LLVM, SVF IR and Control-Flow Reachability

(Week 2)

Yulei Sui

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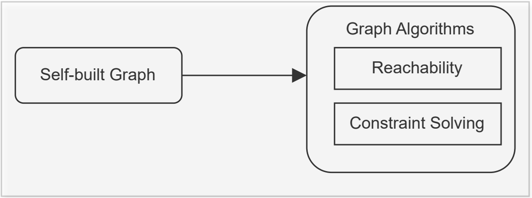
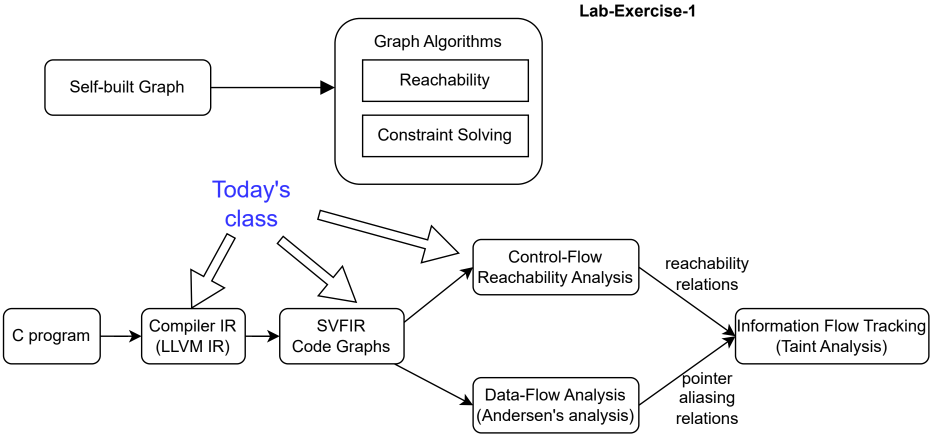
Where We Are Now and Today's Class

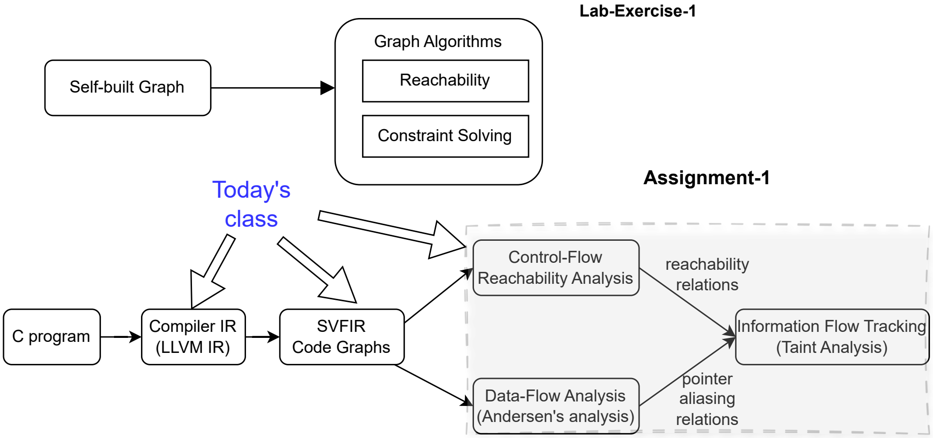


Lab-Exercise-1

Today's Class



Today’s Class



What is LLVM ?

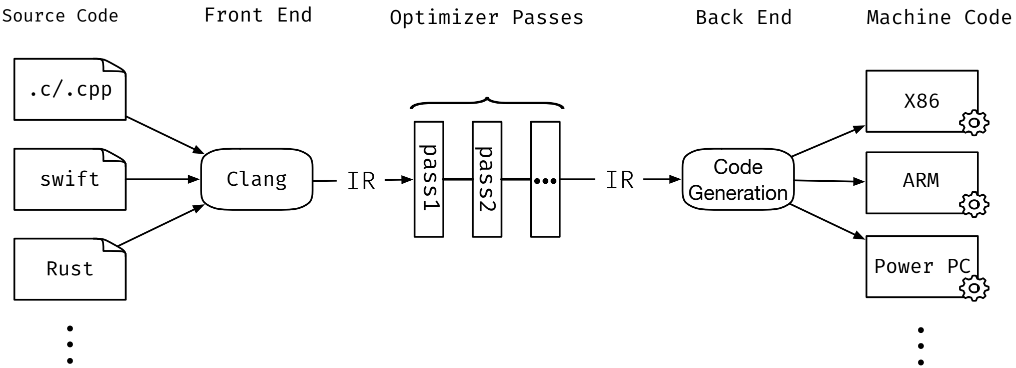
LLVM compiler infrastructure is a collection of compiler and tool-chain technologies.

- 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?

