Introduction to LLVM compiler framework

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This material is strongly based on Ettore Speziale's material for the previous year course.

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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 [10], GCC [9], LLVM [14]
- LLVM is relatively young – GCC performances are better – but . . .
- . . . it is highly modular, well written, kept *clean* by developers.

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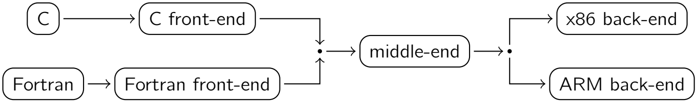
Compiler pipeline

Tipically 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 interemediate 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 structures 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!

[1] e.g. different optimization levels

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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

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

The transformation is trivial:

- move “good” statement outside of the loop

This is the optimization pass. It needs to known:

- loops
- “good” statements

They are analysis passes:

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

When registering loop hoisting, also the required analyses must be declared:

- pipeline automatically built – analyses → optimization

Loop Hoisting

Proving Program Semantic Preservation

The proof is trivial:

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

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

- analyses information cannot induce optimization passes that apply transformations not preserving the 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 the analyses 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 generally not considered – just do not optimize
9. improve the effectiveness of the algorithm by adding normalization passes

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LLVM IR

LLVM IR [11] 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* %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* %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
  br label %return

if.end:
  %1 = load i32* %n.addr, align 4
  %2 = load 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
  br label %return

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

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 [13] 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* [3], then view the CFG with `opt -mem2reg -view-cfg input.ll`

[3] More on this later

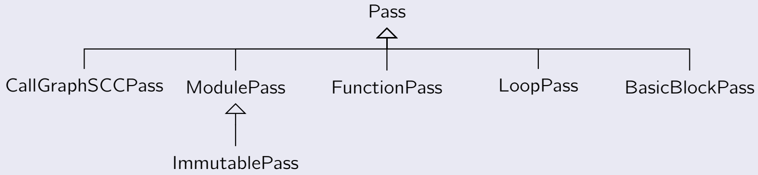
Pass Hierarchy

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 [12] for accurate description of features and limitations of each kind of pass

Examples

Now we will see very simple passes:

- some of them are meaningless
- goal is to show you the LLVM API

The passes are:

instruction-count simple instruction counting analysis

hello-llvm optimization pass building an hello-world program

function-eraser optimization pass removing "small" functions

Hint: take the LLVM pass writing tutorial [12]

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

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 `%5` 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:

$\Rightarrow$ 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

Conclusions

Inside LLVM there a lot of passes:

normalization put program into a canonical form (next lecture)

analysis get info about program (next lecture)

transformation generally code optimization

Please remember that

- a good compiler writer re-uses code
- check LLVM sources before re-implementing a pass

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