LLVM Compiler and Its Intermediate Representation

(Week 2)

Yulei Sui

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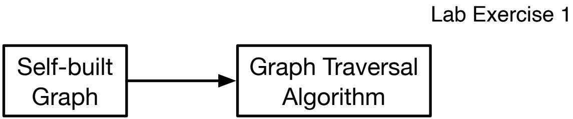
Where We Are Now and Today’s Class



Lab Exercise 1

Self-built Graph

Graph Traversal Algorithm

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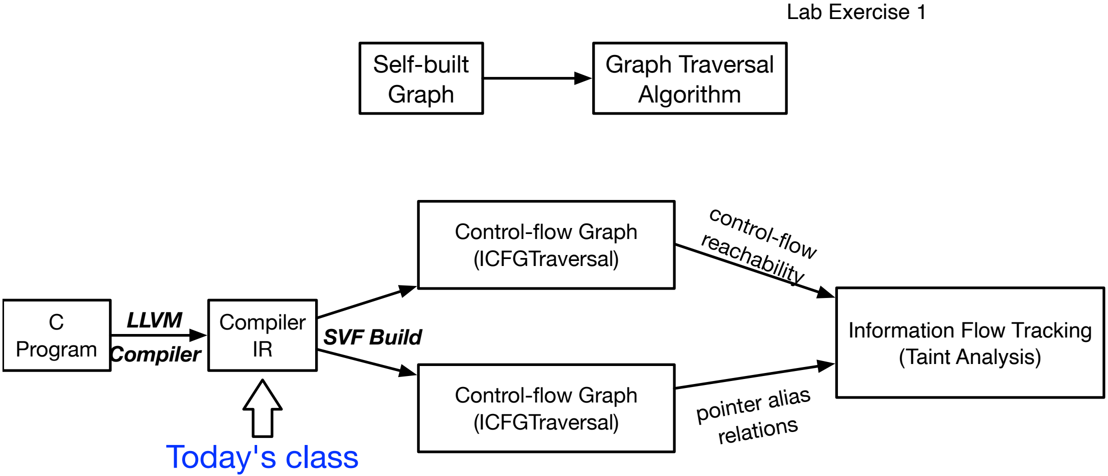

Lab Exercise 1
Self-built Graph
Graph Traversal Algorithm
C Program
LLVM Compiler
Compiler IR
SVF Build
Control-flow Graph (ICFGTraversal)
Control-flow Graph (ICFGTraversal)
control-flow reachability
pointer alias relations
Information Flow Tracking (Taint Analysis)
Today's class

What is LLVM ?

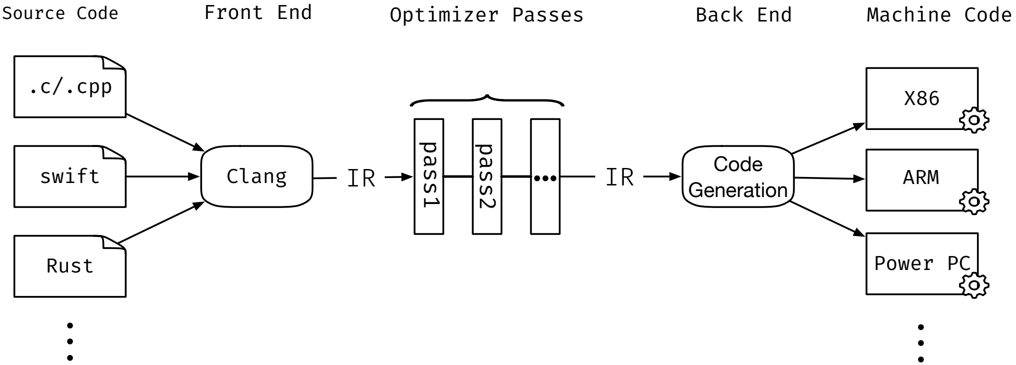
LLVM compiler infrastructure is a collection of compiler and tool-chain technologies.

- Originally started in 2000 from UIUC. An **open-source project** and supported and contributed by a range of high-tech companies such as Apple, Google, Intel, ARM.
- Modern compiler infrastructure can be used to develop a **front-end for any programming language** and a **back-end for any instruction set architecture.**
- A set of **reusable software modules** to quickly design your own compiler or software tool chains.
- **Language-independent intermediate representation (IR)** used for a variety of purposes, such as compiler optimizations, static analysis and bug detection.
- **More information on LLVM's website:** `https://llvm.org/`

Why Learn LLVM or Learn Compilers in General?

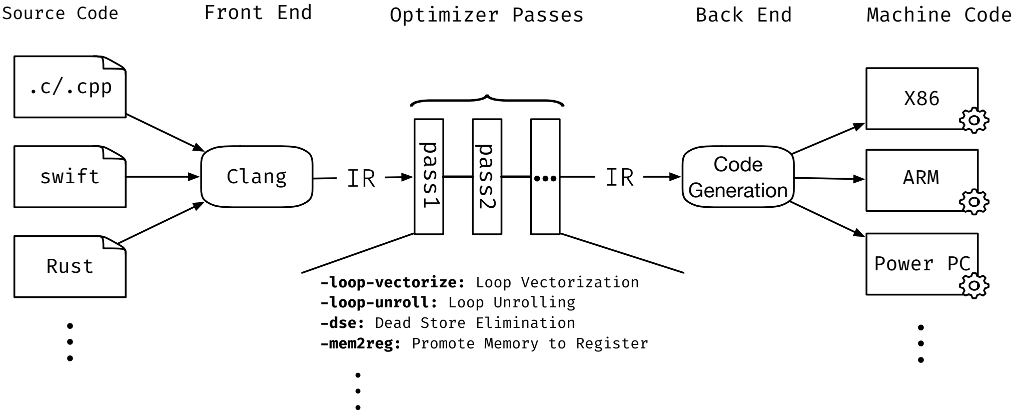
- An essential part of the standard curriculum in computer science.
- One of the most complex systems required for building virtually all other software.
- A perfect base framework to build your own tools for code analysis and verification
- Sharpen your software design and implementation skills.
- Widely used by many major software companies. In-demand skills and competitive salaries in job market.

