∪ {o};
  pushIntoWorklist(p);
while WorkList ≠ **do**
  p := popFromWorklist();
  foreach o ∈ pts(p) **do**
    foreach $q \xrightarrow{\text{Store}} p \in E$ **do** // Store rule
      if $q \xrightarrow{\text{Copy}} o \notin E$ **then**
        $E := E \cup \{q \xrightarrow{\text{Copy}} o\}$; // Add copy edge
        pushIntoWorklist(q);
    foreach $p \xrightarrow{\text{Load}} r \in E$ **do** // Load rule
      if $o \xrightarrow{\text{Copy}} r \notin E$ **then**
        $E := E \cup \{o \xrightarrow{\text{Copy}} r\}$; // Add copy edge
        pushIntoWorklist(o);
  foreach $p \xrightarrow{\text{Copy}} x \in E$ **do** // Copy rule
    $pts(x) := pts(x) \cup pts(p)$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);
  foreach $p \xrightarrow{\text{Gep}} x \in E$ **do** // Gep rule
    foreach o ∈ pts(p) **do**
      $pts(x) := pts(x) \cup \{o.fld\}$;
    if *pts(x) changed* **then**
      pushIntoWorklist(x);

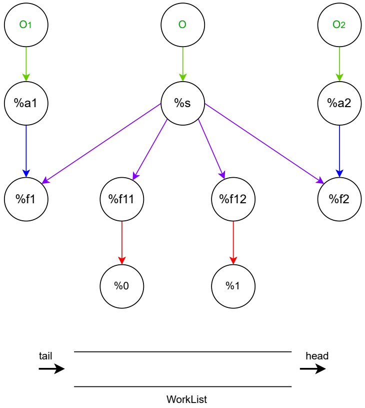
Field-Sensitive Andersen's Pointer Analysis

```c
struct S{
  int* f1;
  int* f2;
};
int main(){
   struct S s;
   int a1, a2;
   s.f1 = &a1;
   s.f2 = &a2;
   int* p = s.f1;
   int* q = s.f2;
}
```

```llvm
define i32 @main() #0 {
entry:
  %s = alloca %struct.S, align 8
  %a1 = alloca i32, align 4
  %a2 = alloca i32, align 4
  %f1 = getelementptr inbounds %struct.S, ptr %s, i32 0, i32 0
  store ptr %a1, ptr %f1, align 8
  %f2 = getelementptr inbounds %struct.S, ptr %s, i32 0, i32 1
  store ptr %a2, ptr %f2, align 8
  %f11 = getelementptr inbounds %struct.S, ptr %s, i32 0, i32 0
  %0 = load ptr, ptr %f11, align 8
  %f22 = getelementptr inbounds %struct.S, ptr %s, i32 0, i32 1
  %1 = load ptr, ptr %f22, align 8
  ret i32 0
}
```



Field-Sensitive Andersen's Pointer Analysis

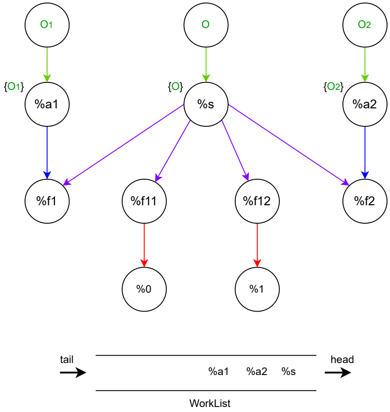


Algorithm 20: 1 Anderson's Pointer Analysis

Input : $G = \langle V, E \rangle$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                    // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};                // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                          // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

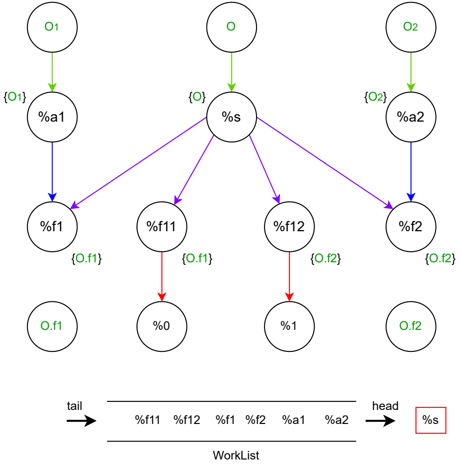
Field-Sensitive Andersen’s Pointer Analysis



