The LLVM compiler framework

Introduction

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Compilers and compilers

You might have already have had experience working in a **toy compiler**...

Toy Compiler	**Production-Quality Compiler**
► small codebase	► huge codebase
► easy to modify	► hard to modify
► limited capabilities	► produces high-quality code

Initially, working with a production-quality compiler might seem **hard**...

...however it provides a huge set of tools that toy compilers **miss**!

Why LLVM

Why is this course focused on LLVM?

- Key technology in the **industry**
  - AMD, Apple, Google, Intel, NVIDIA...
- Biggest platform for **research** about compilers
- **Modular** and **hackable**

Initially started as a small research project at Urbana-Champaign.

Now it has grown to a huge size...

GCC vs LLVM

LLVM [1] is Open Source

If you are familiar with Linux you might have used **GCC** [2]...

GCC is older than LLVM

$\Rightarrow$ GCC produces better code
$\Rightarrow$ LLVM is generally faster
$\Rightarrow$ LLVM is more modular and *clean*

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Compiler pipeline

Typically a compiler is a **pipeline**.

Advantages of the pipeline model:

- **simplicity** – read something, produce something
- **locality** – no superfluous state

Complexity lies on **chaining** together stages.

Frontends and Drivers

The external interface to LLVM is provided by the **compiler driver**.

The **compiler driver** is the program that:

- Provides the interface to the user
- Performs setup of the frontend and LLVM itself.

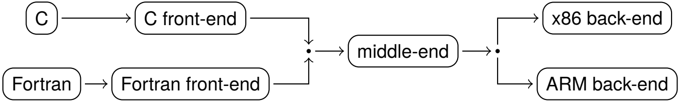
The driver invokes the **first stage of the pipeline**, the **frontend**.

Example

Clang[3] is the frontend for the C language family.
The driver of *Clang* is the `clang` executable (compatible with GCC).

Compiler pipeline

High-level pipeline structure of a compiler:



There are three main components:

Front-end **translates** a source file into the intermediate representation

Middle-end **analyzes** the intermediate representation, **optimizes** it

Back-end **generates** target machine assembly from the intermediate representation

The LLVM compiler pipeline

We will focus on the *middle-end*.
Same concepts are valid also for {front,back}-end.

- The *front-end* is completely language-specific
  - There are no special facilities in LLVM for parsing and AST generation
  - This is slowly changing: **MLIR**
- The *back-end* uses its own machine-specific IR
  - As opposed to the frontend, in LLVM there are generalized facilities for implementing a backend
  - Complex topic, not enough time...
  - Most optimizations happen in the middle-end anyway

The LLVM compiler pipeline

The lingua franca of LLVM is its **Intermediate Representation** called

LLVM-IR

The LLVM-IR is:

- **Produced** by the **front-end**
- **Transformed and optimized** by the **middle-end**
- **Consumed** by the **back-end**

Understanding LLVM-IR is the key to hacking within LLVM.

Remember...

LLVM is a **compiler construction framework**
It operates on the **LLVM-IR** language.

$\Downarrow$

Using LLVM *by itself* does not make much sense!
Writing LLVM-IR by hand is unfeasible.

The Middle End

The middle-end is not a monolithic block,
but it is a pipeline in and of itself.

LLVM-IR	the **language** used in the middle-end
Pass	a **pipeline stage** a Pass may have **dependencies** on other Passes.
Pass Manager	component that **schedules** passes according to their **dependencies** and **executes** them *(builds the pipeline)*

Our focus: **writing a pass**

First insights

A compiler is **complex**:

- passes are the **elementary unit of work**
- Pass Manager must be **advised** about pass chaining
- pipeline shapes are **not fixed** – they can change from one compiler execution to another

  e.g. optimized/not optimized builds, compiler options, ...

A word of warning!

Compilers must be **conservative**:

$\Downarrow$

All passes **must preserve the program semantics**

$\Downarrow$

Compiler passes must be designed **very carefully**!

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Classical Algorithm Design

In algorithm design, a good approach is the following:

1. study the problem
2. make some example
3. identify the **common case**
4. derive the algorithm for the common case
5. add handling for **corner cases**
6. improve performance by **optimizing the common case**

Weakness of the approach:

- **corner cases**:
  a *correct* algorithm **must** consider *all the corner cases*!

Compiler Algorithm Design

Corner cases are difficult to handle, but they cannot be ignored

Compiler algorithms must be **proven** to preserve
program semantic **at all times**

As an aid, a *standard methodology* is employed.