LLVM’s Architecture



*IR: **Human-readable LLVM IR (.ll files) or dense ’bitcode’ binary representation (.bc files)**

LLVM's Architecture



-loop-vectorize: Loop Vectorization
-loop-unroll: Loop Unrolling
-dse: Dead Store Elimination
-mem2reg: Promote Memory to Register

*IR: **Human-readable LLVM IR (.ll files) or dense 'bitcode' binary representation (.bc files)**

LLVM Intermediate Representation (IR)

LLVM IR is LLVM's code representation which is generated by its front-end `clang` **when compiling a program** (`https://llvm.org/docs/LangRef.html`)

- **Language independent.** Not machine code, but one step just above assembly

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- **3-address code style** in **static single assignment (SSA)** form

LLVM Intermediate Representation (IR)

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- **Language independent.** Not machine code, but one step just above assembly
- **Clear lexical scope**, such as modules, functions, basic blocks, and instructions
- **3-address code style** in **static single assignment (SSA)** form
  - Variables are strongly typed
  - Global variable (symbol starting with '@')
  - Stack/register variable (symbol starting with '%')
  - Three addresses and one operator.
    - For example, 'a = b op c', where 'a', 'b', 'c' are either programmer defined variables (e.g., heap, global or stack), constants or compiler-generated temporary names. 'op' stands for an operation which is applied on 'a' and 'b'.

Compiling a C Program to Its LLVM IR

Clang/LLVM compiler options

- Compile a C program ‘swap.c‘ to a human readable IR ‘swap.ll‘.
  - `clang -c -S -emit-llvm swap.c -o swap.ll`
- Compilation without optimisation.
  - `clang -c -S -Xclang -disable-O0-optnone -emit-llvm swap.c -o swap.ll`
- Keep the variable names.
  - `clang -c -S -fno-discard-value-names -Xclang -disable-O0-optnone -emit-llvm swap.c -o swap.ll`
- Convert the LLVM IR to more compact SSA form for later static analysis.
  - `opt -S -p=mem2reg swap.ll -o swap.ll`

Compiling a C Program to Its LLVM IR

An example

```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

C code to LLVM IR

An example

```c
void swap(char **p, char **q){
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```
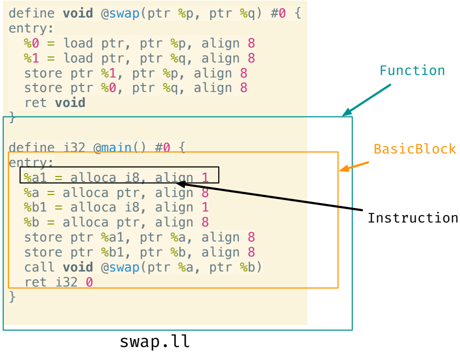

swap.c

Compile ⇨



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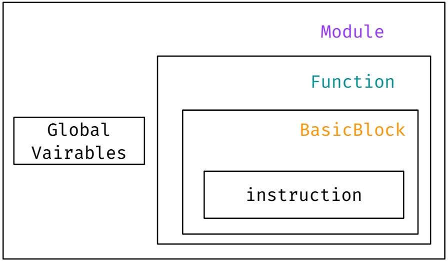
swap.ll

LLVM Intermediate Representation (IR)

Structure Organization



LLVM-IR Scopes

Module contains Functions and Global Variables
- Whole module is the unit of translation, analysis and optimization.

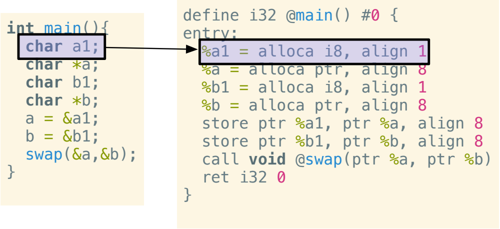
Function contains BasicBlocks and Arguments, which correspond to functions.

BasicBlock contains list of instructions.
- Each block is contiguous chunk of instructions

Instruction is opcode + vector of operands in '3-address' style
- All operands have types
- Instruction result is typed

LLVM Intermediate Representation (IR)

LLVM Instructions



```
int main(){
  char a1;
  char *a;
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  a = &a1;
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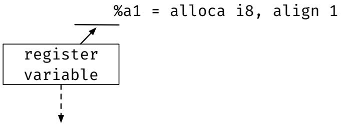


```
%a1 = alloca i8, align 1
```

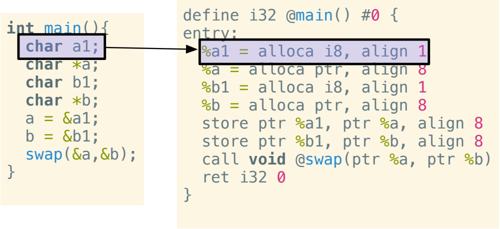
register variable

```
identifiers:
    [% / @] [-a-zA-Z$._][-a-zA-Z$._0-9]

      - % is for local variable
      - @ is for global
      - temporary variables are numbered
```

LLVM Intermediate Representation (IR)

LLVM Instructions



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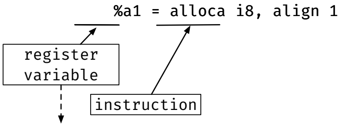

%a1 = alloca i8, align 1

register variable

instruction

identifiers:

[% / @] [-a-zA-Z$._][-a-zA-Z$._0-9]

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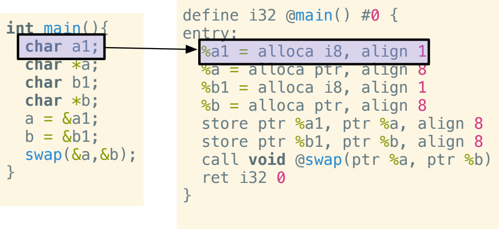
alloca: instruction allocates i8 (sizeof) bytes of memory on runtime stack

LLVM Intermediate Representation (IR)

LLVM Instructions



```
int main(){
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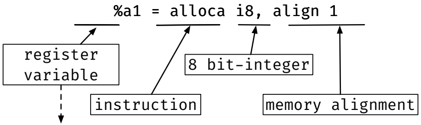

```
%a1 = alloca i8, align 1
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identifiers:

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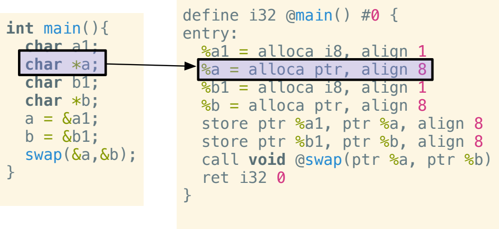
alloca: instruction allocates i8 (sizeof) bytes of memory on runtime stack

align: indicates the memory operation should be aligned to 1 byte

LLVM Intermediate Representation (IR)

LLVM Instructions



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  store ptr %a1, ptr %a, align 8
  store ptr %b1, ptr %b, align 8
  call void @swap(ptr %a, ptr %b)
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}
```

`%a = alloca ptr, align 8`

↓

`allocate 8-bit integer pointer for a`

LLVM Intermediate Representation (IR)

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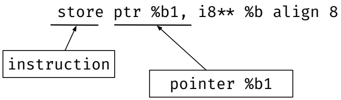

store ptr %b1, i8** %b align 8

store the pointer %b1 to the memory location that %b points to

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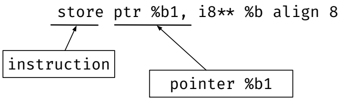

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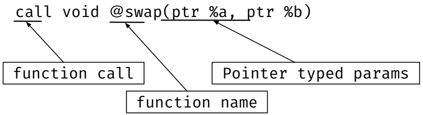

call void @swap(ptr %a, ptr %b)

function call

function name

Pointer typed params

call instruction will be used to
build control flow.

