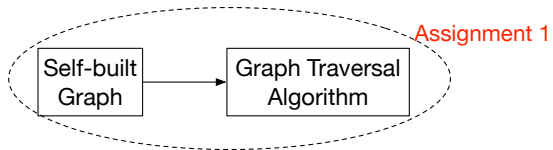


LLVM Compiler and Its Intermediate Representation

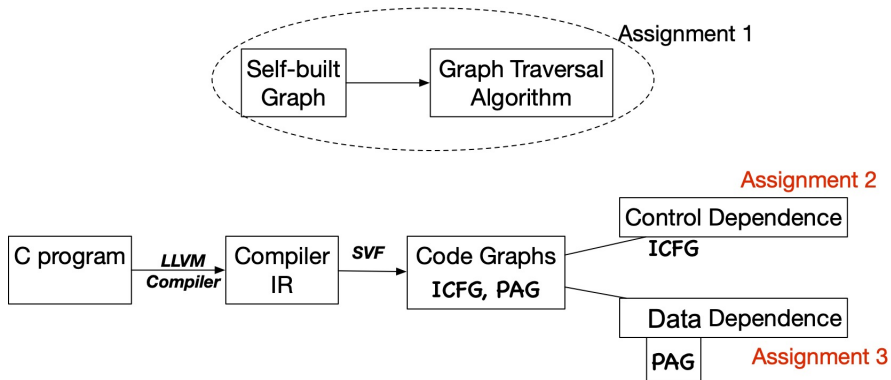
Yulei Sui

University of Technology Sydney, Australia

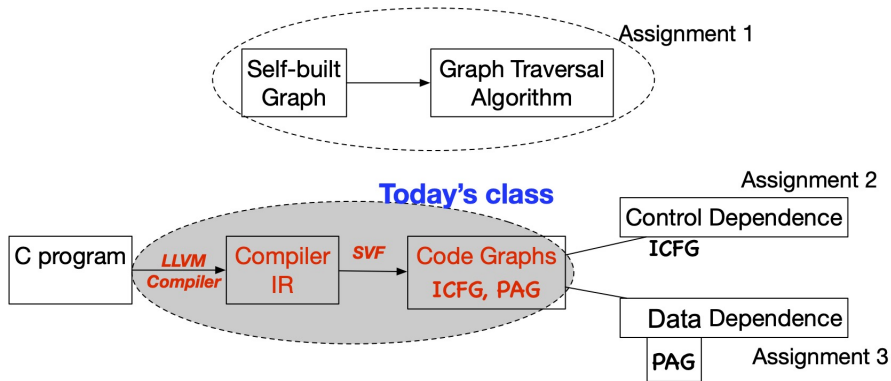
Where We Are Now and Today's Class



Where We Are Now and Today's Class



Where We Are Now and Today's Class



What is LLVM ?

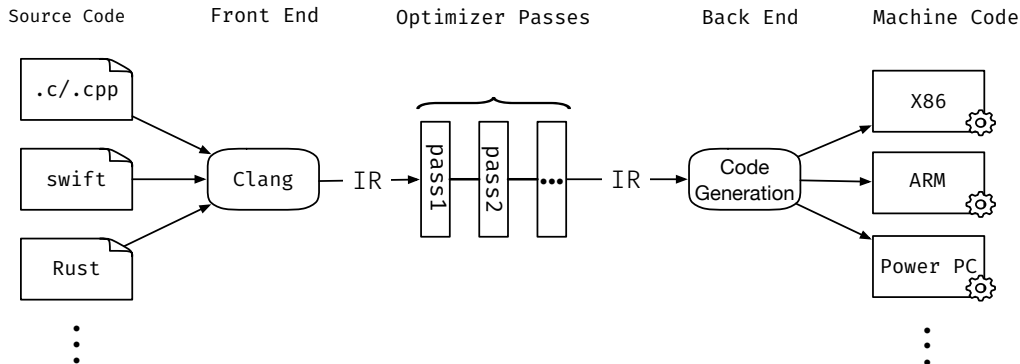
Low-Level Virtual Machine (LLVM) compiler infrastructure is a collection of compiler and tool-chain technologies.

- 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?

