LLVM Compiler and Its Intermediate Representation

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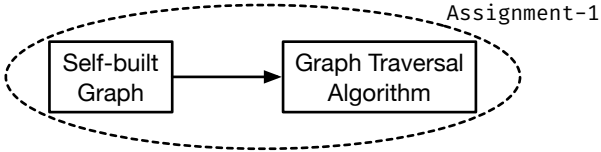
Where We Are Now and Today's Class



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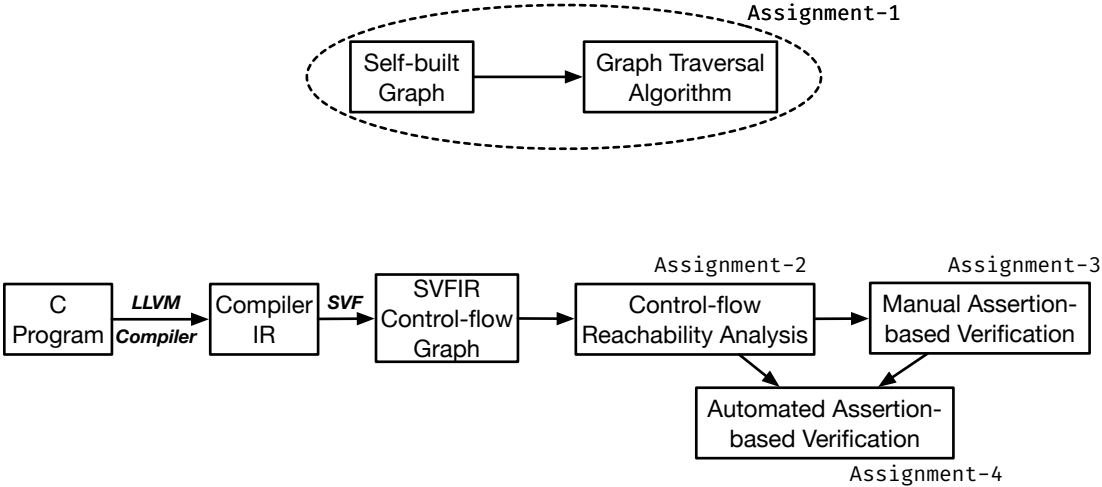

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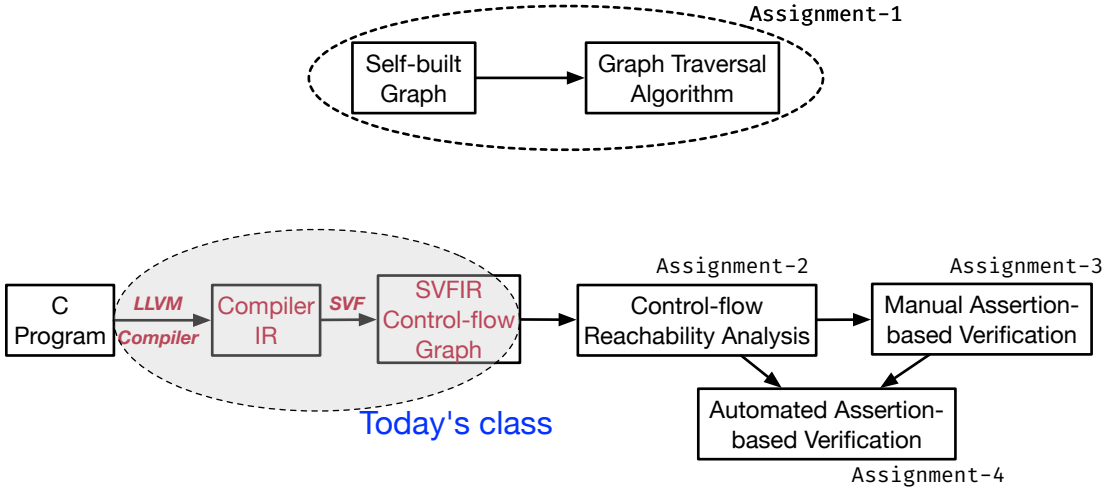


What is LLVM ?

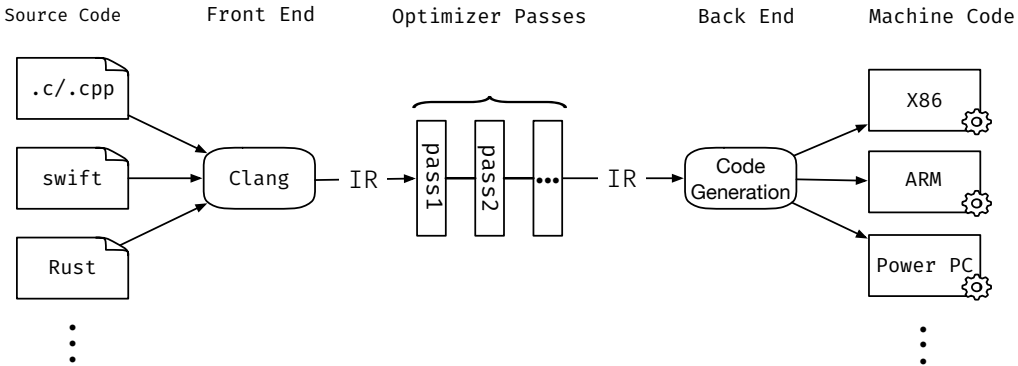
LLVM compiler infrastructure is a collection of compiler and tool-chain technologies.