LLVM Documentations

- LLVM Language Reference Manual https://llvm.org/docs/LangRef.html
- LLVM Programmer's Manual https://llvm.org/docs/ProgrammersManual.html
- Writing an LLVM Pass http://llvm.org/docs/WritingAnLLVMPass.html
- Tutorials for Clang/LLVM https://freecompilercamp.org/clang-llvm-landing
- LLVM Tutorial IEEE SecDev 2020 https://cs.rochester.edu/u/ejohns48/secdev19/secdev20-llvm-tutorial-version4_copy.pdf

SVFIR and Graph Representation of Code

(Week 2)

Yulei Sui

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SVF : Static Value-Flow Analysis Framework for Source Code

A scalable, precise and on-demand interprocedural program dependence analysis framework for both sequential and multithreaded programs.

- The SVF project
  - **Publicly available** since early 2015 and actively maintained: `http://svf-tools.github.io/SVF`.
  - Implemented on top of LLVM compiler (the latest version 12.0.0) with over 100 KLOC C/C++ code and **700+ stars with 40+ contributors** and over 1K commits on Github.
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- Value-Flow Analysis: resolves **both control and data dependence**.
  - Does the information generated at program point A flow to another program point B along some execution paths?
  - Can function F be called either directly or indirectly from some other function F'?
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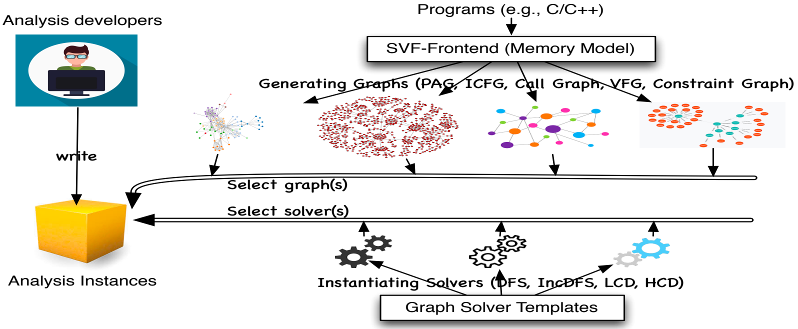
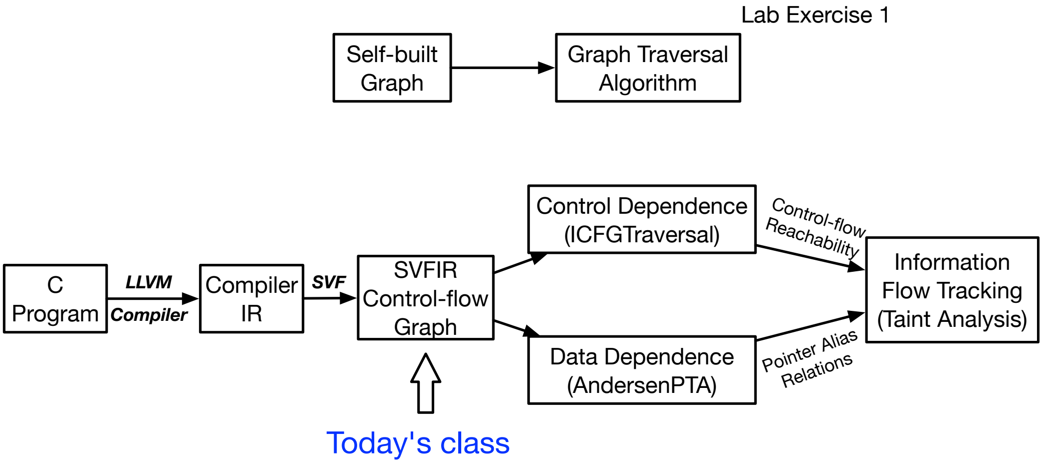
- Key features of SVF
  - **Sparse**: compute and maintain the data-flow facts where necessary
  - **Selective** : support mixed analyses for precision and efficiency trade-offs.
  - **On-demand** : reason about program parts based on user queries.

SVF: Design Principle


Programs (e.g., C/C++)
Analysis developers
SVF-Frontend (Memory Model)
Generating Graphs (PAG, ICFG, Call Graph, VFG, Constraint Graph)
write
Select graph(s)
Select solver(s)
Analysis Instances
Instantiating Solvers (DFS, IncDFS, LCD, HCD)
Graph Solver Templates

- Serving as an open-source foundation for building practical static source code analysis
  - Bridge the gap between research and engineering
  - Minimize the efforts of implementing sophisticated analysis (extendable, reusable, and robust via layers of abstractions)
  - Support developing different analysis variants (flow-, context-, heap-, field-sensitive analysis) in a sparse and on-demand manner.
- Client applications:
  - Static bug detection (e.g., memory leaks, null dereferences, use-after-frees and data-races)
  - Accelerate dynamic analysis (e.g., Google's Sanitizers and AFL fuzzing)

Today’s class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SVFIR Control-flow Graph
Control Dependence (ICFGTraversal)
Data Dependence (AndersenPTA)
Control-flow Reachability
Pointer Alias Relations
Information Flow Tracking (Taint Analysis)
Today's class

SVF IR and Why?

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- Lightweight in terms of fewer types of program variables and statements.

