

Building High-Level Compiler Optimizers and Code Generators for the Multicore Era

Introduction to LLVM compiler framework

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These slides contains material by M. Scandale and E. Speziale

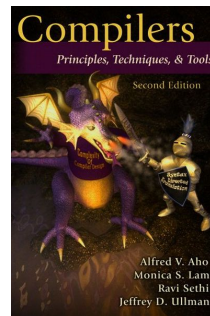
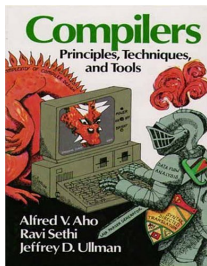


About the dragon

- The LLVM logo [1] is a stylized wyvern (mythological creature often mistaken for a dragon). Dragons have connotations of power, speed and intelligence, and can also be sleek, elegant, and modular (err, maybe not).

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- The LLVM logo [1] is a stylized wyvern (mythological creature often mistaken for a dragon). Dragons have connotations of power, speed and intelligence, and can also be sleek, elegant, and modular (err, maybe not).
- There is a series of compiler books dating back to the 1970s showing illustrations with dragons and knights [2] [3] [4]



About me

Stefano Cherubin

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- 2nd year PhD student @ Politecnico di Milano (Italy)
- working on compilers since relatively short time
- definitely not an experienced knight...

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- ...I'm more like a lazy Hobbit



About you

In order to fully understand the content of this course you should have:

- knowledge of what a compiler is
- proficiency in most common data structures
- proficiency in Object-Oriented Programming
- at least some experience with C++

About this talk

- Compiler design
- LLVM structure overview
- LLVM-IR language
- LLVM Documentation
- LLVM quick start

Goal of this talk

At the end of this speech you should:

- understand the LLVM compiler infrastructure
- be able to read a .ll file (LLVM-IR)
- know where to look for documentation
- navigate the LLVM code base

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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**:

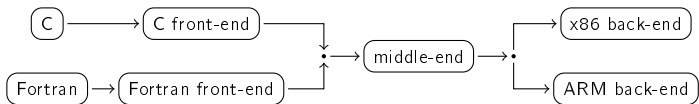
- open-source compilers: Open64 [5], GCC [6], LLVM [7]
- LLVM is relatively **young** – GCC performances are better – but . . .
- . . .it is highly modular, well written, kept *clean* by developers.

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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!

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

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Classical Algorithm Design

Dealing with algorithm design, a naive 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 **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
- normalization
- optimization

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 is then automatically built: analysis → 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 performance 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 [8] 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**)

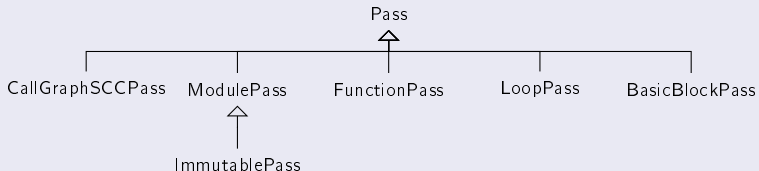
Pass Hierarchy

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

Specializations comes with restrictions:

- e.g. a `FunctionPass` cannot add or delete functions
- refer to [9] 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

Input normalization is **essential**:

- keep passes implementation manageable

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LLVM IR

LLVM IR [10] 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**
- ...

²Virtual 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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LLVM official documentation

llvm.org/docs

A lot of documentation...

`llvm.org/docs` mentions:

- 5 references about *Design & Overview*
- 19 references about *User Guides*
- 12 references about *Programming Documentation*
- 32 references about *Subsystem Documentation*
- 7 references about *Development Process Documentation*
- 5 Mailing Lists
- 5 IRC bots

Most of the above references are **OUT-OF-DATE**.

You probably need documentation about the documentation itself.

Essential documentation

[Intro to LLVM](#) [11] gives a quick and clear introduction to the compiler infrastructure. It is mostly up-to-date.³

[Writing an LLVM pass](#) [9] explains step by step how to implement a Pass for those who never did anything like that.