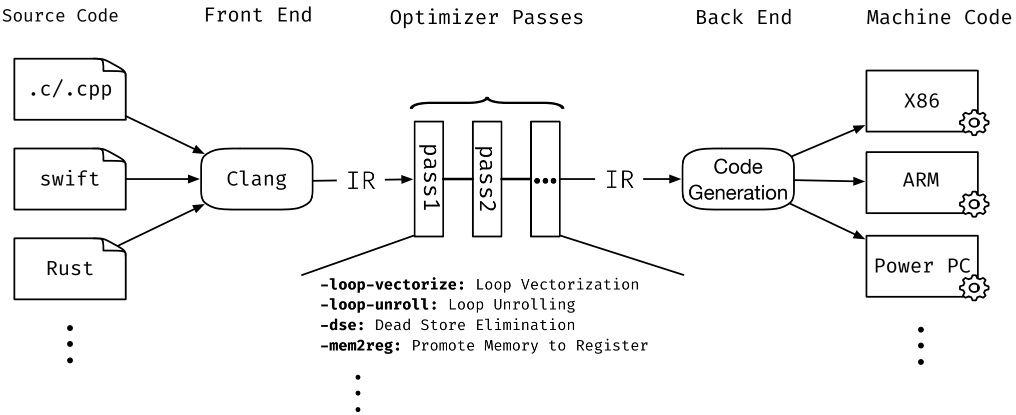
- An essential part of the standard curriculum in computer science.
- One of the most complex systems required for building virtually all other software.
- A perfect base framework to build your own tools for code analysis and verification
- Sharpen your software design and implementation skills.
- Widely 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



*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

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
- **Clear lexical scope**, such as modules, functions, basic blocks, and instructions
  - LLVM IR is higher level than assembly (e.g., call, invoke, switch, aggregate types, etc.).
  - LLVM IR is a good place to start to understand how high level languages get lowered.

LLVM Intermediate Representation (IR)

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- **static single assignment (SSA)** form

LLVM Intermediate Representation (IR)

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- **static single assignment (SSA)** form
  - Variables are strongly typed
  - Global variable (symbol starting with '@'), stack/register var (starting with '%')
  - Each global and stack variable is assigned exactly once.
    - A variable lowered to LLVM IR is renamed if it has multiple definitions, so that each one has a unique name, turning them into a set of static single assignments.

```
x = 1;
x = x + 2;
```

Translate to SSA form ⇒

```
x1 = 1;
x2 = x1 + 2;
```

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    - The SSA form makes it easier to perform data-flow analysis and optimizations such as constant propagation, dead code elimination, and register allocation because the compiler can track the values of variables more precisely.

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```
x = 1;
x = x + 2;
if (x > 3) {
    x = x * 2;
}
```

Translate to SSA form $\Longrightarrow$

```
x1 = 1;
x2 = x1 + 2;
if (x2 > 3) {
    x3 = x2 * 2;
}
x4 = phi(x2, x3);
```

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`)

- **3-address code style**
  - Three addresses and one operator. Each instruction typically has at most three operands, aligning with the principles of SSA form, where each variable is assigned exactly once and allows for efficient analyses and optimizations.
    - 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'.

```
// source code
a = b + c * d;
```

Translate to SSA form ⇒

```
// introducing a temporal variable t.
t = c * d;
a = b + t;
```

Compiling a C Program to Its LLVM IR

- Get your correct version of `clang`, by typing `source env.sh`
  - `clang -v`   // make sure clang/llvm version 16.0
  - `source env.sh`
- Compile `swap.c` to a human readable IR `swap.ll` (default opt level `-O0`).
  - `clang -c -S -emit-llvm swap.c -o swap.ll`
- Keep the variable names.
  - `clang -c -S -fno-discard-value-names -emit-llvm swap.c -o swap.ll`
- Remove `optnone` attribute to perform certain analyses or transformations
  - `clang -c -S -Xclang -disable-O0-optnone -fno-discard-value-names -emit-llvm swap.c -o swap.ll`
- Keep source code debug information (optional).
  - `clang -g -c -S -fno-discard-value-names -Xclang -disable-O0-optnone -emit-llvm swap.c -o swap.ll`
- Convert the LLVM IR to more compact static single assignment form.
  - `opt -p=mem2reg -S swap.ll -o swap.ll`

An Example without Source Code Debug Info

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

clang ...

+

opt -p=mem2reg ...

⇒

```llvm
define void @swap(ptr %p, ptr %q) #0 !9 {
entry:
  %1 = load ptr, ptr %q, align 8
  store ptr %1, ptr %p, align 8
  store ptr %0, ptr %q, align 8
  ret void, !24
}
define i32 @main() #0 !25 {
entry:
  %a1 = alloca i8, align 1
  %b1 = alloca i8, align 1
  %a = alloca ptr, align 8
  %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.c

swap.ll

https://github.com/SVF-tools/Software-Security-Analysis/blob/main/SVFIR/src/swap.c

An Example with Source Code Debug Info (`compile.sh`)

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

swap.c

clang -g ...

\+

opt -p=mem2reg ...

or

SVFIR/compile.sh

⇒

```llvm
define void @swap(ptr %p, ptr %q) #0 !dbg !9 {
entry:
  call void @llvm.dbg.value(metadata ptr %p, metadata !16, metadata !DIExpression()), !dbg!17
  call void @llvm.dbg.value(metadata ptr %q, metadata !18, metadata !DIExpression()), !dbg!17
  %0 = load ptr, ptr %p, align 8, !dbg!19
  call void @llvm.dbg.value(metadata ptr %0, metadata !20, metadata !DIExpression()), !dbg!17
  %1 = load ptr, ptr %q, align 8, !dbg!21
  store ptr %1, ptr %p, align 8, !dbg!22
  store ptr %0, ptr %q, align 8, !dbg!23
  ret void, !dbg !24
}
define i32 @main() #0 !dbg !25 {
entry:
  %a1 = alloca i8, align 1
  %b1 = alloca i8, align 1
  %a = alloca ptr, align 8
  %b = alloca ptr, align 8
  call void @llvm.dbg.declare(metadata ptr %a1, metadata !29, metadata !DIExpression()),!dbg!30
  call void @llvm.dbg.declare(metadata ptr %b1, metadata !31, metadata !DIExpression()),!dbg!32
  call void @llvm.dbg.declare(metadata ptr %a, metadata !33, metadata !DIExpression()),!dbg!34
  call void @llvm.dbg.declare(metadata ptr %b, metadata !35, metadata !DIExpression()),!dbg!36
  store ptr %a1, ptr %a, align 8, !dbg!37
  store ptr %b1, ptr %b, align 8, !dbg!38
  call void @swap(ptr noundef %a, ptr noundef %b), !dbg !39
  ret i32 0, !dbg !40
}
```

