The LLVM compiler framework

Introduction

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Contents

Compilers and compilers

Not all compilers are the same... The traditional distinction was:

Toy Compiler

- small codebase
- easy to modify
- limited capabilities

Production-Quality Compiler

- huge codebase
- hard to modify
- produces high-quality code

Working with a production-quality compiler is *initially* **hard**...

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

LLVM: Low Level Virtual Machine

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

Now it has grown to a huge size...

- Key technology in the **industry**: AMD, Apple, Google, Intel, NVIDIA...
- Still intensively used in **research** about compilers

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*

Contents

Compiler pipeline

Typically a compiler is a **pipeline**.

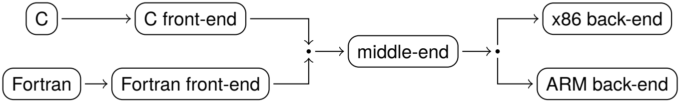
Advantages of the pipeline model:

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

Complexity lies on **chaining** together stages.

Compiler pipeline

High-level pipeline structure of a compiler:



There are three main components:

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

Middle-end **analyze** the intermediate representation, **optimize** it

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

The LLVM compiler pipeline

We will consider only the *middle-end*.

Same concepts are valid also for {front,back}-end.

IR	(a.k.a. Intermediate Representation) 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)*

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**!

Contents

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 performancing **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

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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

Loop Hoisting

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**!

Compiler Algorithm Design

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**

Compiler Algorithm Design

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**!

Contents

Using LLVM

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.

Terminology

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!

Frontends and Drivers

The LLVM-IR input to LLVM is provided by **frontends**.

Example

Clang[3] is the frontend for the C language family

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

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

Example

The driver of *Clang* is the `clang` executable (compatible with GCC)

Frontends and Drivers

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)

Tools

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`

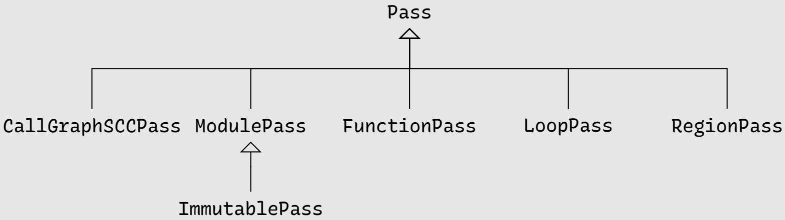
Pass Hierarchy

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

Normalization passes in LLVM

LLVM provides several **normalization/canonicalization** passes:

- Variable-to-register promotion (`Mem2Reg`)
- Loop canonicalization (`LoopSimplify`)
- CFG canonicalization & simplification (`SimplifyCFG`)
- …

They are useful to make your life easier!

Contents

LLVM IR

The LLVM IR [5] language is RISC-based:

- instructions operates on **variables**
  - aka virtual registers, temporary values
- only **`load`** and **`store`** access memory
- **`alloca`** used to reserve memory on the stack

There are also a few **high level instructions**:

- function call – **`call`**
- pointer arithmetics – **`getelementptr`**
- …

LLVM IR

LLVM IR is **strongly typed**:

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

Almost everything is **typed**:

functions	`@fact`	$\rightarrow$	`i32 (i32)`
statements	`%3 = icmp eq i32 %2, 0`	$\rightarrow$	`i1`

A variable can be:

global	`@var = common global i32 0, align 4`
argument	`define i32 @fact(i32 %n)`
local	`%2 = load i32, i32* %1, align 4`

Local variables are defined by statements

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 Language

LLVM IR is SSA-based:

- every variable 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!

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.

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

Contents

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

Contents

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