Algorithm 21: 1 Anderson’s Pointer Analysis

```
Input : G =< V,E >: Constraint Graph
        V: a set of nodes in graph
        E: a set of edges in graph
WorkList := an empty 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 ∈ E do                       // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};                   // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                             // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

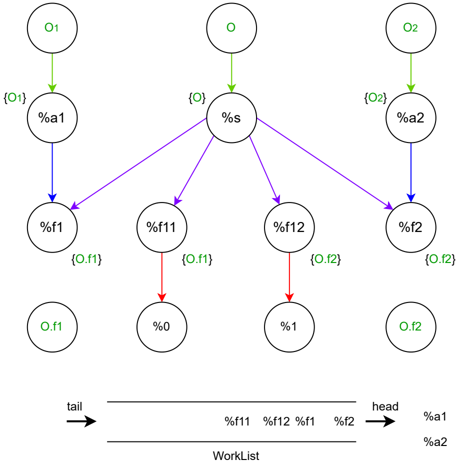
Field-Sensitive Andersen's Pointer Analysis



Algorithm 22: 1 Anderson's Pointer Analysis

```
Input : G =< V, E >: Constraint Graph
        V: a set of nodes in graph
        E: a set of edges in graph
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

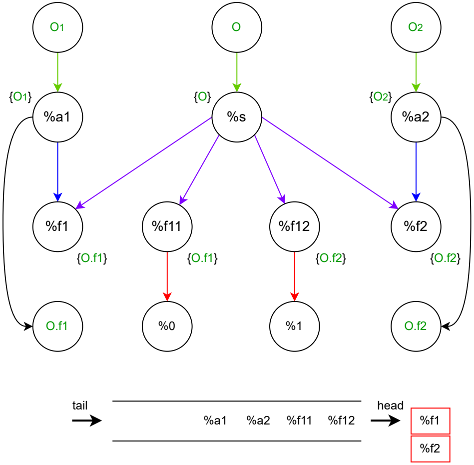
Field-Sensitive Andersen's Pointer Analysis



Algorithm 23: 1 Anderson's Pointer Analysis

```
Input : G =< V,E >: Constraint Graph
        V: a set of nodes in graph
        E: a set of edges in graph
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Field-Sensitive Andersen's Pointer Analysis

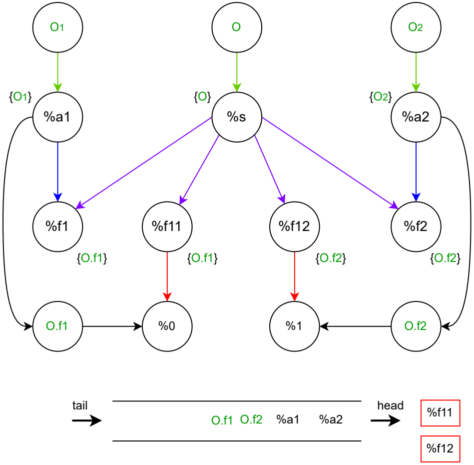


Algorithm 24: 1 Anderson's Pointer Analysis

Input : $G = <V, E>$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

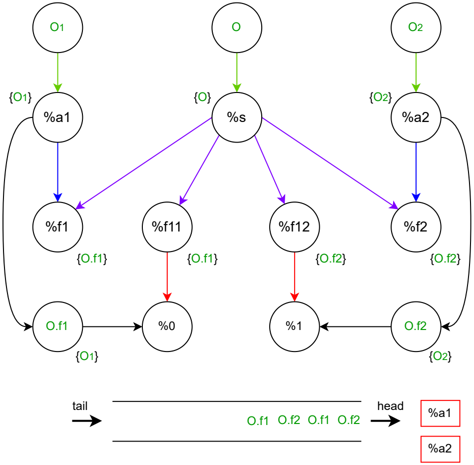
Field-Sensitive Andersen's Pointer Analysis



Algorithm 25: 1 Anderson's Pointer Analysis