swap.ll

Mapping C code to 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
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  %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
}
```

Function

BasicBlock

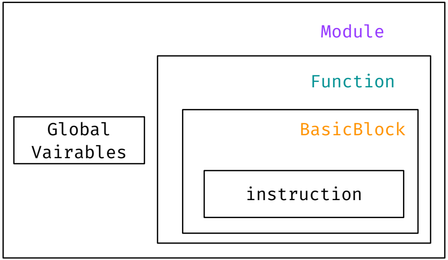
Instruction

swap.ll

https://github.com/SVF-tools/Software-Security-Analysis/blob/main/SVFIR/src/swap.c

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)

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

```llvm
define i32 @main() #0 {
entry:
  %a1 = alloca i8, align 1
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  %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
}
```

```
%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)

```c
int main(){
  char a1;
  char *a;
  char b1;
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  a = &a1;
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  swap(&a,&b);
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define i32 @main() #0 {
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  call void @swap(ptr %a, ptr %b)
  ret i32 0
}
```

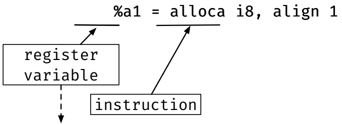

identifiers:

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

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

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

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define i32 @main() #0 {
entry:
  %a1 = alloca i8, align 1
  %a = alloca ptr, align 8
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  %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
}
```

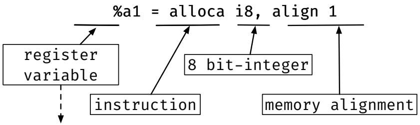

identifiers:

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- temporary variables are numbered

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

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

- `align 8` specifies that the allocated memory should be aligned on an 8-byte boundary. For example, its address could be 0x0008, 0x0010, 0x0018, 0x0020, and so on, but not 0x0001, 0x0002, or any other value that isn't a multiple of 8.

LLVM Intermediate Representation (IR)

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

```llvm
define i32 @main() #0 {
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  %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
}
```

`%a = alloca ptr, align 8`

↓

`allocate 8-bit integer pointer for a`

LLVM Intermediate Representation (IR)

```c
int main(){
  char a1;
  char *a;
  char b1;
  char *b;
  a = &a1;
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```

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define i32 @main() #0 {
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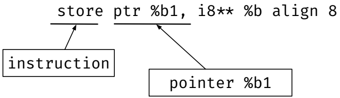

store the pointer %b1 to the memory location that %b points to

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

```llvm
define i32 @main() #0 {
entry:
  %a1 = alloca i8, align 1
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  %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
}
```

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

- `store`: instruction
- `ptr %b1`: pointer %b1

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

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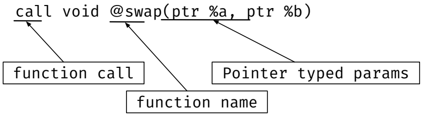
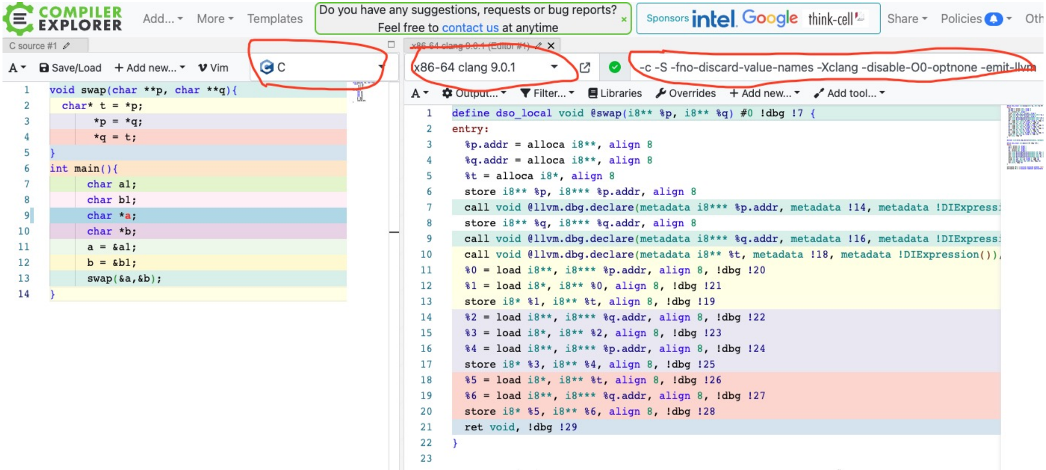


call instruction will be used to build control flow.

Compiler IR Playground https://godbolt.org/z/sra58dhbG



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`

SVF and Graph Representations of Code

(Week 2)

Yulei Sui

School of Computer Science and Engineering

University of New South Wales, Australia

SVF : Static Value-Flow Analysis Framework for Source Code

A scalable, precise and on-demand interprocedural static analysis and verification 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 (version 16.0.0) with over 200 KLOC C/C++ code and **1300+ stars with 80+ contributors** and over 4K commits on Github.
  - Invited for a **plenary talk in EuroLLVM 2016**, and awarded an **ICSE 2018 Distinguished Paper**, an **SAS Best Paper 2019** and an **OOPSLA 2020 Distinguished Paper**.

