

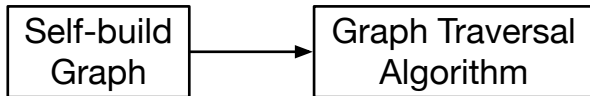
Data-Dependence

Yulei Sui

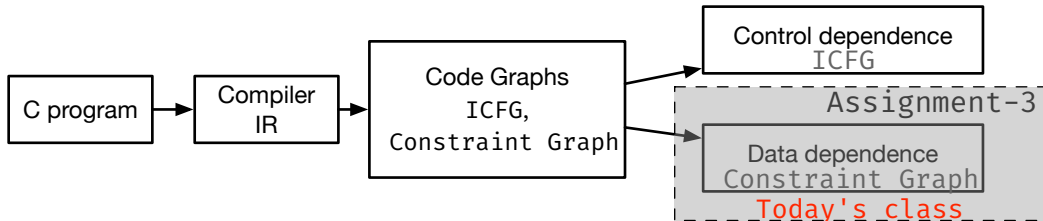
University of Technology Sydney, Australia

Today's class

Assignment-1



Assignment-2



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 on LLVM’s SSA form.**
 - For example, def-use for **%a1** from Instruction-1 to Instruction-2.
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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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- **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**.
 - **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: $\text{pts}(p) = \text{pts}(q) = \{a\}$

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- 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., $\text{pts}(p) \cap \text{pts}(q)$ is not empty) then p and q are aliases. The dereferences 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).

Pointer analysis

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y has the same value as x since `*p` and `*q` both refer to a.

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 - `p = &a; q = p; *p = x; y = *q;`
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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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 - 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 of all calling contexts when analysing a program method

Path-insensitive analysis:

- Merges all incoming path information at the joint point 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

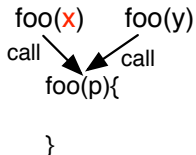
Assume **x** is a tainted value

$p = \mathbf{x}$

$p = y$

flow-sensitivity

at which
program point
 p is tainted?



context-sensitivity

under which
calling context
 p is tainted?

if(cond)

$p = \mathbf{x}$

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 Andersen's 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 (PAGNode in SVF)

¹ Andersen, L. O. (1994). Program analysis and specialization for the C programming language (Doctoral dissertation, University of Copenhagen).

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

- A `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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Andersen's Pointer Analysis

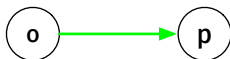
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Constraint Type	C code	LLVM IR	Constraint rules
Address:	<code>p = &o</code>	<code>%p = alloca //o</code>	$\text{pts}(p) = \text{pts}(p) \cup \{o\}$
Copy:	<code>q = p</code>	<code>%q = bitcast %p</code>	$\text{pts}(q) = \text{pts}(q) \cup \text{pts}(p)$
Load:	<code>q = *p</code>	<code>%q = load %p</code>	$\forall o \in \text{pts}(p): \text{pts}(q) = \text{pts}(o) \cup \text{pts}(q)$
Store:	<code>*p = q</code>	<code>store %q, %p</code>	$\forall o \in \text{pts}(p): \text{pts}(o) = \text{pts}(q) \cup \text{pts}(o)$

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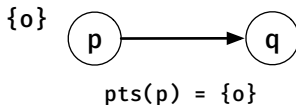
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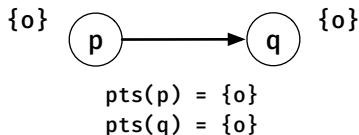
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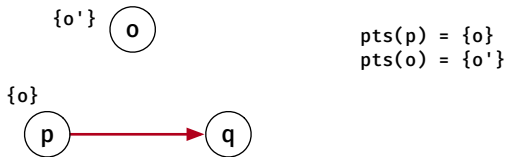
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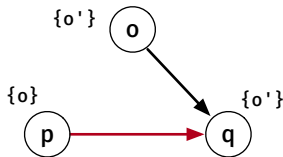
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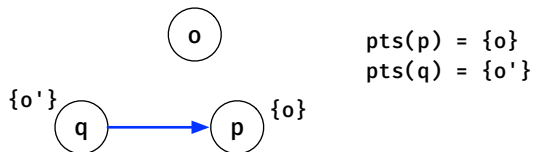
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$\text{pts}(p) = \{o\}$
 $\text{pts}(o) = \{o'\}$
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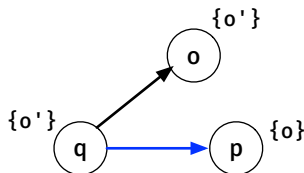
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Compile C Code to LLVM IR