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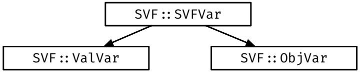
- SVFVar: program variables



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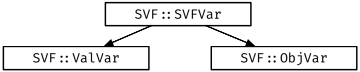
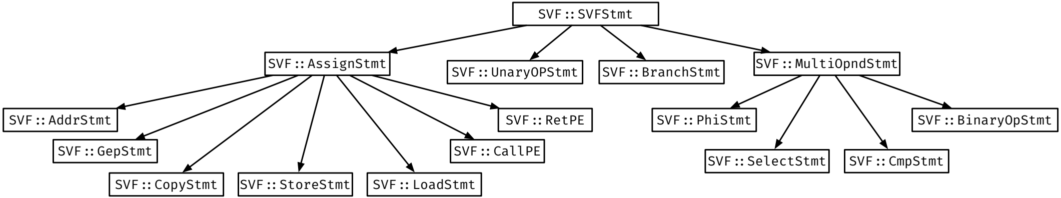


- SVFStmt: program statements



SVF Program Variables (SVFVar)

- An SVFVar represent either a top-level variable ($\mathbb{P}$) or a memory object variable ($\mathbb{O}$)
- Each SVFVar has a unique identifier (ID)
- SVFVar ID 0-4 are reserved

Program Variables	Domain	Meanings
SVFVar	$\mathbb{V} = \mathbb{P} \cup \mathbb{O}$	Program Variables
ValVar	$\mathbb{P}$	Top-level variables (scalars and pointers)
ObjVar	$\mathbb{O} = \mathbb{S} \cup \mathbb{G} \cup \mathbb{H} \cup \mathbb{C}$	Memory Objects (stack, global[1], heap and constant data)
FIObjVar	$o \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H})$	A single (base) memory object
GepObjVar	$o_i \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H}) \times \mathbb{P}$	*i*-th subfield/element of an (aggregate) object
ConstantData	$\mathbb{C}$	Constant data (e.g., numbers and strings)
Program Statement	$l \in \mathbb{L}$	Statements labels

SVF Program Statements (SVFStmt)

An SVFStmt is one of the following program statements representing the relations between SVFVars.

SVFStmt	LLVM-Like form	C-Like form	Operand types
AddrStmt	$\%ptr = alloca_o$	$p = alloc$	$\mathbb{P} \times \mathbb{O}$
ConsStmt	$\%ptr = constantData$	$p = c$	$\mathbb{P} \times \mathbb{C}$
CopyStmt	$\%p = bitcast\ \%q$	$p = q$	$\mathbb{P} \times \mathbb{P}$
LoadStmt	$\%p = load\ \%q$	$p = *q$	$\mathbb{P} \times \mathbb{P}$
StoreStmt	$store\ \%p, \%q$	$*p = q$	$\mathbb{P} \times \mathbb{P}$
GepStmt	$\%p = getelementptr\ \%q, \%i$	$p = \&(q \to i)$ or $p = \&q[i]$	$\mathbb{P} \times \mathbb{P} \times \mathbb{P}$
PhiStmt	$\%p = phi\ [\ l_1, \%q_1\ ], [\ l_2, \%q_2\ ]$	$p = phi(l_1 : q_1,\ l_2 : q_2)$	$\mathbb{P} \times (\mathbb{L} \to \mathbb{P}^2)$
BranchStmt	$br\ i1\ \%p, label\ \%l_1, label\ \%l_2$	$if\ (p)\ l_1$ else l_2	$\mathbb{P} \times \mathbb{L}^2$
UnaryOPStmt	$p = \neg q$	$p = \neg q$	$\mathbb{P} \times \mathbb{P}$
BinaryOPStmt/CmpStmt	$r = \otimes\ p, q$	$r = p \otimes q$	$\mathbb{P} \times \mathbb{P} \times \mathbb{P}$
	$\%r = call\ f(\ldots\%q_i\ldots)$ $f(\ldots\%p_i\ldots)\{\ \ldots\ ret\ \%z\}$	$r = f(\ldots, q_i, \ldots)$ $f(\ldots, p_i, \ldots)\{\ldots\ return\ z\}$	
CallPE	$\%p_i = \%q_i \quad (1 < i < n)$	$p_i = q_i \quad (1 < i < n)$	$(\mathbb{P} \times \mathbb{P})^n$
RetPE	$\%r = \%z$	$r = z$	$\mathbb{P} \times \mathbb{P}$

$\otimes \in \{+, -, *, /, \%, <<, >>, <, >, \&, \&\&, <=, >=, \equiv, \sim, |, \wedge\}$

SVF Program Statements (SVFStmt)

- SVFStmt follows the LLVM's SSA form for top-level variables
  - Top-level variables ($\mathbb{P}$) can only be defined once
  - Memory objects (i.e., $\mathbb{S} \cup \mathbb{G} \cup \mathbb{H}$ excluding constant data) can only be modified/read through top-level pointers at `StoreStmt` and `LoadStmt`.
  - For example, `p = &a; *p = r;` The value of `a` can only be modified/read via dereferencing `p`.
- A ConstantData ($\mathbb{C}$) object needs first to be assigned to a temp top-level variable and can only be read through that top-level variable in any `SVFStmt`.
  - For example, `*p = 3;` $\Rightarrow$ `t = 3; *p = t;`
- `CallPE` represents the parameter passing from an actual parameter at a callsite to a formal parameter of a callee function.
- `RetPE` represents the parameter passing from a function return to a callsite return variable.

Graph Representation of Code

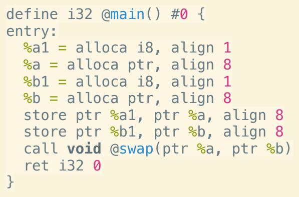
- What is a graph representation of code (code graph)?
  - Put the LLVM IR or SVF IR on a graph representation.
  - Represent a program's control-flow (i.e., execution order) and/or data-flow (variable definition and use relations) using nodes and edges of a graph.

Graph Representation of Code

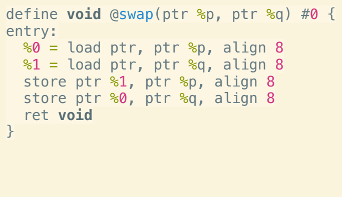
- What is a graph representation of code (code graph)?
    - Put the LLVM IR or SVF IR on a graph representation.
    - Represent a program's control-flow (i.e., execution order) and/or data-flow (variable definition and use relations) using nodes and edges of a graph.
- Why a graph representation?
    - Abstracting code from low-level complicated instructions
    - Applying general graph algorithms
    - Easy to maintain and extend

Call Graph

- Program calling relations between methods
- Whether a method A can call method B directly or transitively.



```
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
}
```



```
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
}
```

