中山大學
SUN YAT-SEN UNIVERSITY

国家超级计算广州中心
NATIONAL SUPERCOMPUTER CENTER IN GUANGZHOU

Compiler Design
编 译 器 构 造 实 验

Lab 11：Project-3

张献伟、吴坎

xianweiz.github.io

DCS292, 4/28/2022

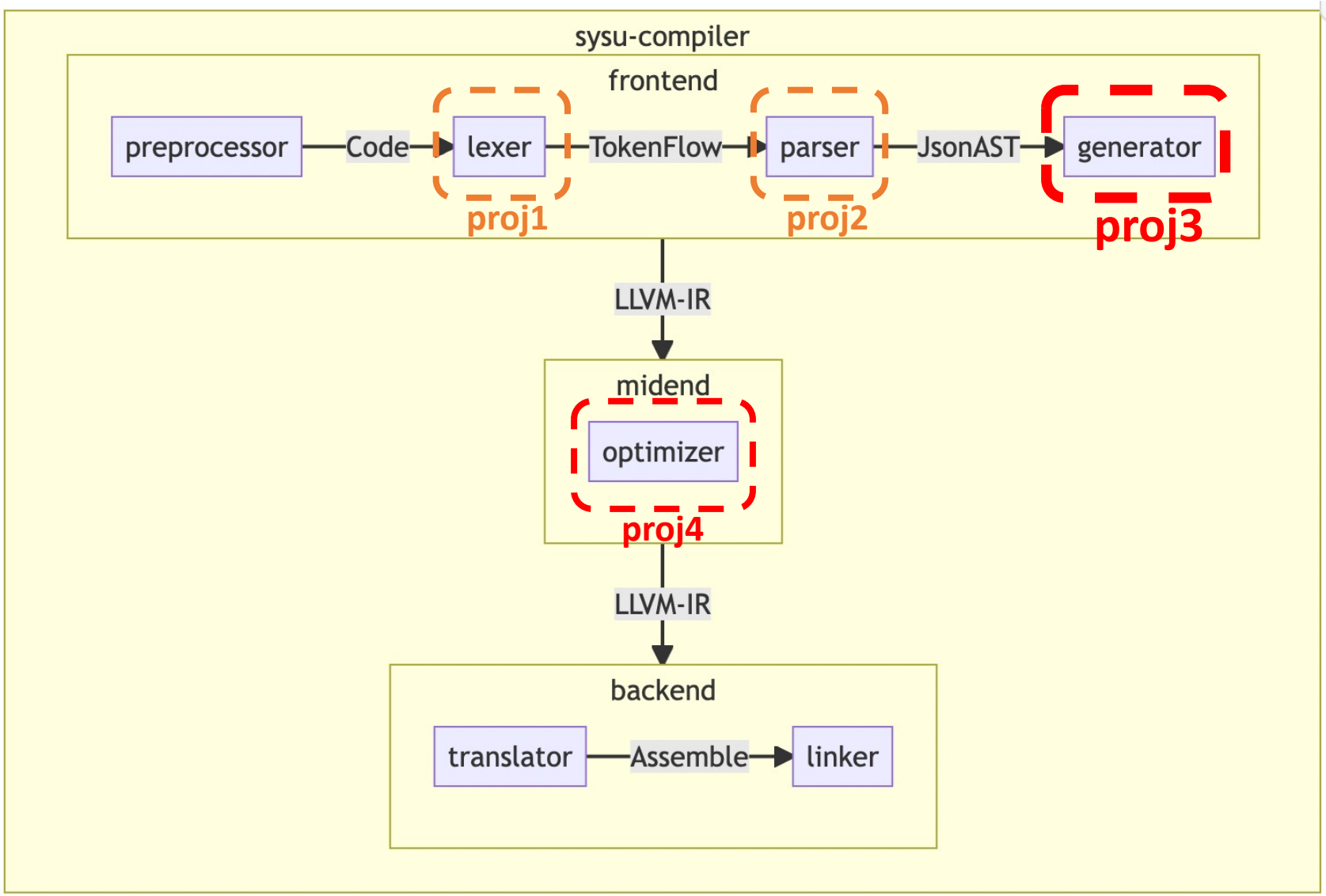
Project 3: What?