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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'?
  - Is there an unsafe memory access that may trigger a bug or security risk?

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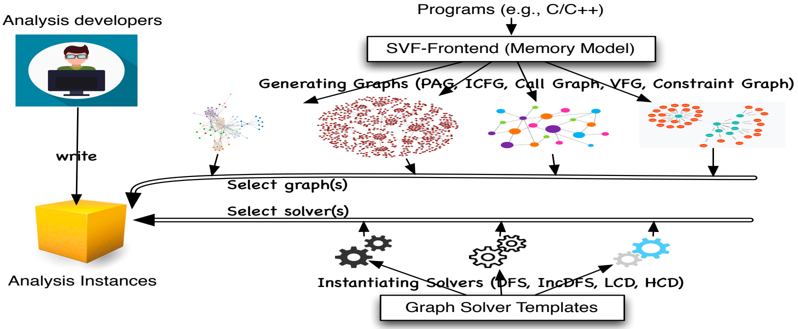
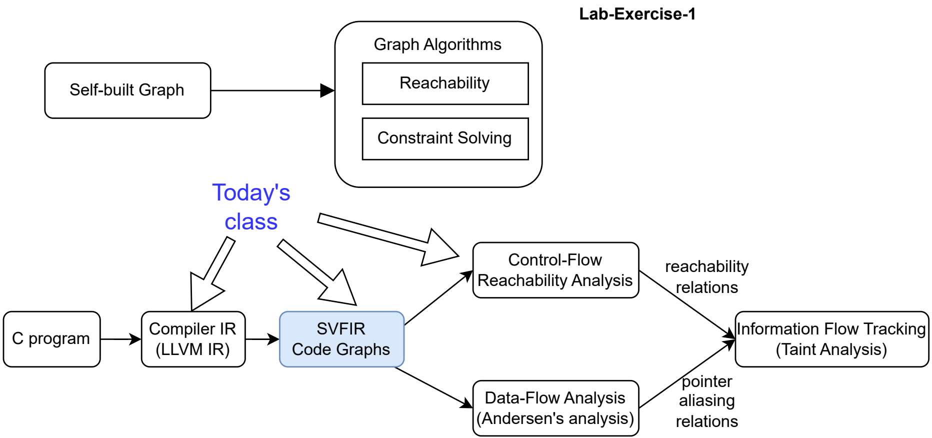
- Value-Flow Analysis: resolves **both control and data dependence**.
  - Does the information generated at program point *A* flow to another program point *B* along some execution paths?
  - Can function *F* be called either directly or indirectly from some other function F'?
  - Is there an unsafe memory access that may trigger a bug or security risk?
- 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



- 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



SVFIR and Why?

- **SVFIR = SVFValue + SVFVar + SVFStmt + Code Graphs**
- A **lightweight wrapper and abstraction** with fewer types of LLVM instructions/vars. Complicated ones are broken down into basic SVFStmts.
- SVFIR aims to accommodate any modern language for fast **static analysis** prototyping but **NOT** for code generation or optimizations.

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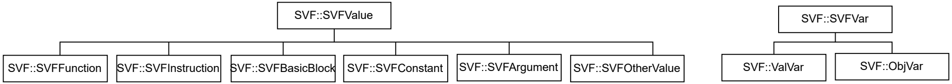
- SVFIR aims to accommodate any modern language for fast **static analysis** prototyping but **NOT** for code generation or optimizations.
- **SVFValue** and **SVFVar**: program values and variables



SVFIR and Why?

- **SVFIR = SVFValue + SVFVar + SVFStmt + Code Graphs**
- A **lightweight wrapper and abstraction** with fewer types of LLVM instructions/vars. Complicated ones are broken down into basic SVFStmts.
- SVFIR aims to accommodate any modern language for fast **static analysis** prototyping but **NOT** for code generation or optimizations.
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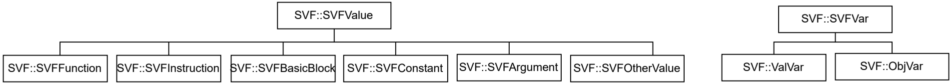
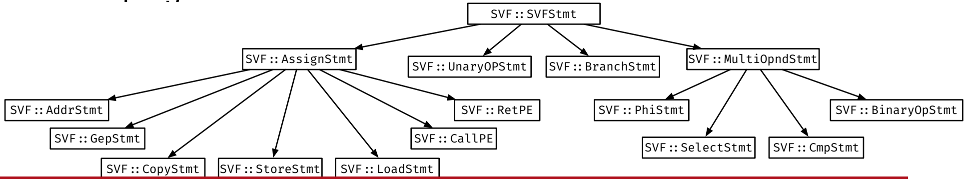


- **SVFStmt**: program statements



Mapping between SVF-IR and LLVM-IR

- **1:1 mapping from an `LLVM::Value` to one of `SVFValue`'s six subclasses.**
  - `LLVM::Value` ⇐ `LLVMModuleSet::getSVFValue(llvm_value)`
  - `SVFValue` ⇐ `LLVMModuleSet::getLLVMValue(svf_value)`

