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: Open64 [1], GCC [2], LLVM [3]
- LLVM is relatively young – GCC performances are better – but . . .
- . . . it is highly modular, well written, kept *clean* by developers.

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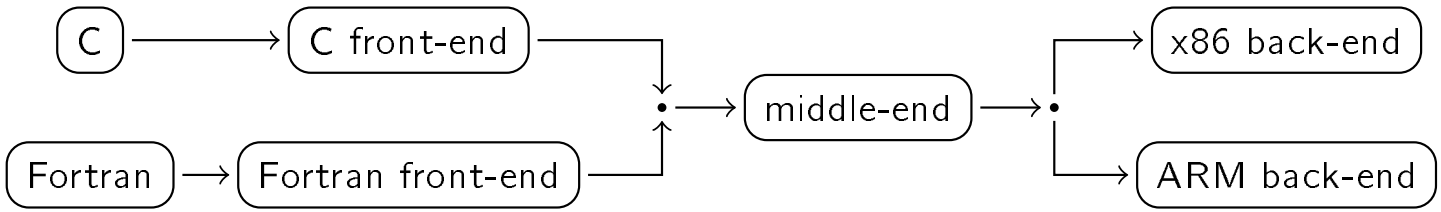
Compiler pipeline

Typically a compiler is a pipeline:



There are three main components:

Front-end translate a source file in the intermediate representation

Middle-end analyze intermediate representation, optimize it

Back-end generate target machine assembly from the intermediate representation

Compiler pipeline
Internal pipelines

Each component is composed internally by pipelines:

- simple model of computations – read something, produce something
- only needed to specify 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

Be Conservative

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

Be Conservative

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)

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

Loop Hoisting

It is a transformation that:

- looks for statements (inside the 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

Focus on the Transformation

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 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

Proving Program Semantic Preservation

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

More Loops

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

A methodology

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 optimize corner cases
9. improve the effectiveness of the algorithm by adding normalization passes

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Terminology
Speaking About LLVM IR

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

C Language Family Front-end

Writing LLVM assembly by hand is unfeasible:

- different front-ends available for LLVM
- use Clang [4] 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
Playing with LLVM Passes

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)

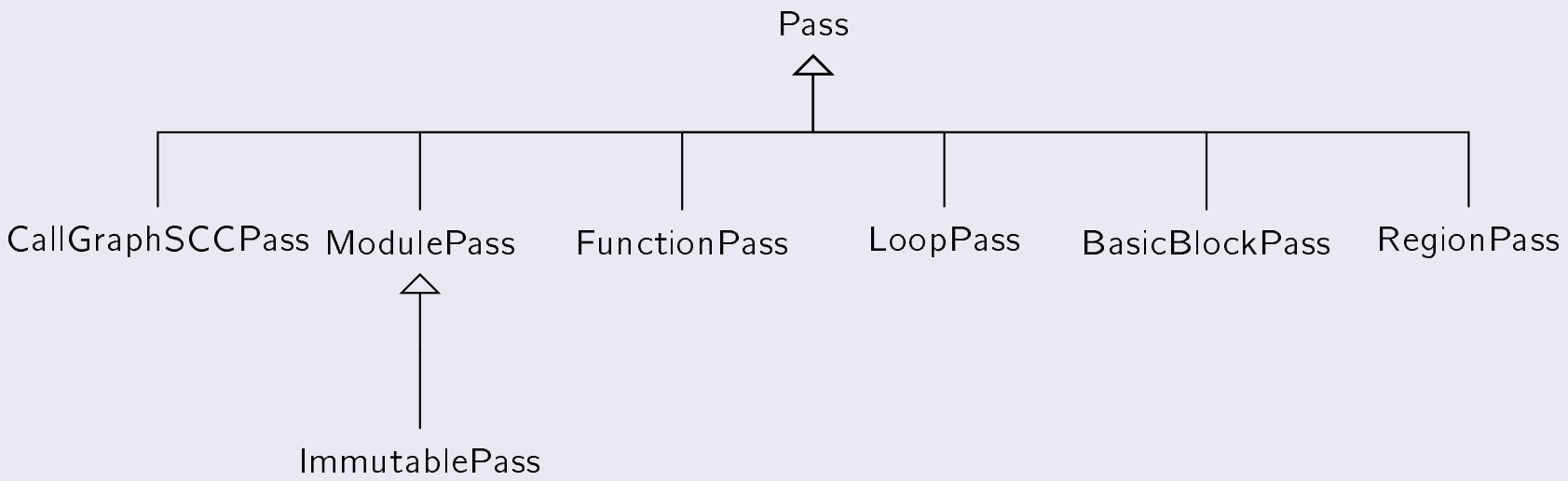
Pass Hierarchy

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
BasicBlockPass	visit basic blocks
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" [5] 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 [6] 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
Types & Variables

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

Example: factorial

```
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

Static Single Assignment

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
Examples

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
Examples

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
Handling Multiple Assignments

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:
  ret float %2
```

Why is it bad?

Static Single Assignment

Use **phi** to Avoid Troubles

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

Definition and Uses

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
Rationale

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

All modern compilers are SSA-based:

- exception are old version of the HotSpot Client compiler

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Conclusions

LLVM is a production-quality compiler framework:

⇒ impossible knowing all details

But:

- is well organized
- if you known compilers theory is “easy” finding what you need inside sources

Please take into account C++:

- basic skills required

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