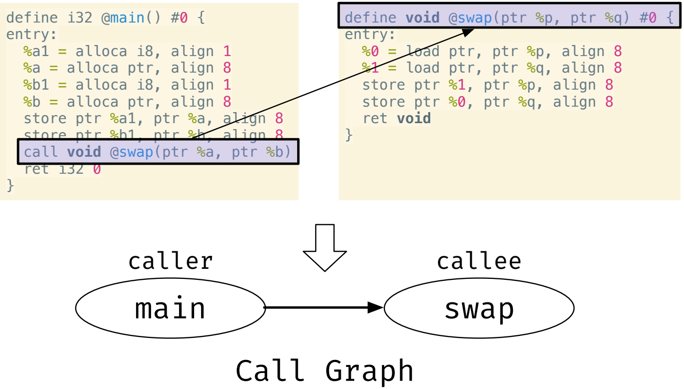
caller
main
callee
swap

Call Graph

https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#3-call-graph

Call Graph

- Program calling relations between methods
- Whether a method A can call method B directly or transitively.



```
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
}
```

```
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
}
```

Call Graph

https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#3-call-graph

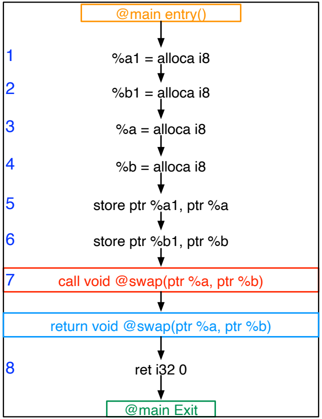
1. Each node represents a program method
2. Each edge represents a calling relation between two program methods

Control Flow Graph

Program execution order **between two LLVM instructions (SVFStmts)**.

- Intra-procedural control-flow graph: control-flow within a program method.
- Inter-procedural control-flow graph: control-flow across program methods.

Intra-procedural Control Flow Graph



@main entry()

1 %a1 = alloca i8

2 %b1 = alloca i8

3 %a = alloca i8

4 %b = alloca i8

5 store ptr %a1, ptr %a

6 store ptr %b1, ptr %b

7 call void @swap(ptr %a, ptr %b)

return void @swap(ptr %a, ptr %b)

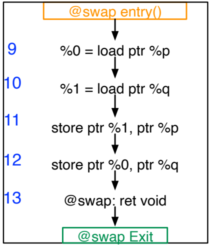
8 ret i32 0

@main Exit

Program execution order between instructions

- Each node represents an instruction or a statement

- Each edge represents a control-flow dependence between two nodes



@swap entry()

9 %0 = load ptr %p

10 %1 = load ptr %q

11 store ptr %1, ptr %p

12 store ptr %0, ptr %q

13 @swap: ret void

@swap Exit

■ IntraBlockNode

■ FunEntryBlockNode

■ FunExitBlockNode

■ RetBlockNode

■ CallBlockNode

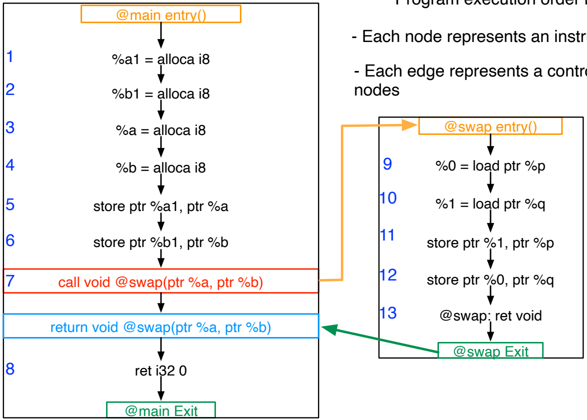
https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#4-interprocedural-control-flow-graph

Inter-procedural Control Flow Graph (ICFG)

Program execution order between instructions

- Each node represents an instruction or a statement

- Each edge represents a control-flow dependence between two nodes



■ IntraBlockNode
🟧 FunEntryBlockNode
🟩 FunExitBlockNode
🟦 RetBlockNode
🟥 CallBlockNode

https://github.com/svf-tools/SVF/wiki/Analyze-a-Simple-C-Program#4-interprocedural-control-flow-graph

SVF IR Example

https://github.com/SVF-tools/Software-Security-Analysis/wiki/svfir

```c
int foo(int b){
    return b;
}
int main(){
    int a = foo(0);
}
```

SVF IR Example

https://github.com/SVF-tools/Software-Security-Analysis/wiki/svfir

```c
int foo(int b){
    return b;
}
int main(){
    int a = foo(0);
}
```

```llvm
define i32 @foo(i32 %b) {
entry:
  %b.addr = alloca i32
  store i32 %b, ptr %b.addr,
  %0 = load i32, ptr %b.addr,
  ret i32 %0
}
define i32 @main() {
  %a = alloca i32
  %call = call i32 @foo(i32 0)
  store i32 %call, i32* %a
  ret i32 0
}
```

SVF IR Example

https://github.com/SVF-tools/Software-Security-Analysis/wiki/svfir

```c
int foo(int b){
    return b;
}
int main(){
    int a = foo(0);
}
```

```
define i32 @foo(i32 %b) {
entry:
  %b.addr = alloca i32
  store i32 %b, ptr %b.addr,
  %0 = load i32, ptr %b.addr,
  ret i32 %0
}
define i32 @main() {
  %a = alloca i32
  %call = call i32 @foo(i32 0)
  store i32 %call, i32* %a
  ret i32 0
}
```

Variables introduced by SVF
(created internally)

SVFVar	Meaning
DummyValVar ID: 0	reserved
DummyValVar ID: 1	reserved
DummyObjVar ID: 2	reserved
DummyObjVar ID: 3	reserved
ValVar ID: 4	foo
FIObjVar ID: 5	foo
RetPN ID: 6	ret of foo
ValVar ID: 13	main
FIObjVar ID: 14	main
RetPN ID: 15	ret of main

SVF IR Example

https://github.com/SVF-tools/Software-Security-Analysis/wiki/svfir

```c
int foo(int b){
    return b;
}
int main(){
    int a = foo(0);
}
```

```llvm
define i32 @foo(i32 %b) {
entry:
  %b.addr = alloca i32
  store i32 %b, ptr %b.addr,
  %0 = load i32, ptr %b.addr,
  ret i32 %0
}
define i32 @main() {
  %a = alloca i32
  %call = call i32 @foo(i32 0)
  store i32 %call, i32* %a
  ret i32 0
}
```

Variables introduced by SVF
(created internally)

SVFVar	Meaning
DummyValVar ID: 0	reserved
DummyValVar ID: 1	reserved
DummyObjVar ID: 2	reserved
DummyObjVar ID: 3	reserved
ValVar ID: 4	foo
FIObjVar ID: 5	foo
RetPN ID: 6	ret of foo
ValVar ID: 13	main
FIObjVar ID: 14	main
RetPN ID: 15	ret of main

Variables introduced by LLVM
(created by LLVM Values)