- 文档描述： https://github.com/arcsysu/SYsU-lang/tree/main/generator
- 实现一个IR生成器
  - 输入：抽象语法树（由Project 2或Clang提供）
  - 输出：LLVM-IR
- 总体流程
  - 引入Project2的parser（或使用clang）
  - 遍历得到的AST
  - 对各Function和Statement等生成IR代码
- 截止时间
  - **5/26/2022**

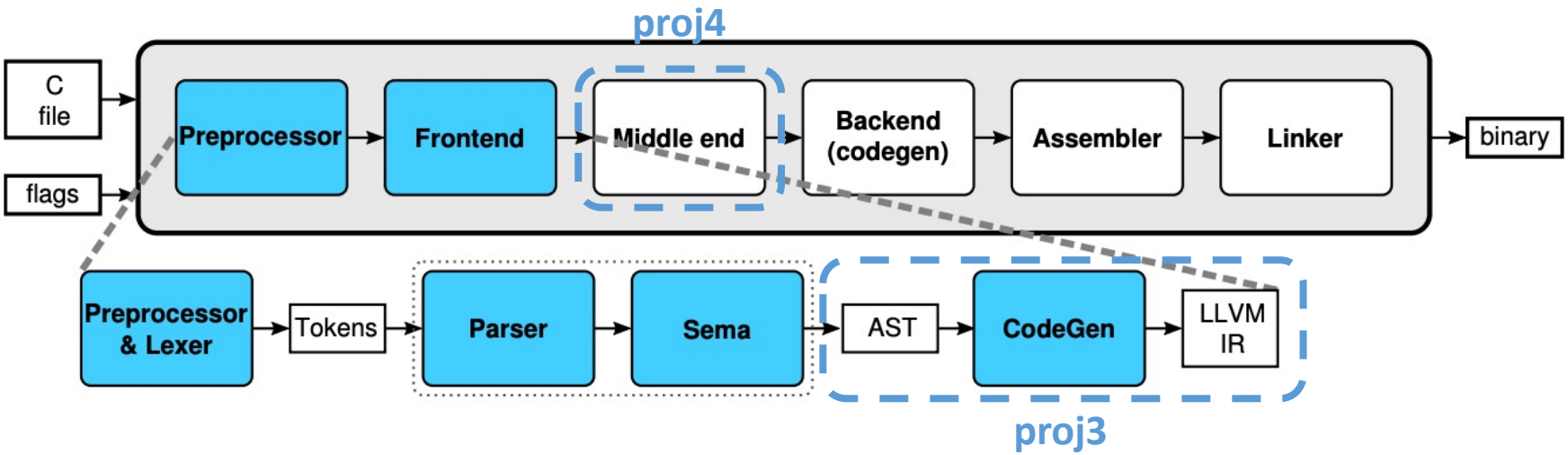
Project 3: How?

- 实现
  - $vim generator/generator.cc
- 编译
  - $cmake --build ~/sysu/build -t install
    - 输出：~/sysu/build/generator
- 运行
  - (export PATH=~/sysu/bin:$PATH \
    CPATH=~/sysu/include:$CPATH \
    LIBRARY_PATH=~/sysu/lib:$LIBRARY_PATH \
    LD_LIBRARY_PATH=~/sysu/lib:$LD_LIBRARY_PATH && clang -E tester/functional/000_main.sysu.c | <THE_PARSER> | sysu-generator)
    - Clang提供AST：<THE_PARSER> = clang -cc1 -ast-dump=json
    - Project2提供AST： <THE_ PARSER > = sysu-parser

Where we are NOW?



CodeGen[中间代码生成]



- Not to be confused with LLVM CodeGen! (which generates machine code)
- Uses AST visitors, IRBuilder, and TargetInfo
  - AST visitors
    - RecursiveASTVisitor for visiting the full AST
    - StmtVisitor for visiting Stmt and Expr
    - TypeVisitor for Type hierarchy

https://llvm.org/devmtg/2019-10/slides/ClangTutorial-Stulova-vanHaastregt.pdf
https://clang.llvm.org/docs/RAVFrontendAction.html

AST → IR: Example

$clang -Xclang -ast-dump -fsyntax-only ../tester/functional/000_main.sysu.c

```
TranslationUnitDecl 0x1d2654a8 <<invalid sloc>> <invalid sloc>
... cutting out internal declarations of clang ...
`-FunctionDecl 0x2cf71448 <../tester/functional/000_main.sysu.c:1:1, line:3:1> line:1:5 main 'int ()'
  `-CompoundStmt 0x2cf71560 <col:11, line:3:1>
    `-ReturnStmt 0x2cf71550 <line:2:5, col:12>
      `-IntegerLiteral 0x2cf71530 <col:12> 'int' 3
```