[Doxygen](#) [12] *The best code documentation is the code itself.* Sometimes the generated doxygen documentation is enough. It also contains links to the web version of the source code. It is always up-to-date.

[llvm-dev](#) Mailing List. Last resource: ask other developers.
Warning: 24/7 many people are posting in this ML.

³at the time I am writing

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Commands

`llvm-as` LLVM assembler

`llvm-dis` LLVM disassembler

`opt` LLVM optimizer

`llc` LLVM static compiler

`lli` directly execute programs from LLVM bitcode

`llvm-link` LLVM bitcode linker

`llvm-lib` LLVM lib.exe compatible library tool

`llvm-nm` list LLVM bitcode and object file's symbol table

`llvm-config` Print LLVM compilation options

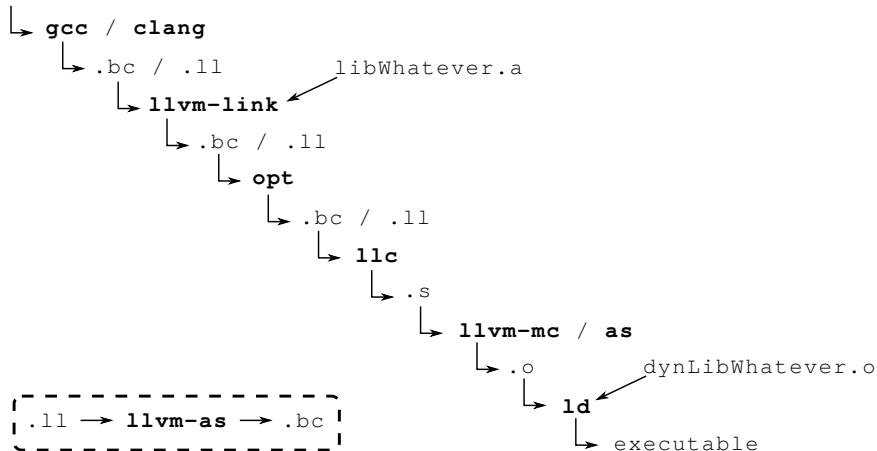
`llvm-stress` generate random .ll files

`llvm-dwarfdump` print contents of DWARF sections

For a complete reference, see LLVM command guide ⁴

⁴<http://llvm.org/docs/CommandGuide/index.html>

.c source



Writing a LLVM pass

There are a lot of tutorials available:

- Official developer guide
llvm.org/docs/WritingAnLLVMPass
- Out-of-source pass
github.com/quarkslab/llvm-dev-meeting-tutorial-2015

Testing

LLVM has an internal testing infrastructure. ⁵ Please use it.

`llvm-lit` LLVM Integrated Tester

- 1 Forge a proper LLVM-IR input file (.ll) for your test case
- 2 Instrument it with `lit` script comments
- 3 Run `lit` on your test
 - `llvm-lit /llvm/test/myTests/singleTest.ll`
run a single test
 - `llvm-lit /llvm/test/myTests`
run the test suite (folder)
- 4 Run `lit` on the LLVM test suite (regression testing)

To submit a bug report to LLVM developers you will be asked to write a `lit` test case that highlights the bug.

⁵<http://llvm.org/docs/TestingGuide.html>

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Understanding LLVM

LLVM is not a compiler.

Understanding LLVM

LLVM is not a compiler.

LLVM is a collection of components
which is useful to build a compiler.

What LLVM is made of

- C++ libraries
 - `src/include/llvm/...`
 - `src/lib/...`

- small application (tools)
 - `src/tools/...`
 - `src/utils/...`

You can find binaries of them in the installation directory under `root/bin/...`

clang

- **clang** is a compiler based on LLVM.
- It compiles all major C-like languages
- It can be added as a tool in the LLVM framework but must be manually cloned in the tool directory
 - 1 `cd src/tools`
 - 2 `git clone http://llvm.org/git/clang`
- You can easily see on a production quality compiler the impact of changes you made on your local copy of LLVM

Conclusions

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

⇒ impossible knowing all details

But:

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

Please take into account C++:

- basic skills required

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