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

compile to

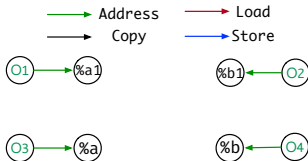


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define i32 @main() #0 {  
entry:  
    %a1 = alloca i8, align 1      // O1  
    %b1 = alloca i8, align 1      // O2  
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    store i8* %a1, i8** %a, align 8  
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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

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

Construct a Constraint Graph from LLVM IR

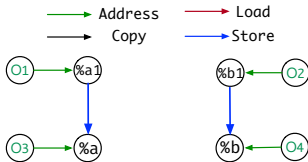
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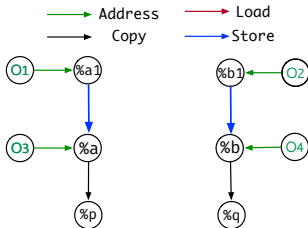
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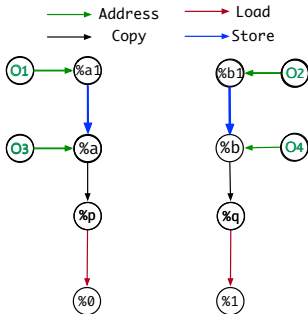
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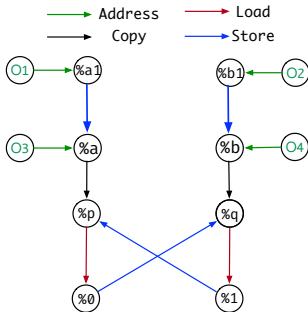
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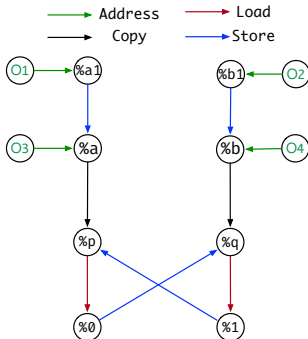


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Andersen's Pointer Analysis

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  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  
}
```



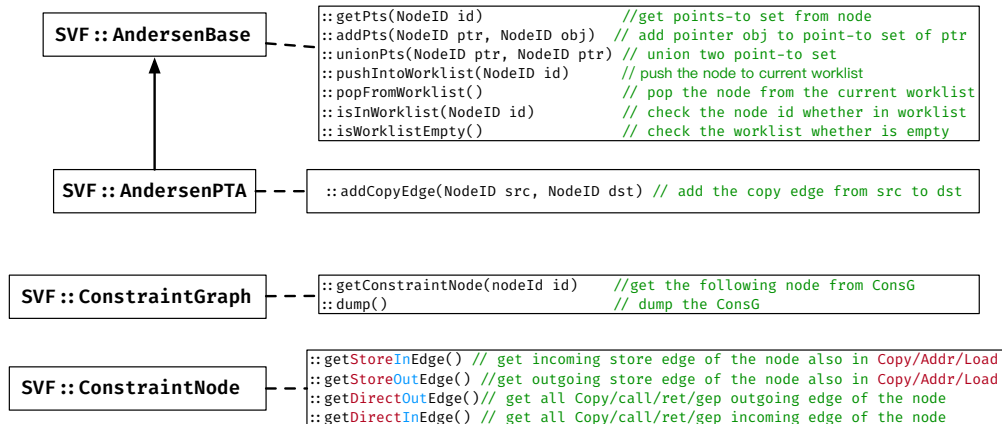
```
G = < V, E > // Constraint Graph  
V: a set of nodes in graph  
E: a set of edges in graph  
WorkList: a vector of nodes  
1 foreach address p = &o do // Address rule  
2   pts(p) = {o}  
3   pushIntoWorklist(p)  
4 while WorkList ≠ ∅ do  
5   p ← popFromWorklist()  
6   foreach o ∈ pts(p) do  
7     foreach store *p = q do // Store rule  
8       if q → o ∉ E then  
9         E ← E ∪ {q → o} // Add copy edge  
10        pushIntoWorklist(q)  
11      foreach load r = *p do // Load rule  
12        if o → r ∉ E then  
13          E ← E ∪ {o → r} // Add copy edge  
14          pushIntoWorklist(o)  
15    foreach p → x ∈ E do // Copy rule  
16      pts(x) ← pts(x) ∪ pts(p)  
17      if pts(x) changed then  
18        pushIntoWorklist(x)
```

Andersen's Pointer Analysis

Constraint solving Algorithm

- A worklist holds a set 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



<https://github.com/SVF-tools/SVF-Teaching/wiki/SVF-CPP-API#worklist-operations>

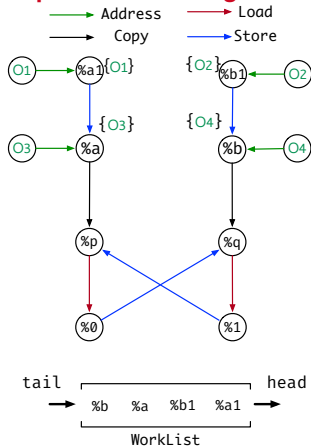
<https://github.com/SVF-tools/SVF-Teaching/wiki/SVF-CPP-API#points-to-set-operations>

<https://github.com/SVF-tools/SVF-Teaching/wiki/SVF-CPP-API#constraintgraph-constraintnode-and-constrainededge>

Andersen's Pointer Analysis

Constraint graph before the while loop worklist solving