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  - **1:1 mapping from each `SVFValue` to an `ValVar`. Only memory-allocation-related `SVFValue` can map to `ObjVar`.**
  - `ValVar` ⇐ `SVFIR::getGNode(SVFIR::getValueNode(svf_value));`
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- **1:1 mapping from an `SVFInstruction` to an `ICFGNode` (containing one or more `SVFStmts`).**
  - `ICFGNode` ⇐ `ICFG::getICFGNode(svf_inst);`
  - `SVFStmts` ⇐ `ICFGNode::getSVFStmts();`
- **Always use the `toString` method** in SVF's data structures to understand their meanings and the mappings.
  - `SVFVar::toString()`
  - `ICFGNode::toString()` `ICFGEdge::toString()`

SVF Program Variables (SVFVar)

- An `SVFVar` represent either a top-level variable (`ValVar`, $\mathbb{P}$) or a memory object variable (`ObjVar`, $\mathbb{O}$)
- 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 (constant data, stack, heap, global) (function objects are considered as global objects)
`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	$\ell \in \mathbb{L}$	Statements labels

SVF Program Statements (SVFStmt)

An SVFStmt is one of the following 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	$\%p = getelementptr\ \%q, \%i$	$p = \&(q \rightarrow i)$ or $p = \&q[i]$	$\mathbb{P} \times \mathbb{P} \times \mathbb{P}$
PhiStmt	$\%p = phi\ [\ \ell_1, \%q_1\ ], [\ \ell_2, \%q_2\ ]$	$p = phi(\ell_1 : q_1,\ \ell_2 : q_2)$	$\mathbb{P} \times (\mathbb{L} \times \mathbb{P})^2$
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`.

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- 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;`
  - `t` is a temporal `ValVar`. For any constant (e.g., 3) SVF will create a `ValVar` and an `ObjVar`.

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  - `t` is a temporal `ValVar`. For any constant (e.g., 3) SVF will create a `ValVar` and an `ObjVar`.
- `CallPE` represents the **call p**arameter **e**dge passing from an actual parameter at a callsite to a formal parameter of a callee function.
- `RetPE` represents the **ret**urn **p**arameter **e**dge passing from a function return to a callsite return variable.

Graph Representations of Code

- What are graph representations of code (code graphs)?
  - Put `SVFVars` and `SVFStmts` on one or more graph representations. For example:
    - **Call Graph**: each node represents a function and each edge represents a calling relation.
    - **ICFG** (Interprocedural Control-Flow Graph): where each node represents a statement and each edge represents a program's control-flow (i.e., execution order)
    - **PAG** (Program Assignment Graph): where each represents a variable (`SVFVar`) and each edge represents a program statement (`SVFStmt`).
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    - **Constraint Graph**: A subgraph of PAG where each node is either a variable of pointer type or a memory object.
- Why graph representations?
  - 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
}
```

Call Graph

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

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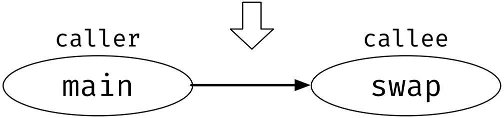

Call Graph

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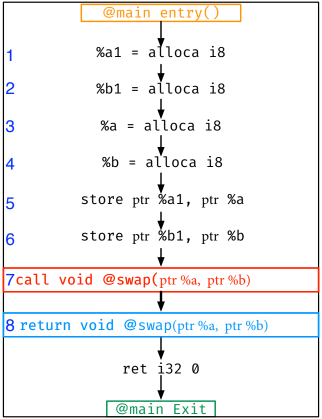
1. Each node represents a program method
2. Each edge represents a calling relation between two program methods

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



Program execution order between instructions

- Each node represents an instruction or a statement

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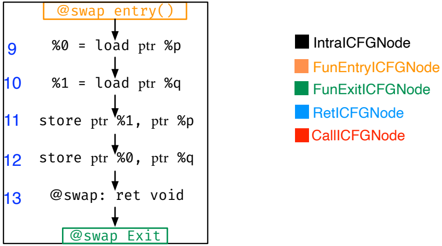

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Inter-procedural Control Flow Graph (ICFG)

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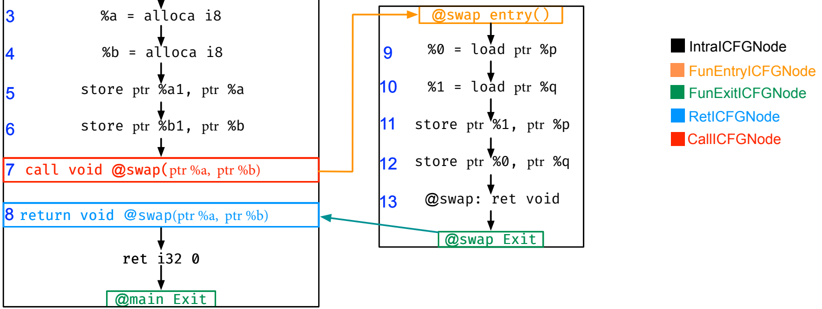

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SVFIR Example (SVFVar + SVFStmt = PAG)

clang -S -c -Xclang -disable-O0-optnone -fno-discard-value-names -emit-llvm example.c -o example.ll

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int foo(int b){
    return b;
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int main(){
    int a = foo(0);
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}
define i32 @main() {
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  store i32 %call, i32* %a
  ret i32 0
}
```

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Variables introduced by SVF
(created internally)

