Introduction to LLVM compiler framework

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Compilers and compilers

Approaching to compilers, we need to understand the difference between a *toy-compiler* and *production-quality compiler*.

Toy Compiler

- small code-base
- easy doing tiny edits
- impossible doing normal/big edits

Production-Quality Compiler

- huge code-base
- difficult performing any kind of edits
- compiler-code extremely optimized

Key concepts:

- working with a production-quality compiler is *initially* **hard**, but . . .
- . . . an huge set of tools for analyzing/transforming/testing code is provided – toy compilers **miss these things**!

LLVM: Low Level Virtual Machine

Initially started as a research project at Urbana-Champaign:

- now intensively used for **researches** involving compilers
- key technology for **leading industries** – AMD, Apple, Intel, NVIDIA

If you are there, then it is **your key-technology**:

- open-source compilers: GCC [**?**], LLVM [**?**]
- LLVM is relatively **young** – GCC performances may be better – …
- … LLVM is more modular, well written, kept *clean* by developers.

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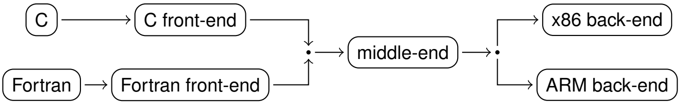
Compiler pipeline

Typically a compiler is a **pipeline**:



There are three main components:

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

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

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

Compiler pipeline

Each component is composed internally by pipelines:

- simple model – read something, produce something
- specify only how to transform input data into output data

Complexity lies on **chaining** together stages.

Compiler pipeline

We will consider only the *middle-end*: same concepts are valid also for {front,back}-end.

Technical terms:

Pass a pipeline stage

IR (a.k.a. Intermediate Representation) is the language used in the middle-end.

The **pass manager** manages a set of passes:

- build the compilation pipeline: **schedule** passes together according to **dependencies**.

Dependencies are **hints** used by the pass manager in order to schedule passes.

First insights

A compiler is **complex**:

- passes are the **elementary unit of work**
- pass manager must be **advisee** about pass chaining
- pipeline shapes are **not fixed** – it can change from one compiler execution to another [1]

Moreover, compilers must be **conservative**:

- apply a transformation only if program **semantic is preserved**

Compiler algorithms are designed differently w.r.t. standard algorithms!

[1] e.g. optimized/not optimized builds, compiler options, ...

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Classical Algorithm Design

Dealing with 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:

- compiler algorithms must be **proved** to preserve program semantic
- having a common methodology helps on that

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

- analysis
- optimization
- (normalization)

Compiler Algorithm Design

Corner cases are difficult to handle:

- compiler algorithms must be **proved** to preserve program semantic
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Compiler algorithms are built combining three kind 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

Transformation

The transformation is trivial:

- move “good” statement outside of the loop

This is the **optimization pass**. It needs to know:

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

They are **analysis**, which have to be implemented by other passes:

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

When registering loop hoisting, also declare needed analysis:

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

Loop Hoisting

The **proof** is trivial:

- transformation is correct if analysis are correct, but . . .
- . . . usually analysis are built starting from other analysis already implemented inside the compiler

You have to prove that combining all analysis information gives you a correct view of the code:

- analysis information cannot induce optimization passes applying a transformation not preserving program semantic

Loop Hoisting

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

- `do-while` loops?
- `while` loop?
- `for` loops?

We have seen loop hoisting on:

- `do-while` loops

What about other kinds of loops?

- they must be normalized – i.e. transformed to `do-while` loops

Normalization passes do that:

- before running loop hoisting, you must tell to the pass manager that loop normalization must be run before

This allows to recognize more loops, thus potentially **improving optimization impact**!