SVFVar	LLVM Value
ValVar ID: 7	`i32 %b { 0th arg foo }`
ValVar ID: 8	`%b.addr = alloca i32`
FIObjVar ID: 9	`%b.addr = alloca i32`
ValVar ID: 11	`%0 = load i32, ptr %b.addr`
ValVar ID: 16	`%a = alloca i32`
FIObjVar ID: 17	`%a = alloca i32`
ValVar ID: 18	`%call = call i32 @foo(i32 0)`
ValVar ID: 19	`i32 0 { constant data }`
FIObjVar ID: 20	`i32 0 { constant data }`
ValVar ID: 21	`store i32 %call, ptr %a`
ValVar ID: 22	`ret i32 0`

ICFG and SVFStmt Example[2]

```
define i32 @foo(i32 %b) {
entry:
  %b.addr = alloca i32
  store i32 %b, ptr %b.addr,
  %0 = load i32, ptr %b.addr,
  ret i32 %0
}

define i32 @main() {
  %a = alloca i32
  %call = call i32 @foo(i32 0)
  store i32 %call, i32* %a
  ret i32 0
}
```

ICFGNode	SVFStmt	LLVM Value
GlobalICFGNode0	CopyStmt: Var1 ← Var0	`ptr null (constant data)`
	AddrStmt: Var19 ← Var20	`i32 0 (constant data)`
	AddrStmt: Var4 ← Var5	`foo`
	AddrStmt: Var13 ← Var14	`main`
FunEntryICFGNode1	fun: foo	
IntraICFGNode2	AddrStmt: Var8 ← Var9	`%b.addr = alloca i32`
IntraICFGNode3	StoreStmt Var8 ← Var7	`store i32 %b, ptr %b.addr`
IntraICFGNode4	LoadStmt: Var11 ← Var8	`%0 = load i32, ptr %b.addr`
IntraICFGNode5	fun:foo	`ret i32 %0`
FunExitICFGNode6	PhiStmt: [Var6 ← ([Var11, ICFGNode5],)]	`ret i32 %0`
FunEntryICFGNode7	fun: main	
IntraICFGNode8	AddrStmt: [Var16 ← Var17]	`%a = alloca i32`
CallICFGNode9	CallPE: [Var7 ← Var19]	`%call = call i32 @foo(i32 0)`
RetICFGNode10	RetPE: [Var18 ← Var6]	`%call = call i32 @foo(i32 0)`
IntraICFGNode11	StoreStmt: [Var16 ← Var18]	`store i32 %call, ptr %a`
IntraICFGNode12	fun: main	`ret i32 0`
FunExitICFGNode13	PhiStmt: [Var15 ← ([Var19, ICFGNode12],)]	`ret i32 0`

What's next?

- (1) Compile two C programs (`SVFIR/src/example.c` and `SVFIR/src/swap.c`) into their LLVM IR.
  - A guide can be found at `https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVFIR`
  - Understand the mapping from a C program to its corresponding LLVM IR.
- (2) Generate and visualize the graph representation of LLVM IR (`example.ll` `swap.ll`).
  - `https://github.com/SVF-tools/Software-Security-Analysis/wiki/SVFIR#3-run-and-debug-your-svfir`
- (3) Write code to iterate SVFVars and also the nodes and edges of ICFG and print their contents.
  - `https://github.com/SVF-tools/Software-Security-Analysis/blob/main/SVFIR/SVFIR.cpp#L74-L98`
- (4) More about LLVM IR and SVF's graph representation
  - LLVM language manual `https://llvm.org/docs/LangRef.html`
  - SVF website `https://github.com/SVF-tools/SVF`

Control-Flow and Reachability Analysis

(Week 2)

Yulei Sui

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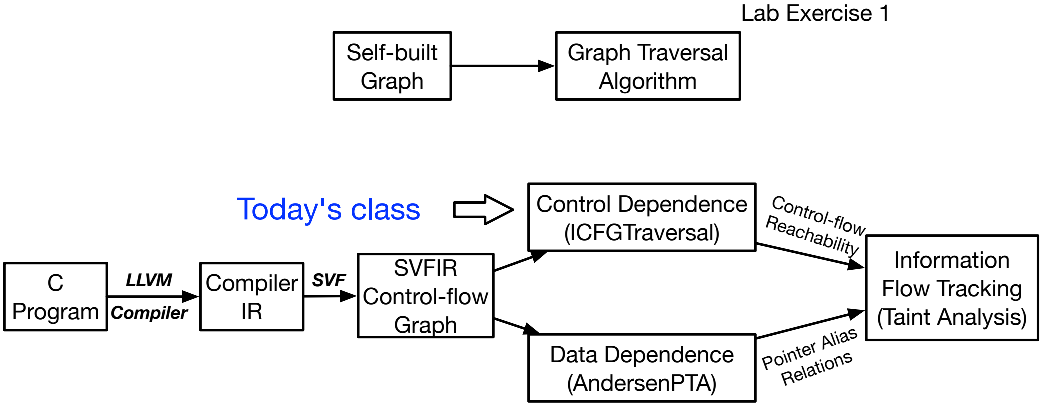
Today’s Class


Lab Exercise 1
Self-built Graph
Graph Traversal Algorithm
Today's class
Control Dependence (ICFGTraversal)
Control-flow Reachability
Information Flow Tracking (Taint Analysis)
C Program
LLVM
Compiler
Compiler IR
SVF
SVFIR Control-flow Graph
Data Dependence (AndersenPTA)
Pointer Alias Relations

Control- and Data-Dependence

What are control- and data-dependence?

- **Control-dependence**
  - Execution order between two program statements/instructions.
  - Can program point B be reached from point A in the control-flow graph of a program?
  - Obtained through traversing the ICFG of a program
- **Data-dependence**
  - Definition-use relation between two program variables.
  - Will the definition of a variable X be used and passed to another variable Y?
  - Obtained through analyzing the SVFIR of a program
  - Combining SVFIR with ICFG to conduct symbolic execution (mimic the runtime path-based execution) of a program.

Control- and Data-Dependence

Why learn control- and data-dependence?

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

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  - Dead code elimination: If a subgraph of an ICFG is not connected from the entry block of a program, that subgraph is possibly dead code.

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  - Identifying infinite loops: If the exit block is unreachable from the entry block, an infinite loop may exist.
  - . . .

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- **Applications of data-dependence**
  - Pointer alias analysis: statically determine possible runtime values of a pointer to detect memory errors, such as null pointer dereferences and use-after-frees.