SVFVar	Meaning
DummyValVar ID: 0	nullptr
DummyValVar ID: 1	reserved
DummyObjVar ID: 2	reserved
DummyObjVar ID: 3	reserved
ValVar ID: 4	foo
FIObjVar ID: 5	foo (object)
RetPN ID: 6	ret of foo
ValVar ID: 15	main
FIObjVar ID: 16	main (object)
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}
define i32 @main() {
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ValVar ID: 15	main
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RetPN ID: 17	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: 10	`i32 1 { constant data }`
FIObjVar ID: 11	`i32 1 { constant data }`
ValVar ID: 12	`store i32 %b, ptr %b.addr`
ValVar ID: 13	`%0 = load i32, ptr %b.addr`
ValVar ID: 14	`ret i32 %0`
ValVar ID: 18	`%a = alloca i32`
FIObjVar ID: 19	`%a = alloca i32`
ValVar ID: 20	`%call = call i32 @foo(i32 0)`
ValVar ID: 21	`i32 0 { constant data }`
FIObjVar ID: 22	`i32 0 { constant data }`
ValVar ID: 23	`store i32 %call, ptr %a`
ValVar ID: 24	`ret i32 0`

SVFIR Example (ICFG and SVFStmt)

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

define i32 @main() {
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  %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: [Var21 ← Var22]	`i32 0 (constant data)`
	AddrStmt: [Var10 ← Var11]	`i32 1 (constant data)`
	AddrStmt: [Var4 ← Var5]	`foo`
	AddrStmt: [Var15 ← Var16]	`main`
FunEntryICFGNode1	fun: foo	
IntraICFGNode2	AddrStmt: [Var8 ← Var9]	`%b.addr = alloca i32`
IntraICFGNode3	StoreStmt [Var8 ← Var7]	`store i32 %b, ptr %b.addr`
IntraICFGNode4	LoadStmt: [Var13 ← Var8]	`%0 = load i32, ptr %b.addr`
IntraICFGNode5	fun:foo	`ret i32 %0`
FunExitICFGNode6	PhiStmt: [Var6 ← ([Var13, ICFGNode5],)]	`ret i32 %0`
FunEntryICFGNode7	fun: main	
IntraICFGNode8	AddrStmt: [Var18 ← Var19]	`%a = alloca i32`
CallICFGNode9	CallPE: [Var7 ← Var21]	`%call = call i32 @foo(i32 0)`
RetICFGNode10	RetPE: [Var20 ← Var6]	`%call = call i32 @foo(i32 0)`
IntraICFGNode11	StoreStmt: [Var18 ← Var20]	`store i32 %call, ptr %a`
IntraICFGNode12	fun: main	`ret i32 0`
FunExitICFGNode13	PhiStmt: [Var17 ← ([Var21, ICFGNode12],)]	`ret i32 0`

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

SVFIR and Code Graphs in DOT Fomat

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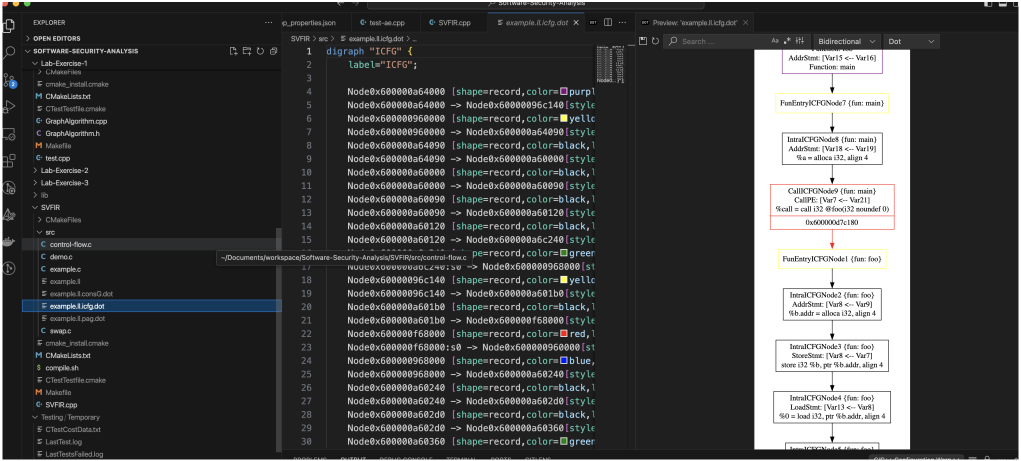


Control-Flow and Reachability Analysis

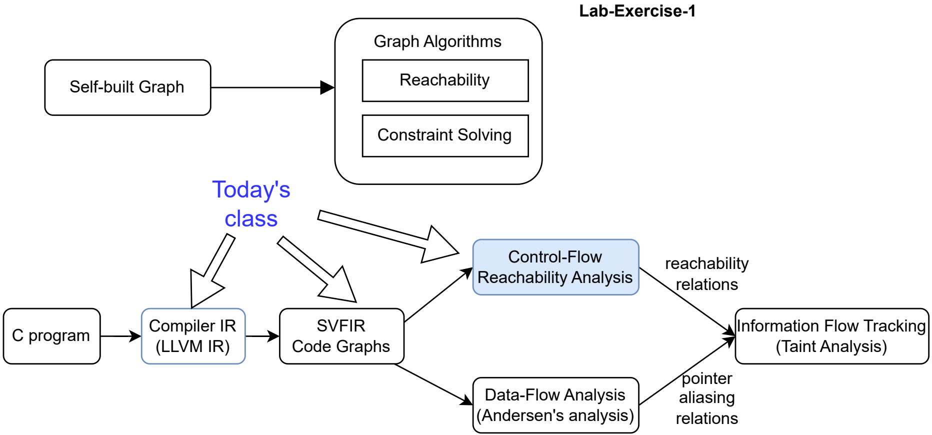
(Week 2)

Yulei Sui

School of Computer Science and Engineering

University of New South Wales, Australia

Today’s Class



What are Control-Flow and Data-Flow?