```
Input : G =< V,E >: Constraint Graph
        V: a set of nodes in graph
        E: a set of edges in graph
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

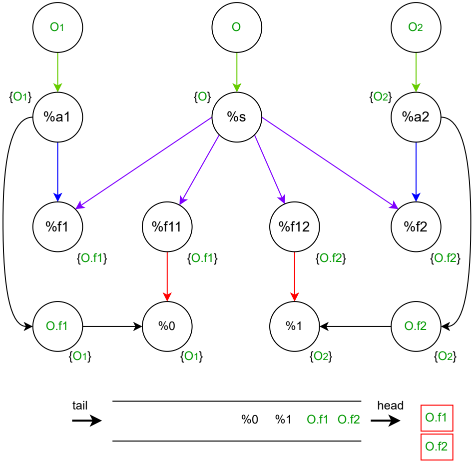
Field-Sensitive Andersen's Pointer Analysis



Algorithm 26: 1 Anderson's Pointer Analysis

```
Input : G =< V,E >: Constraint Graph
        V: a set of nodes in graph
        E: a set of edges in graph
WorkList := an empty 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 ∈ E do                      // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};                  // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                            // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Field-Sensitive Andersen’s Pointer Analysis

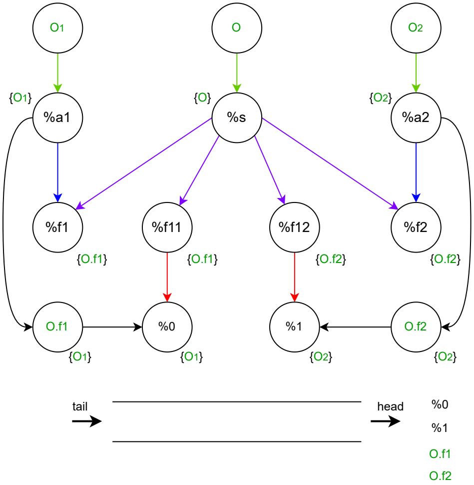


Algorithm 27: 1 Anderson’s Pointer Analysis

Input : $G = < V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};           // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Field-Sensitive Andersen's Pointer Analysis



Algorithm 28: 1 Anderson's Pointer Analysis

Input : $G = < V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Constraint solving Algorithm for Andersen's Analysis

- 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

```
::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

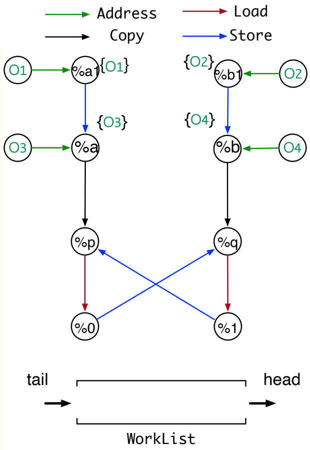
```
::getStoreInEdge()                  // get incoming store edges of the node
::getStoreOutEdge()                 //get outgoing store edges of the node
::getDirectOutEdge()                // get outgoing copy edges of the node
::getDirectInEdge()                 // get incoming copy edges of the node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

https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVF-CPP-API#worklist-operations
https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVF-CPP-API#points-to-set-operations
https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVF-CPP-API#alias-relations
https://github.com/SVF-tools/Software-Security-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 {
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
}
```



Algorithm 29: 1 Anderson's Pointer Analysis

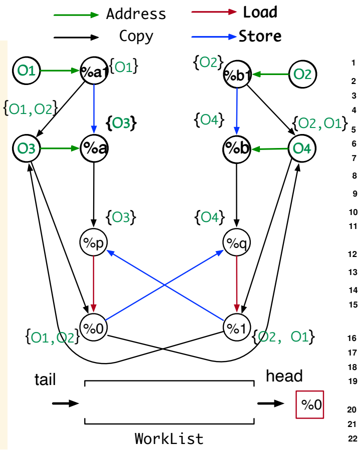
Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                 // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                       // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        if pts(x) changed then
            pushIntoWorklist(x);
```

Andersen's Pointer Analysis

Constraint graph after the while loop worklist solving