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  - Dead code elimination: If a subgraph of an ICFG is not connected from the entry block of a program, that subgraph is possibly dead code.
  - Identifying infinite loops: If the exit block is unreachable from the entry block, an infinite loop may exist.
  - . . .
- **Applications of data-dependence**
  - Pointer alias analysis: statically determine possible runtime values of a pointer to detect memory errors, such as null pointer dereferences and use-after-frees.
  - Taint analysis: if two program variables v1 and v2 are aliases (e.g., representing the same memory location), if v1 is tainted by user inputs, then v2 is also tainted.
  - . . .

Control-Dependence

We say that a program statement (ICFG node) `snk` is control-flow dependent on `src` if `src` can reach `snk` on the ICFG.

- Context-insensitive control-dependence
  - control-flow traversal without matching calls and returns.
  - fast but imprecise

Control-Dependence

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- Context-insensitive control-dependence
  - control-flow traversal without matching calls and returns.
  - fast but imprecise
- Context-sensitive control-dependence
  - control-flow traversal by matching calls and returns.
  - precise but maintains an extra abstract call stack (storing a sequence of callsite ID information) to mimic the runtime call stack.

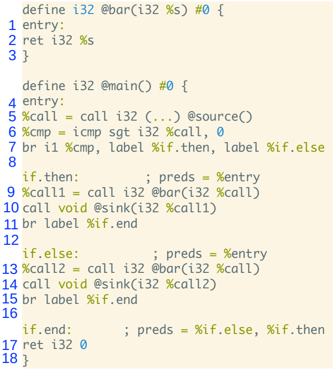
Control-Dependence

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

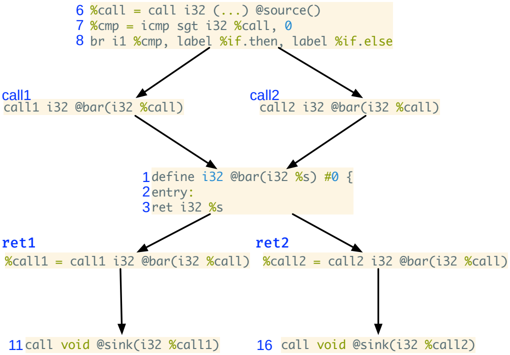
Control-Dependence

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

define i32 @main() #0 {
entry:
%call = call i32 (...) @source()
%cmp = icmp sgt i32 %call, 0
br i1 %cmp, label %if.then, label %if.else

if.then:          ; preds = %entry
%call1 = call i32 @bar(i32 %call)
call void @sink(i32 %call1)
br label %if.end

if.else:           ; preds = %entry
%call2 = call i32 @bar(i32 %call)
call void @sink(i32 %call2)
br label %if.end

if.end:       ; preds = %if.else, %if.then
ret i32 0
}
```

Control-Dependence



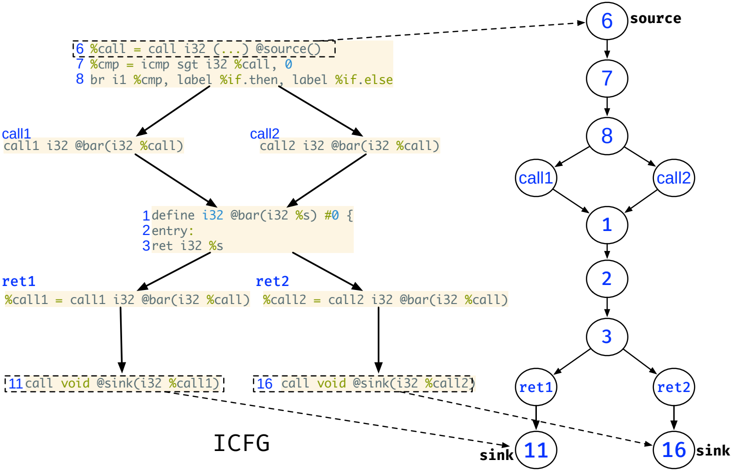
```
   define i32 @bar(i32 %s) #0 {
1  entry:
2  ret i32 %s
3  }

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


6 %call = call i32 (...) @source()
7 %cmp = icmp sgt i32 %call, 0
8 br i1 %cmp, label %if.then, label %if.else
call1
call1 i32 @bar(i32 %call)
call2
call2 i32 @bar(i32 %call)
1 define i32 @bar(i32 %s) #0 {
2 entry:
3 ret i32 %s
ret1
%call1 = call1 i32 @bar(i32 %call)
ret2
%call2 = call2 i32 @bar(i32 %call)
11 call void @sink(i32 %call1)
16 call void @sink(i32 %call2)