```
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  
}
```

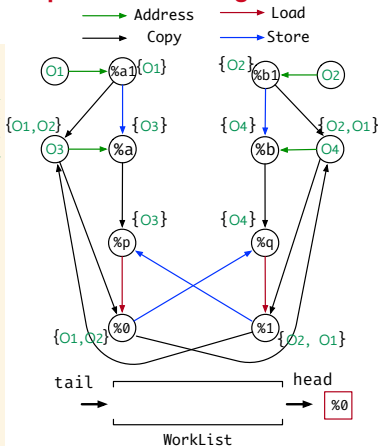


```
G = < V, E > // Constraint Graph  
V: a set of nodes in graph  
E: a set of edges in graph  
WorkList: a vector of nodes  
1 foreach address p = &o do // Address rule  
2   pts(p) = {o}  
3   pushIntoWorklist(p)  
4 while WorkList ≠ ∅ do  
5   p ← popFromWorklist()  
6   foreach o ∈ pts(p) do  
7     foreach store *p = q do // Store rule  
8       if q → o ∉ E then  
9         E ← E ∪ {q → o} // Add copy edge  
10        pushIntoWorklist(q)  
11      foreach load r = *p do // Load rule  
12        if o → r ∉ E then  
13          E ← E ∪ {o → r} // Add copy edge  
14          pushIntoWorklist(o)  
15      foreach p → x ∈ E do // Copy rule  
16        pts(x) ← pts(x) ∪ pts(p)  
17        if pts(x) changed then  
18          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  
  %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  
}
```



$G = \langle V, E \rangle$ // Constraint Graph

V: a set of nodes in graph

E: a set of edges in graph

WorkList: a vector of nodes

```
1 foreach address p = &o do // Address rule  
2   pts(p) = {o}  
3   pushIntoWorklist(p)  
4 while WorkList  $\neq \emptyset$  do  
5   p  $\leftarrow$  popFromWorklist()  
6   foreach o  $\in$  pts(p) do  
7     foreach store *p = q do // Store rule  
8       if q  $\rightarrow$  o  $\notin E$  then  
9         E  $\leftarrow E \cup \{q \rightarrow o\}$  // Add copy edge  
10        pushIntoWorklist(q)  
11      foreach load r = *p do // Load rule  
12        if o  $\rightarrow$  r  $\notin E$  then  
13          E  $\leftarrow E \cup \{o \rightarrow r\}$  // Add copy edge  
14          pushIntoWorklist(o)  
15      foreach p  $\rightarrow$  x  $\in E$  do // Copy rule  
16        pts(x)  $\leftarrow$  pts(x)  $\cup$  pts(p)  
17        if pts(x) changed then  
18          pushIntoWorklist(x)
```

What's next?

- (1) Understand data-dependence in today's slides
- (2) Implement Andersen's pointer analysis, i.e., Task in Assignment 3
 - Refer to 'Assignment-3.pdf' on Canvas to know more about Assignment 3.