- 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?

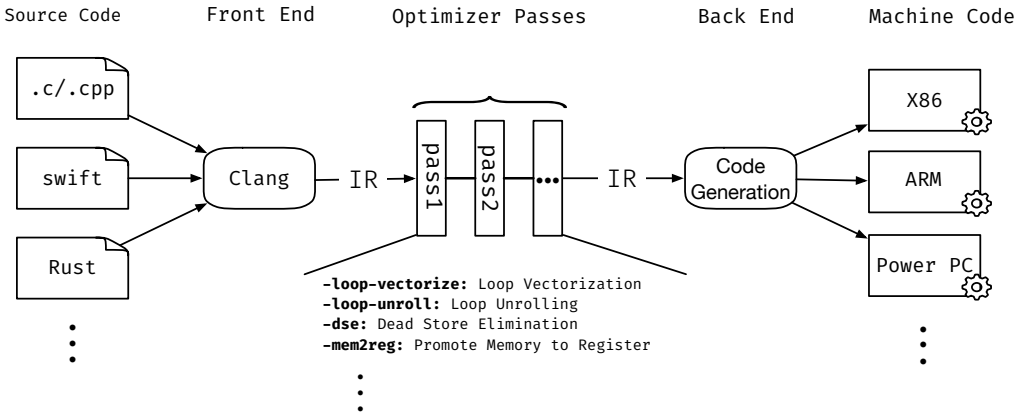
- An essential part of the standard curriculum in computer science.
- One of the most complex systems required for building virtually all other software.
- A perfect base framework to build your own tools for code analysis and verification
- Sharpen your software design and implementation skills.
- Widely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

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- **Clear lexical scope**, such as modules, functions, basic blocks, and instructions

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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

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 ‘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 -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

```
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 IR

An example

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

swap.c

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define void @swap(i8** %p, i8** %q) #0 {
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store i8* %a1, i8** %a, align 8
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call void @swap(i8** %a, i8** %b)
ret i32 0
}
```

Function

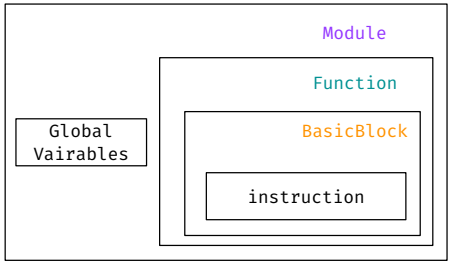
BasicBlock

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
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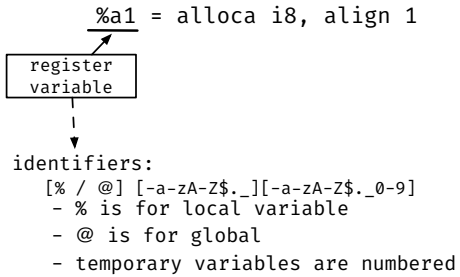
```



LLVM Intermediate Representation (IR)

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    b = &b1;
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ret i32 0
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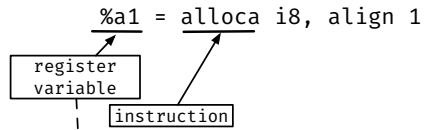


identifiers:

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

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

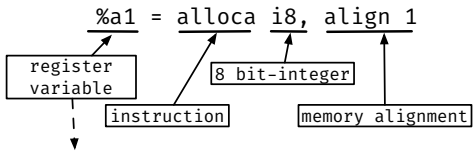
alloca: instruction allocates i8 (sizeof) bytes of memory on run-time stack

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
}
```



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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
}
```

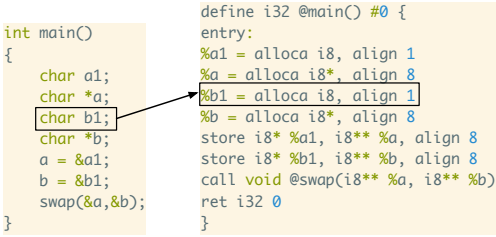
```
%a = alloca i8*, align 8
```

↓

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
```

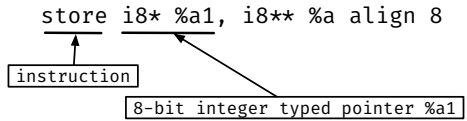

allocate 8-bit integer pointer for b

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 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;
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```

```
define i32 @main() #0 {
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%a1 = alloca i8, align 1
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%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* %b1, i8** %b align 8
```

instruction

8-bit integer typed pointer %b1

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`