ICFG

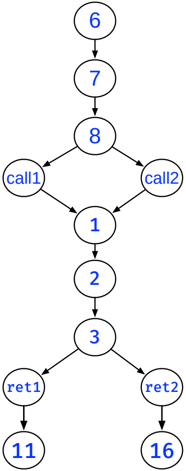
Control-Dependence

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

   define i32 @main() #0 {
 4 entry:
 5 %call = call i32 (...) @source()
 6 %cmp = icmp sgt i32 %call, 0
 7 br i1 %cmp, label %if.then, label %if.else
 8
   if.then:          ; preds = %entry
 9 %call1 = call i32 @bar(i32 %call)
10 call void @sink(i32 %call1)
11 br label %if.end
12
   if.else:           ; preds = %entry
13 %call2 = call i32 @bar(i32 %call)
14 call void @sink(i32 %call2)
15 br label %if.end
16
   if.end:      ; preds = %if.else, %if.then
17 ret i32 0
18 }
```


6 %call = call i32 (...) @source()
7 %cmp = icmp sgt i32 %call, 0
8 br i1 %cmp, label %if.then, label %if.else
call1
call1 i32 @bar(i32 %call)
call2
call2 i32 @bar(i32 %call)
1 define i32 @bar(i32 %s) #0 {
2 entry:
3 ret i32 %s
ret1
%call1 = call1 i32 @bar(i32 %call)
ret2
%call2 = call2 i32 @bar(i32 %call)
11 call void @sink(i32 %call1)
16 call void @sink(i32 %call2)
ICFG
6
source
7
8
call1
call2
1
2
3
ret1
ret2
sink
11
16
sink

Context-Insensitive Control-Dependence

Obtaining a path from source to sink on ICFG

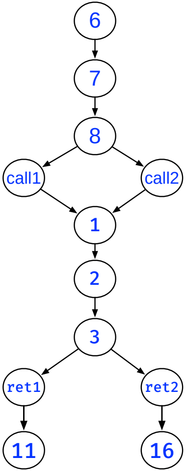


Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 11 on the ICFG



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

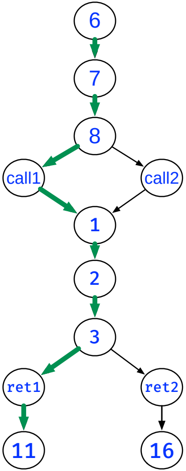
ICFG paths: node 6 → node 11

Path 1:
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:
6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Dependence

Feasible paths from node 6 to node 11



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

ICFG paths: node 6 → node 11

Path 1: **feasible path**

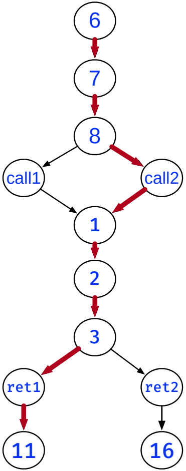
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:

6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Dependence

Infeasible path from node 6 to node 11



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

ICFG paths: node 6 → node 11

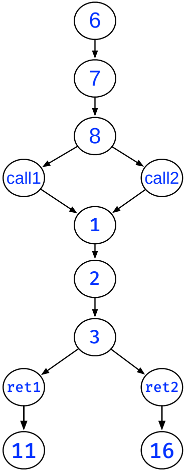
Path 1:
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:
6→7→8→**call2**→1→2→3→**ret1**→11

spurious path

Context-Insensitive Control-Dependence

Obtaining paths from node 6 to node 16 on ICFG



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

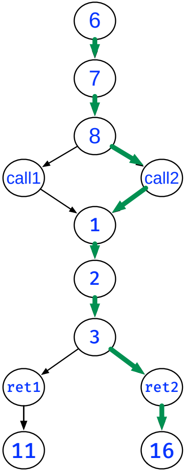
ICFG paths: node 6 → node 16

Path 3:
6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:
6→7→8→**call1**→1→2→3→**ret2**→16

Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

ICFG paths: node 6 → node 16

Path 3: **feasible path**

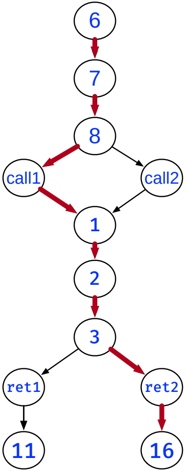
6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:

6→7→8→**call1**→1→2→3→**ret2**→16

Context-Insensitive Control-Dependence

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



Basic DFS on ICFG: source → sink

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

DFS(visited, path, src, dst)
   visited.insert(src);
   path.push_back(src);
   if src == dst then
     Print path;
   foreach edge e ∈ outEdges(src) do
      if (e.dst ∉ visited)
          DFS(visited, path, e.dst, dst);
   visited.erase(src);
   path.pop_back();
```

ICFG paths: node 6 → node 16

Path 3:

6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:

6→7→8→**call1**→1→2→3→**ret2**→16

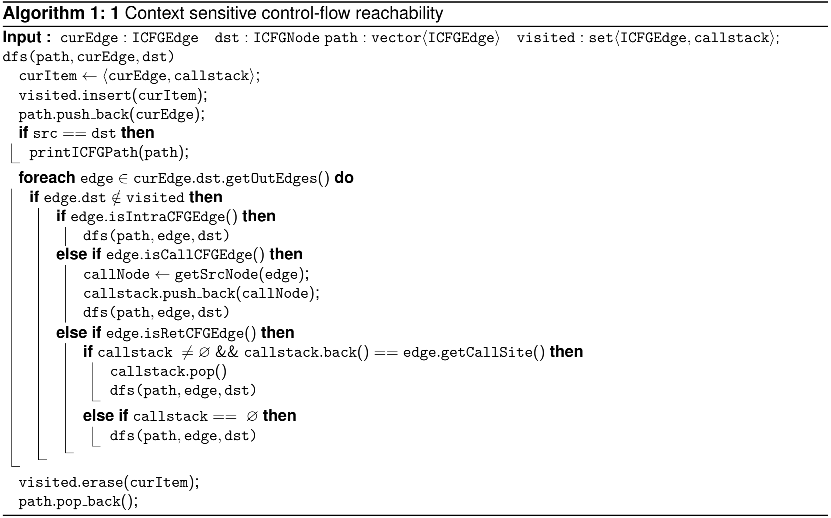
spurious path

Context-Sensitive Control-Dependence

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

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

Context-Sensitive Control-Dependence (Algorithm)

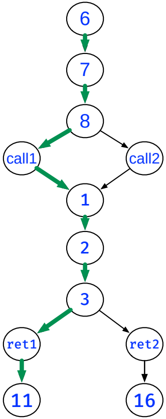


Algorithm 1: 1 Context sensitive control-flow reachability

```
Input : curEdge : ICFGEdge   dst : ICFGNode path : vector$\langle$ICFGEdge$\rangle$   visited : set$\langle$ICFGEdge, callstack$\rangle$;
dfs(path, curEdge, dst)
  curItem $\leftarrow$ $\langle$curEdge, callstack$\rangle$;
  visited.insert(curItem);
  path.push_back(curEdge);
  if src == dst then
    printICFGPath(path);
  foreach edge $\in$ curEdge.dst.getOutEdges() do
    if edge.dst $\notin$ visited then
      if edge.isIntraCFGEdge() then
        dfs(path, edge, dst)
      else if edge.isCallCFGEdge() then
        callNode $\leftarrow$ getSrcNode(edge);
        callstack.push_back(callNode);
        dfs(path, edge, dst)
      else if edge.isRetCFGEdge() then
        if callstack $\neq \varnothing$ && callstack.back() == edge.getCallSite() then
          callstack.pop()
          dfs(path, edge, dst)
        else if callstack == $\varnothing$ then
          dfs(path, edge, dst)
  visited.erase(curItem);
  path.pop_back();
```

Context-Sensitive Control-Dependence (Example)

call1 matches with ret1

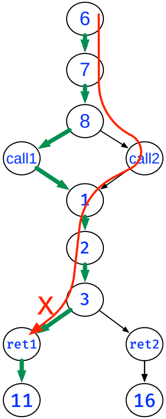


Algorithm 2: 1 Context sensitive control-flow reachability

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

Context-Sensitive Control-Dependence (Example)

call2 does not match with ret1



Algorithm 3: 1 Context sensitive control-flow reachability

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

What's next?

- Understand control-flow reachability in this slides
- Debug and work with the code under the `SVFIR` and `CodeGraph` folders
- If you finished `Quiz-1` and `Lab-Exercise-1`, you could have a look at the spec of `Assignment-1`. Once the data flow is taught in Week 3, you could start coding `Assignment-1`
  - `Assignment-1`'s specification: `https://github.com/SVF-tools/Software-Security-Analysis/wiki/Assignment-1`