Compiler algorithms are built combining **three** kinds of passes:

Analysis, Optimization, Normalization

Compiler Algorithm Design

Corner cases are difficult to handle, but they cannot be ignored

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Compiler algorithms are built combining **three** kinds of passes:

Analysis, Optimization, Normalization

We now consider a simple example: *loop hoisting*.

Loop Hoisting

It is a transformation that:

- looks for statements (inside a loop) not depending on the loop state
- move them outside the loop body

Loop Hoisting – Before

```
do {
  a += i;
  b = c;
  i++;
} while (i < k);
```

Loop Hoisting – After

```
b = c;
do {
  a += i;
  i++;
} while (i < k);
```

Loop Hoisting

The general idea:

- move “good” statement outside of the loop

This **pass** modifies the code, thus it is an **optimization pass**.
It needs to know:

- which pieces of code are loops
- which statements are “good” statements

This information is computed by the the **analysis** passes:

- detecting loops in the program
- detecting loop-independent statements

The loop hoisting pass declares which analyses it needs:

- pipeline automatically built: **analysis** $\rightarrow$ **optimization**

Loop Hoisting

The **proof** is trivial:

- the transformation shall preserve program semantics
- the analyses shall be correct

Analysis passes are usually built starting from other analyses already implemented inside the compiler, or are already present in LLVM

- often, no proof is necessary for the analyses

However...

You also have to prove that the combination of analysis + transformation is correct!

”Beware of bugs in the above code;
I have only proved it correct, not tried it.”
— Knuth

The importance of normalization

We have spoken about loops, but which kind of loop?

`do-while`? **`while`**? **`for`**?

Almost all loops are different forms of the **same exact thing**

$\Downarrow$

We can convert a lot of loops to a loop of another kind!

To account for the various kinds of loops, we choose a **normal** kind of loop, and then we write a **normalization** pass.

Usually, **`do-while`** loops are chosen to be the *normal* loops.
Sometimes, normalization is also called **canonicalization**.

The more loops we recognize, the higher the potential **optimization impact**!

A Methodology

You have to:

1. analyze the problem
2. make some examples
3. detect the common case
4. determine the **input conditions**
5. determine which **analyses** you need
6. design the **optimization** pass
7. proof its **correctness**
8. improve algorithm perfomance on the common case
9. improve the effectiveness of the algorithm by adding **normalization passes**

Ignore corner cases!

Something is missing...

Corner Cases!

Why?

1. It makes no sense to optimize code that is seldom executed
2. Your optimization will be based on **properties of the code that are true only in the common case you are considering**
   - If the code does not fit the common case, it shall stay as-is
   - Otherwise you **risk breaking program semantics**!

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LLVM-IR is like a box of chocolates

LLVM-IR comes in 3 different flavours:

assembly	on-disk human-readable format (file extension: `.ll`)
bitcode	on-disk machine-oriented binary format (file extension: `.bc`)
in-memory	in-memory binary format (used during compilation process)

All formats have the same expressiveness!

Using the driver to produce LLVM-IR

We can generate LLVM-IR assembly using the `clang` driver:

```
clang -emit-llvm -S -o out.ll in.c
```

If you want to generate bitcode instead:

```
clang -emit-llvm -o out.bc in.c
```

The compiler driver can also generate native code starting from LLVM-IR assembly

(Like compiling an assembly file with GCC)

Playing with LLVM Passes

Run one or more passes on the LLVM-IR on-demand by using `opt`:

- Syntax is like `clang` (supports even `-O1`, `-O2`...)
- One command line argument per pass to run
- Order of execution is the same as the argument order
  - Different order, different results! (**phase/stage ordering**)

Some useful passes for debugging (they do not transform anything):

print CFG	`opt -view-cfg input.ll`
print dominator tree	`opt -view-dom input.ll`
print current IR	`opt -print-module input.ll`

Example

- Run *mem2reg*, then view the CFG:
  - `opt -mem2reg -view-cfg input.ll`

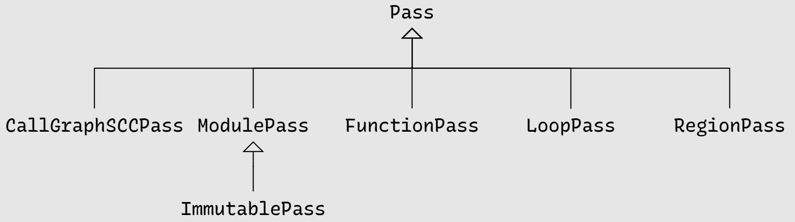
Pass Hierarchy

LLVM provides a lot of passes...

- Try `opt -help`!