Compiler Algorithm Design

You have to:

1. analyze the problem
2. make some examples
3. detect the common case
4. declare the **input format**
5. declare **analysis** you need
6. design an **optimization** pass
7. proof its **correctness**
8. improve algorithm perfomance by acting on common case – the only considered up to now. Please notice that corner cases are not considered – just do not try to optimize the corner cases
9. improve the effectiveness of the algorithm by adding **normalization passes**

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Terminology

LLVM IR comes with 3 different flavours:

assembly	human-readable format
bitcode	binary on-disk machine-oriented format
in-memory	binary in-memory format, used during compilation process

All formats have the same expressiveness!

File extensions:

.ll	for assembly files
.bc	for bitcode files

Tools

Writing LLVM assembly by hand is unfeasible:

- different front-ends available for LLVM
- use Clang [**?**] for the C family

The clang driver is compatible with GCC:

- $\approx$ same command line options

To generate LLVM IR:

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

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

It can also generate native code starting from LLVM assembly or LLVM bitcode – like compiling an assembly file with GCC

Tools

LLVM IR can be manipulated using `opt`:

- read an input file
- run specified LLVM passes on it
- respecting user-provided order

Useful passes:

- print CFG with `opt -view-cfg input.ll`
- print dominator tree with `opt -view-dom input.ll`
- …

Pass chaining:

- run *mem2reg*, then view the CFG with
  `opt -mem2reg -view-cfg input.ll`
- potentially different results using different option order (**phase/stage ordering**)

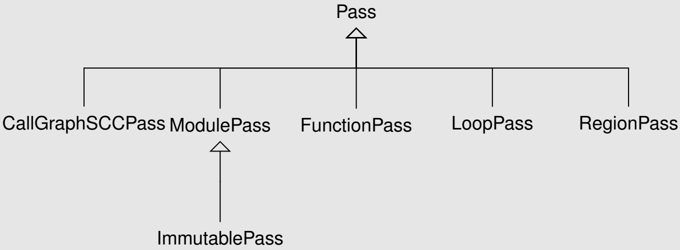
Pass Hierarchy

LLVM provides a lot of passes:

- try `opt -help`

For performance reasons there are different kind of passes:

LLVM Passes



LLVM Passes

Each pass kind 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 comes with restrictions:

- e.g. a **FunctionPass** cannot add or delete functions
- refer to "Writing a LLVM Pass" [**?**] for accurate description of features and limitations of each kind of pass

What is Available Inside LLVM?

LLVM provides passes performing basic transformations:

- variables promotion
- loops canonicalization
- …

They can be used to **normalize/canonicalize** the input

- transform into a form analyzable for further passes
- it is essential because keeps passes implementation manageable

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LLVM IR

LLVM IR [**?**] language is RISC-based:

- instructions operates on **variables** [2]
- only `load` and `store` access memory
- `alloca` used to reserve memory on function stacks

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

- function call – `call`
- pointer arithmetics – `getelementptr`
- ...

[2] Virtual registers

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** – e.g.:

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

A variable can be:

global	`@var = common global i32 0, align 4`
function parameter	`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
```

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 is different from dynamic:

- a static assignment can be executed more than once

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:
```

Static Single Assignment

Max

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

LLVM Max – Bad

```
  %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:
```

Static Single Assignment

The `%2` variable must be statically set 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 $(variable_i, label_i)$ pairs
- if coming from predecessor identified by $label_i$, its value is $variable_i$

Static Single Assignment

Each SSA variable is set only once:

- variable **definition**

Each SSA variable can be used by multiple instructions:

- variable **uses**

Algorithms and technical language abuse of these terms:

Let `%foo` be a variable. If `%foo` definition has not side-effects, and no uses, dead-code elimination can be efficiently performed by erasing `%foo` definition from the CFG.

Static Single Assignment

Old compilers are not SSA-based:

- putting input into SSA-form is expensive
- cost must be amortized

New compilers are SSA-based:

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

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Conclusions

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

$\Rightarrow$ impossible knowing all details

But:

- it is well organized
- given you known compilers theory, it is relatively easy to find what you need inside its sources

Please take into account C++:

- basic skills required

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