```
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
}
```



Algorithm 30: 1 Anderson's Pointer Analysis

Input : $G =< V, E >$: Constraint Graph
V: a set of nodes in graph
E: a set of edges in graph

```
WorkList := an empty 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 ∈ E do                // Store rule
            if q --Copy--> o ∉ E then
                E := E ∪ {q --Copy--> o};            // Add copy edge
                pushIntoWorklist(q);
        foreach p --Load--> r ∈ E 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);
    foreach p --Gep--> x ∈ E do                      // Gep rule
        foreach o ∈ pts(p) do
            pts(x) := pts(x) ∪ {o.fld};
        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

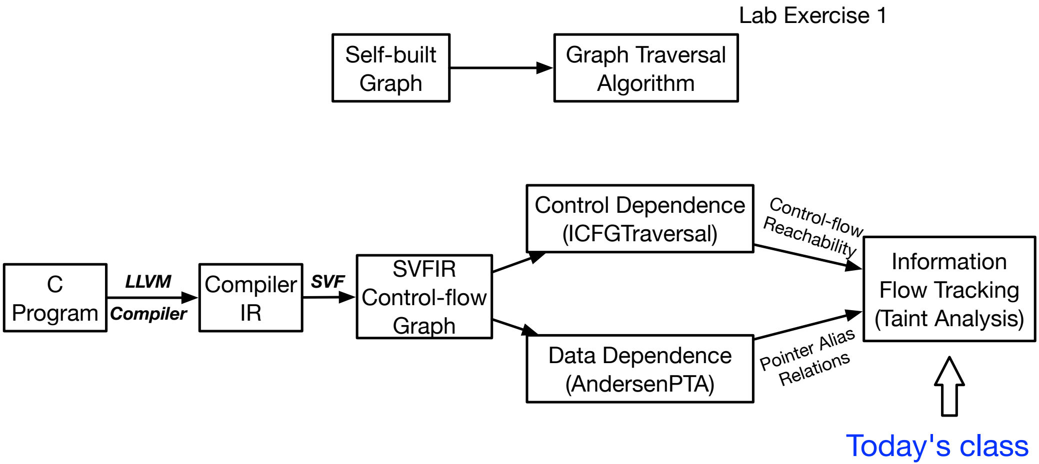
(Week 3)

Yulei Sui

School of Computer Science and Engineering

University of New South Wales, Australia

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.

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.

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** $\mathbf{v_{src}@s_{src}}$ is a tuple consisting of a variable $\mathbf{v_{src}}$ and a statement $\mathbf{s_{src}}$ where $\mathbf{v_{src}}$ is defined.
- A **sink** $\mathbf{v_{snk}@s_{snk}}$ 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?

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** $\mathbf{v_{src}@s_{src}}$ is a tuple consisting of a variable $\mathbf{v_{src}}$ and a statement $\mathbf{s_{src}}$ where $\mathbf{v_{src}}$ is defined.
- A **sink** $\mathbf{v_{snk}@s_{snk}}$ 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`.
- Given a **tainted** source $\mathbf{v_{src}@s_{src}}$, we say that a sink $\mathbf{v_{snk}@s_{snk}}$ is also **tainted** if both of the following two conditions satisfy:
  - (1) $\mathbf{s_{src}}$ reaches $\mathbf{s_{snk}}$ on the ICFG (**reachability**), and
  - (2) $\mathbf{v_{src}}$ is aliased with $\mathbf{v_{snk}}$, i.e., $pts(v_{src}) \cap pts(v_{snk}) \neq \varnothing$ (**solveWorklist**)

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 $\mathbf{v_{src}}@\mathbf{s_{src}}$ 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.

Configuring Sources and Sinks for Taint Analysis

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

- Given a source $\mathbf{v_{src}}$@$\mathbf{s_{src}}$ 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 $\mathbf{s_{snk}}$.

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- 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 $\mathbf{s_{snk}}$.