For performance reasons there are different kind of passes:

LLVM Passes



LLVM Passes

Each kind of pass visits particular elements of a module:

ImmutablePass	compiler configuration – never run
CallGraphSCCPass	post-order visit of CallGraph SCCs
ModulePass	visit the whole module
FunctionPass	visit functions
LoopPass	post-order visit of loop nests
RegionPass	visit a custom-defined region of code

Specializations come with restrictions:

- e.g. a **FunctionPass** cannot add or delete functions
- refer to “Writing a LLVM Pass” [4] for documentation on features and limitations of each kind of pass

Recap

- The **user** invokes the **compiler** via the **driver**
- The **compiler** is made of three **stages** (front-end, middle-end, back-end)
- The **middle-end** is made of **passes**

If you want things done, you want to work on a **pass**.

- Edit an existing pass
- Create a new pass

To design a pass, you must follow the principle of **conservativeness**.

Next step: how to actually code a pass!

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How passes work

A **pass** is a **subroutine** that programmatically transforms a piece of code.

The code of the pass operates on the LLVM-IR using a set of **object-oriented APIs**.

Let's examine the LLVM-IR [5] more closely, first by looking at its **human-readable** form.

LLVM-IR

```
define i32 @fact(i32 %n) {
entry:
  %retval = alloca i32, align 4
  %n.addr = alloca i32, align 4
  store i32 %n, i32* %n.addr, align 4
  %0 = load i32, i32* %n.addr, align 4
  %cmp = icmp eq i32 %0, 0
  br i1 %cmp, label %if.then, label %if.end

if.then:
  store i32 1, i32* %retval, align 4
  br label %return

if.end:
  %1 = load i32, i32* %n.addr, align 4
  %2 = load i32, i32* %n.addr, align 4
  %sub = sub nsw i32 %2, 1
  %call = call i32 @fact(i32 %sub)
  %mul = mul nsw i32 %1, %call
  store i32 %mul, i32* %retval, align 4
  br label %return

return:
  %3 = load i32, i32* %retval, align 4
  ret i32 %3
}
```

LLVM-IR

LLVM-IR looks a lot like a RISC assembly language:

- Few instructions, all perfectly orthogonal
  - There are infinite registers
  - There are no special-purpose registers
  - No implicit flags register
- Basic block boundaries are denoted by **labels**
- Only **`load`** and **`store`** access memory

There are also a few CISC-like **high level instructions**:

- Reserve memory on the stack – **`alloca`**
- Function call – **`call`**
  - The calling convention is abstracted away
  - There is an implicit call stack
- Pointer arithmetics – **`getelementptr`**
- …

LLVM-IR

In reality LLVM-IR is much more high-level than assembly.

- The topmost object of a LLVM-IR program is the **Module**.
- **Modules** contain a list of **Globals**.
  - Globals can be either **Functions** or **Global Variables**.
  - A global can be a **Forward declaration**.
- **Functions** contain a list of **Basic Blocks** + **Arguments**.
- **Basic Blocks** are a list of **Instructions**.

The in-memory representation

All these parts will correspond directly to **C++ objects**.
The abundance of lists guarantees low overhead and scalability to very large programs.

LLVM-IR

LLVM-IR is **strongly typed**:

- e.g. you cannot assign a floating point value to an integer register without an explicit cast

Almost everything is **typed**:

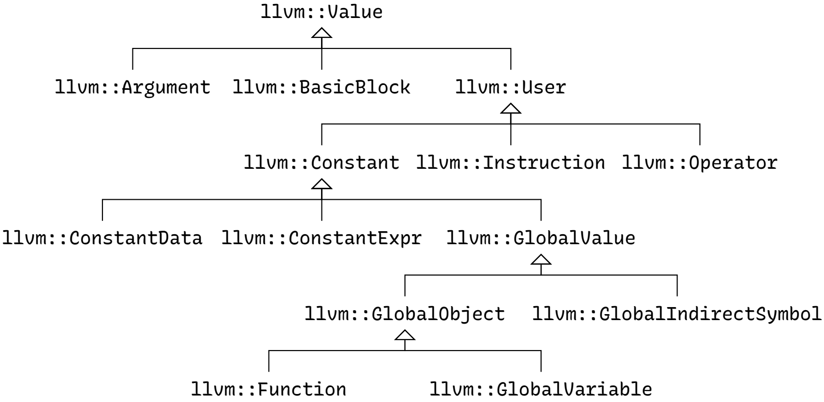
functions	`@fact`	$\longrightarrow$	`i32 (i32)`
registers	`%3 = icmp eq i32 %2, 0`	$\longrightarrow$	`i1`
globals var.	`@var = common global i32 0`	$\longrightarrow$	`i32`

These objects that have a type are called (somewhat confusingly) **LLVM Values**.