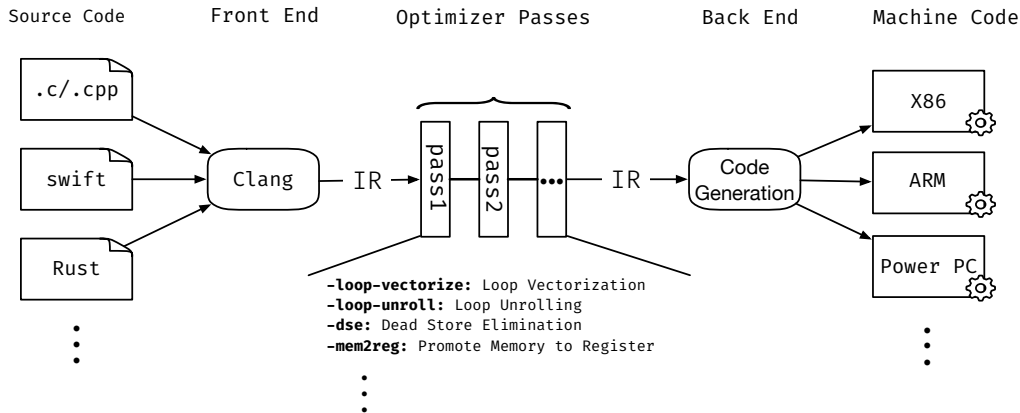
- An essential part of the standard curriculum in computer science.
- One of the most complex system for building virtually all other software.
- Sharpen your software design and implementation skills.
- Widely used by many major software companies. In-demand skills and competitive salaries in job market.

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)

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- **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)

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
- **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 'example.ll'.
 - `clang -c -S -emit-llvm swap.c -o swap.ll`
- Compilation without optimisation.
 - `clang -c -S -Xclang -disable-00-optnone -emit-llvm swap.c -o swap.ll`
- Keep the variable names.
 - `clang -c -S -fno-discard-value-names -Xclang -disable-00-optnone -emit-llvm swap.c -o swap.ll`
- Convert the LLVM IR to SSA form's IR for later static analysis.
 - `opt -S -mem2reg swap.ll -o swap.ll`

Compiling a C Program to Its LLVM IR

An example

```
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



```
define void @swap(i8** %p, i8** %q) #0 {
entry:
    %0 = load i8*, i8** %p, align 8
    %1 = load i8*, i8** %q, align 8
    store i8* %1, i8** %p, align 8
    store i8* %0, i8** %q, align 8
    ret void
}
```

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

swap.ll

C code to LLVM's IR

An example

```
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



```
define void @swap(i8** %p, i8** %q) #0 {
entry:
    %0 = load i8*, i8** %p, align 8
    %1 = load i8*, i8** %q, align 8
    store i8* %1, i8** %p, align 8
    store i8* %0, i8** %q, align 8
    ret void
}
```

Function

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

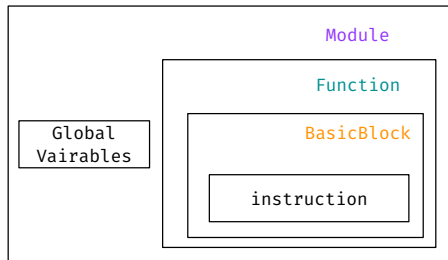
BasicBlock

Instruction

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;
    char b1;
    char *b;
    a = &a1;
    b = &b1;
    swap(&a,&b);
}

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

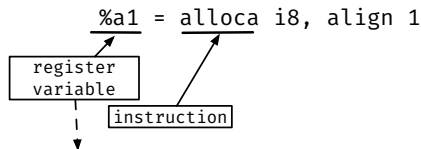
- temporary variables are numbered

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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



identifiers:

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

- % is for local variable

- @ is for global

- temporary variables are numbered

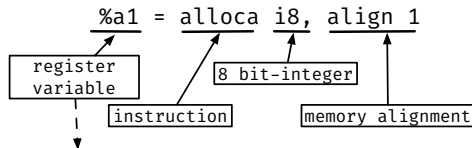
`alloca`: instruction allocates `i8` (`sizeof`) bytes of memory on run-time stack

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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



identifiers:

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

- % is for local variable

- @ is for global

- temporary variables are numbered

`alloca`: instruction allocates `i8` (`sizeof`) bytes of memory on run-time stack

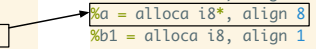
`align`: indicates the memory operation should be aligned to 1 byte

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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



`%a = alloca i8*, align 8`



allocate 8-bit integer pointer for a

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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

%b1 = alloca i8, align 1



allocate 8-bit integer for b1

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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

`%b = alloca i8*, align 8`



allocate 8-bit integer pointer for b

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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

store i8* %a1, i8** %a align 8

↑
instruction

↙
8-bit integer typed pointer %a1

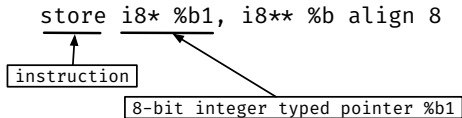
store the pointer %a1 to the memory location that %a points to

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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



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

LLVM Intermediate Representation (IR)

LLVM Instructions

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

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

call void @swap(i8** %a, i8** %b)

function call

function name

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