- **Control-flow or 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-data or 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 SVFVars' dependence

Why Learning Control-Flow and Data-Flow?

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

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  - ...
- **Applications of 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 variables `v1` and `v2` are aliases (their points-to sets intersect, indicating they may reference the same memory location), then if `v1` is tainted by user inputs, `v2` may also be tainted.
  - ...

Control-Flow Reachability

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-flow reachability
  - control-flow traversal without matching calls and returns.
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  - control-flow traversal without matching calls and returns.
  - fast but imprecise
- Context-sensitive control-flow reachability
  - 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-Flow Reachability

```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);
    }
}
```

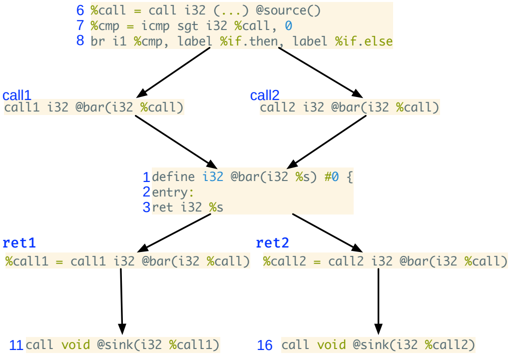
https://github.com/SVF-tools/Software-Security-Analysis/blob/main/SVFIR/src/control-flow.c

Control-Flow Reachability - An Example

```
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-Flow Reachability - An Example

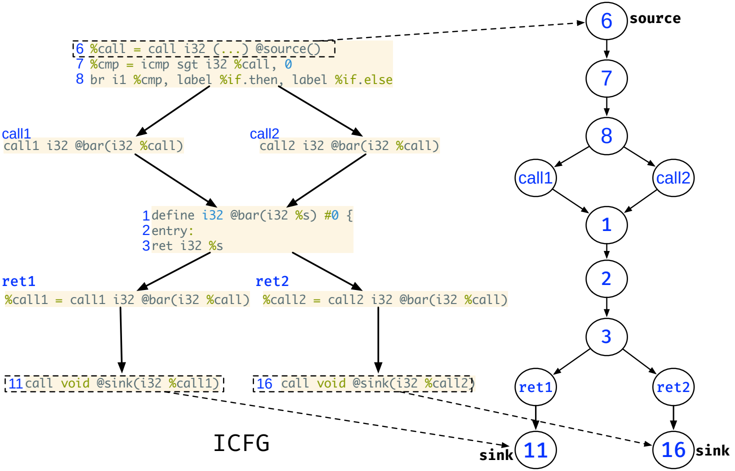
```
   define i32 @bar(i32 %s) #0 {
1  entry:
2  ret i32 %s
3  }

   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 }
```



ICFG

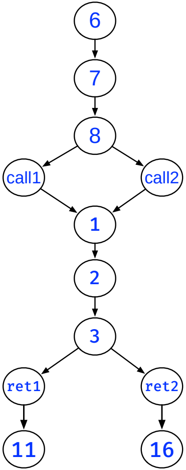
Control-Flow Reachability - An Example

```
   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 }
```



Context-Insensitive Control-Flow Reachability

Obtaining a path from source to sink on ICFG

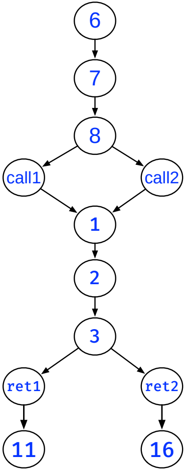


Basic DFS on ICFG: source → sink

```
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-Flow Reachability

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();
```

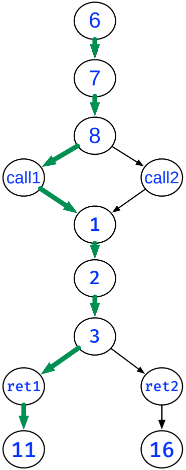
ICFG paths: node 6 → node 11

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-Flow Reachability

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**

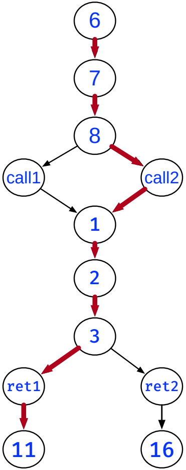
6→7→8→**call1**→1→2→3→**ret1**→11

Path 2:

6→7→8→**call2**→1→2→3→**ret1**→11

Context-Insensitive Control-Flow Reachability

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

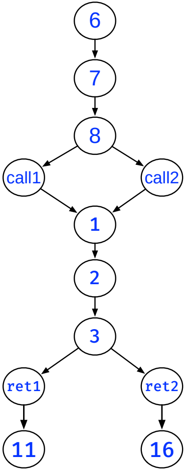
Path 1:
6→7→8→**call1**→1→2→3→**ret1**→11

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

spurious path

Context-Insensitive Control-Flow Reachability

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();
```