The in-memory representation

`llvm::Value` is the **base class** of almost all interesting LLVM-IR objects!

LLVM-IR


llvm::Value
llvm::Argument
llvm::BasicBlock
llvm::User
llvm::Constant
llvm::Instruction
llvm::Operator
llvm::ConstantData
llvm::ConstantExpr
llvm::GlobalValue
llvm::GlobalObject
llvm::GlobalIndirectSymbol
llvm::Function
llvm::GlobalVariable

LLVM-IR

LLVM-IR is SSA-based:

- every register is **statically assigned** exactly **once**

Statically means that:

- inside each function...
- ...for each variable `%foo`...
- ...there is **only one** statement in the form `%foo = ...`

Static (compile time) $\neq$ **dynamic** (runtime)

- Single *Dynamic* Assignment:
  in the execution trace there is only one assignment to a variable `x`
- Single *Static* Assignment:
  in the code listing there is only one assignment to a variable `x`
  - Assignments **can** be performed multiple times (in a loop for example)

Static Single Assignment

Scalar SAXPY

```
float saxpy(float a, float x, float y) {
    return a * x + y;
}
```

Scalar LLVM SAXPY

```
define float @saxpy(float %a, float %x, float %y) {
  %1 = fmul float %a, %x
  %2 = fadd float %1, %y
  ret float %2
}
```

Temporary %1 not reused! %2 is used for the second assignment!

Static Single Assignment

Array SAXPY

```
void saxpy(float a, float x[4], float y[4], float z[4]) {
  for(unsigned i = 0; i < 4; ++i)
    z[i] = a * x[i] + y[i];
}
```

Array LLVM SAXPY

```
for.cond:
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %cmp = icmp ult i32 %i.0, 4
  br i1 %cmp, label %for.body, label %for.end
  [...]
for.inc:
  %inc = add i32 %i.0, 1
  br label %for.cond
```

One assignment for loop counter `%i.0`

Static Single Assignment

Max

```
float max(float a, float b) {
  return a > b ? a : b;
}
```

LLVM Max – WRONG

```
  %1 = fcmp ogt float %a, %b
  br i1 %1, label %if.then, label %if.else
if.then:
  %2 = %a
  br label %if.end
if.else:
  %2 = %b
  br label %if.end
if.end:
  ret float %2
```

Why is it **wrong**?

Static Single Assignment

The `%2` variable must be statically assigned once!
How do we handle conditional assignments then?

LLVM Max

```
  %1 = fcmp ogt float %a, %b
  br i1 %1, label %if.then, label %if.end
if.then:
  br label %if.end
if.else:
  br label %if.end
if.end:
  %2 = phi float [ %a, %if.then ], [ %b, %if.else ]
  ret float %2
```

The **`phi`** instruction is a *conditional move*:

- it takes $(\text{variable}_i, \text{label}_i)$ pairs
- if coming from predecessor identified by label_i, its value is variable_i

Static Single Assignment

Each SSA variable is assigned only once:

- variable **definition**

Each SSA variable can be referenced by multiple instructions:

- variable **uses**

Algorithms and technical language abuse of these terms!

Let %foo be a variable. If the definition of %foo does not have side-effects nor uses, the aforementioned %foo variable can be erased from the CFG without altering program semantics.

SSA & LLVM-IR

Important observation

SSA means that
there is always a 1:1 correspondence
between a register and the instruction that assigns it.

Consequence

As a result, in LLVM-IR
registers are not separate objects
but **every LLVM Instruction**
is the output “register” of itself.

Static Single Assignment

Old compilers are not SSA-based:

- converting non-SSA input into SSA form is expensive
- cost must be amortized

New compilers are SSA-based:

- SSA easier to work with
- SSA-based analysis/optimizations are faster

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A step back...

Remember how we described the internal structure of an LLVM-IR module:

- `llvm::Module` is a list of `llvm::GlobalValues`.
  - `llvm::Function` is a kind of `llvm::GlobalValue`.
- `llvm::Function` is a list of `llvm::BasicBlocks`.
- `llvm::BasicBlock` is a list of `llvm::Instruction`.

Functions and basic blocks act like containers:

- STL-like accessors: `front()`, `back()`, `size()`, …
- STL-like iterators: `begin()`, `end()`

Each contained element is aware of its container:

- `getParent()`

Warning for BBs: order of iteration $\neq$ order of execution!

A step back...

In a `llvm::BasicBlock`, the `llvm::Instructions` execute in the order specified by the list.

- In which order do the `llvm::BasicBlocks` execute?