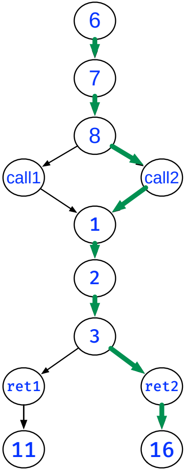
ICFG paths: node 6 → node 16

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-Flow Reachability

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**

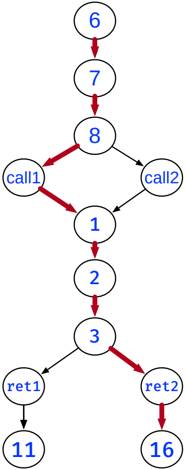
6→7→8→**call2**→1→2→3→**ret2**→16

Path 4:

6→7→8→**call1**→1→2→3→**ret2**→16

Context-Insensitive Control-Flow Reachability

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-Flow Reachability

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.

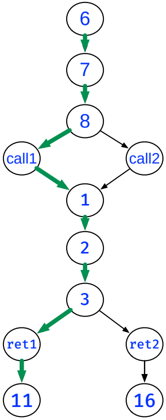
Context-Sensitive Control-Flow Reachability (Algorithm)

Algorithm 1: 1 Context sensitive control-flow reachability

```
Input : curNode : ICFGNode   snk : ICFGNode   path : vector⟨ICFGNode⟩   callstack : vector⟨SVFInstruction⟩
        visited : set⟨ICFGNode, callstack⟩;
dfs(curNode, snk)
  pair = ⟨curNode, callstack⟩;
  if pair ∈ visited then
      return;
  visited.insert(pair);
  path.push_back(curNode);
  if src == snk then
    collectICFGPath(path);
  foreach edge ∈ curNode.getOutEdges() do
    if edge.isIntraCFGEdge() then
      dfs(edge.dst, snk);
    else if edge.isCallCFGEdge() then
      callstack.push_back(edge.getCallSite());
      dfs(edge.dst, snk);
      callstack.pop_back();
    else if edge.isRetCFGEdge() then
      if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
        callstack.pop_back();
        dfs(edge.dst, snk);
        callstack.push_back(edge.getCallSite());
      else if callstack == ∅ then
        dfs(edge.dst, snk);
  visited.erase(pair);
  path.pop_back();
```

Context-Sensitive Control-Flow Reachability (Example)

call1 matches with ret1



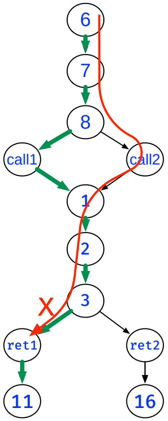
Algorithm 2: 1 Context sensitive control-flow reachability

Input : curNode : ICFGNode snk : ICFGNode path : vector⟨ICFGNode⟩ callstack : vector⟨SVFInstruction⟩ visited : set⟨ICFGNode, callstack⟩;

```
dfs(curNode, snk)
  pair = ⟨curNode, callstack⟩;
  if pair ∈ visited then
      return;
  visited.insert(pair);
  path.push_back(curNode);
  if src == snk then
    collectICFGPath(path);
  foreach edge ∈ curNode.getOutEdges() do
    if edge.isIntraCFGEdge() then
      dfs(edge.dst, snk);
    else if edge.isCallCFGEdge() then
      callstack.push_back(edge.getCallSite());
      dfs(edge.dst, snk);
      callstack.pop_back();
    else if edge.isRetCFGEdge() then
      if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
        callstack.pop_back();
        dfs(edge.dst, snk);
        callstack.push_back(edge.getCallSite());
      else if callstack == ∅ then
        dfs(edge.dst, snk);
  visited.erase(pair);
  path.pop_back();
```

Context-Sensitive Control-Flow Reachability (Example)

call2 does not match with ret1



Algorithm 3: 1 Context sensitive control-flow reachability

```
Input : curNode : ICFGNode   snk : ICFGNode   path : vector⟨ICFGNode⟩
        callstack : vector⟨SVFInstruction⟩   visited : set⟨ICFGNode, callstack⟩;
dfs(curNode, snk)
  pair = ⟨curNode, callstack⟩;
  if pair ∈ visited then
      return;
  visited.insert(pair);
  path.push_back(curNode);
  if src == snk then
    collectICFGPath(path);
  foreach edge ∈ curNode.getOutEdges() do
    if edge.isIntraCFGEdge() then
      dfs(edge.dst, snk);
    else if edge.isCallCFGEdge() then
      callstack.push_back(edge.getCallSite());
      dfs(edge.dst, snk);
      callstack.pop_back();
    else if edge.isRetCFGEdge() then
      if callstack ≠ ∅ && callstack.back() == edge.getCallSite() then
        callstack.pop_back();
        dfs(edge.dst, snk);
        callstack.push_back(edge.getCallSite());
      else if callstack == ∅ then
        dfs(edge.dst, snk);
  visited.erase(pair);
  path.pop_back();
```

What's next?

- Debug and work with the code under the `SVFIR` and `CodeGraph` folders, including the understanding of `ICFG`, `PAG` and `ConstraintGraph`.
- Understand control-flow reachability in the today's slides
- If you finished `Quiz-1` and `Lab-Exercise-1`, you could have a look at the spec of `Assignment-1` and start implementing the `readSrcSnkFromFile` and `reachability` methods or all other methods (if you want) in `Assignment-1`
    - `Assignment-1`'s specification: `https://github.com/SVF-tools/Software-Security-Analysis/wiki/Assignment-1`