The way the basic blocks are executed is implcitly described by the **branches** in each block.

- These branches describe the **Control Flow Graph** of the function.

Control Flow Graph

LLVM automatically maintains a simple API for operating on the CFG:

- no need to run passes
- no need to search the branch instructions in each basic block

Every CFG has an **entry** basic block:

- the **first** executed basic block
- it is the **root/source** of the graph
- get it with `llvm::Function::getEntryBlock()`

Control Flow Graph

At the end of a basic blocks there's always a **terminator** instruction:

- **`ret`**, **`br`**, **`switch`**, **`unreachable`**, …

More than one **exit** block can be present in a function:

- they are the **leaves/sinks** of the graph
- their terminator instructions are always **`ret`**s
    1. `llvm::BasicBlock::getTerminator()`
    2. check the opcode of the terminator

Side Note

For performance reasons, a custom casting framework is used:

- you cannot use **`static_cast`** and **`dynamic_cast`** with types/classes provided by LLVM

LLVM Casting Functions

Static cast of `Y*` to `X`	`X *llvm::cast<X>(Y *)`
Dynamic cast of `Y*` to `X`	`X *llvm::dyn_cast<X>(Y *)`
Is `Y*` an instance of `X`?	`bool llvm::isa<X>(Y *)`

Example:

- is `BB` a sink?
  `llvm::isa<llvm::ReturnInst>(BB.getTerminator())`

Control Flow Graph

Every basic block `BB` has one or more*:

predecessors from `pred_begin(BB)` to `pred_end(BB)`

successors from `succ_begin(BB)` to `succ_end(BB)`

Other convenience methods available in `llvm::BasicBlock`:

- useful getters
  - `BasicBlock *getUniquePredecessor()`
  - …
- moving a basic block
  - `moveBefore(llvm::BasicBlock *)`
  - `moveAfter(llvm::BasicBlock *)`
- split a basic block:
  - `splitBasicBlock(llvm::BasicBlock::iterator)`
- …

---

*see include/llvm/IR/CFG.h

Control Flow Graph

The `llvm::Instruction` class defines common operations:

- getting an operand
  - `getOperand(unsigned)`

Subclasses provide specialized accessors:

- the **`load`** instruction takes as operand the pointer to the memory to be loaded:
  - `llvm::LoadInst::getPointerOperand()`

Instructions

Instructions are created using:

- constructors
  - `llvm::LoadInst::LoadInst(...)`
- factory methods
  - `llvm::GetElementPtrInst::Create(...)`
- the helper class `llvm::IRBuilder`
  - ```
    llvm::IRBuilder<> builder(insPoint);
    builder.CreateAdd(...);
    ```

Interface is not homogeneous!
Some instructions support all methods, others support only one.
    ```

Instructions

Instructions can be inserted:

- automatically by `IRBuilder`
  - insertion point is given at `IRBuilder` instantiation
- manually by appending to a basic block
- manually by inserting after/before another instruction

From Control Flow to Data Flow

In LLVM, the data flow generated by the various instructions is represented by a simple hierarchy:

value	something that can be used: `llvm::Value`
user	something that can use: `llvm::User`
use	the link between the **value** and the **user**: `llvm::Use`

A value is a **definition**:

- Visiting where a definition is used:
  - `llvm::Value::use_begin()`, `llvm::Value::use_end()`

An user accesses **definitions**:

- Visiting the definitions that are used:
  - `llvm::User::op_begin()`, `llvm::User::op_end()`

From Control Flow to Data Flow

- `llvm::Value` inherits from `llvm::User`
- `llvm::Instruction` inherits from `llvm::Value`
  - $\Rightarrow$ The value produced by the instruction is the **instruction itself**!

Example

```
%6 = load i32, i32* %1, align 4
```

The **`load`** is described by an instance of `llvm::Instruction`.
That instance also represents the `%6` variable.

Not all instances of `llvm::Value` are also `llvm::Instructions`!

i.e. function arguments

From Control Flow to Data Flow

Every `llvm::Value` is typed:

- use `llvm::Value::getType()` to get the type

Since every instruction is a value:

- instructions are typed

Example

```
%6 = load i32, i32* %1, align 4
```

The type of the `%6` variable is the type of the return value of the **`load`** instruction, `i32`

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Conclusions

LLVM is a **production-quality** compiler framework:

$\Rightarrow$ impossible knowing all details

But:

- it is well organized
- if you know compiler theory, it is relatively easy to find what you need inside the source code

Remember it's written in C++!

- To hack around LLVM you need at least basic C++ skills
- C++ $\neq$ C

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