$clang -emit-llvm -S ../tester/functional/000_main.sysu.c

```
; ModuleID = '../tester/functional/000_main.sysu.c'
source_filename = "../tester/functional/000_main.sysu.c"
target datalayout = "e-m:e-i8:8:32-i16:16:32-i64:64-i128:128-n32:64-S128"
target triple = "aarch64-unknown-linux-gnu"

; Function Attrs: noinline nounwin
define dso_local i32 @main() #0 {
  %1 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  ret i32 3
}

attributes #0 = { noinline nounwind optnone "correctly-rounded-divide-sqrt-fp-math"
="false" "disable-tail-calls"="false" "frame-pointer"="non-leaf" "less-precise-fpma
d"="false" "min-legal-vector-width"="0" "no-infs-fp-math"="false" "no-jump-tables"=
"false" "no-nans-fp-math"="false" "no-signed-zeros-fp-math"="false" "no-trapping-ma
th"="true" "stack-protector-buffer-size"="8" "target-cpu"="generic" "target-feature
s"="+neon" "unsafe-fp-math"="false" "use-soft-float"="false" }

!llvm.module.flags = !{!0}
!llvm.ident = !{!1}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{!"Debian clang version 11.0.1-2"}
```

注释

源文件名

目标平台：数据布局[1]

目标平台：arch-vendor-os

函数定义：define <返回类型> @<函数名>（参数）#属性[2]

临时寄存器/变量：分配栈空间，地址存入%1，大小同i32类型，4B对齐

数据写入内存：将0写入%1对应的内存中，4B对齐

函数返回

函数属性

模块级别元数据信息[3]

Clang版本信息

[1] https://llvm.org/docs/LangRef.html#data-layout

[2] https://llvm.org/docs/LangRef.html#function-attributes

[3] LLVM之IR 篇（1）：零基础快速入门 LLVM IR

AST → IR: Example (cont.)

Source

```
1 int main(){
2     return 3;
3 }
```

AST

```
TranslationUnitDecl 0x1d2654a8 <<invalid sloc>> <invalid sloc>
            ... cutting out internal declarations of clang ...
`-FunctionDecl 0x2cf71448 <../tester/functional/000_main.sysu.c:1:1, line:3:1> line:1:5 main 'int ()'
  `-CompoundStmt 0x2cf71560 <col:11, line:3:1>
    `-ReturnStmt 0x2cf71550 <line:2:5, col:12>
      `-IntegerLiteral 0x2cf71530 <col:12> 'int' 3
```

IR

```
define i32 @main() {
  %1 = alloca i32
  store i32 0, i32* %1
  ret i32 3
}
```

```
define i32 @main() {
  ret i32 3
}
```

LLVM IR[中间代码]

- Three different forms (these three forms are equivalent)
  - in-memory compiler IR[在内存中的编译中间语言]
  - on-disk bitcode file[.bc, 在硬盘上存储的二进制中间语言]
  - human readable text asembly language file[.ll, 人类可读的代码语言]
- LLVM IR is machine independent[机器无关]
  - An unlimited set of virtual registers (labelled %0, %1, %2, %3…)
    - It's the backend's job to map from virtual to physical registers
  - Rather than allocating specific sizes of datatypes, we retain types
    - Again, the backend will take this type info and map it to the size of the datatype
  - We write LLVM IR in Static Single Assignment (SSA) form, making life easier for optimization writers[静态单赋值]
    - SSA just means we define variables before use and assign to variables only once

generator.cc

```
void buildTranslationUnitDecl(const llvm::json::Object *O) {
  if (O == nullptr)
    return;
  if (auto kind = O->get("kind")->getAsString()) {
    assert(*kind == "TranslationUnitDecl");
  } else {
    assert(0);
  }
  if (auto inner = O->getArray("inner"))
    for (const auto &it : *inner)
      if (auto P = it.getAsObject())
        if (auto kind = P->get("kind")->getAsString()) {
          if (*kind == "FunctionDecl")
            buildFunctionDecl(P);
        }
}
} // namespace

int main() {
  auto llvmin = llvm::MemoryBuffer::getFileOrSTDIN("-");
  auto json = llvm::json::parse(llvmin.get()->getBuffer());
  buildTranslationUnitDecl(json->getAsObject());
  TheModule.print(llvm::outs(), nullptr);
}
```

根节点

遍历内部节点

具体IR生成

从文件或stdin获取AST文本

解析为JSON格式

遍历AST，生成IR

输出IR

generator.cc (cont.)

```
llvm::LLVMContext TheContext;
llvm::Module TheModule("-", TheContext);

llvm::Function *buildFunctionDecl(const llvm::json::Object *O) {
  // First, check for an existing function from a previous declaration.
  auto TheName = O->get("name")->getAsString()->str();
  llvm::Function *TheFunction = TheModule.getFunction(TheName);

  if (!TheFunction)
    TheFunction = llvm::Function::Create(
        llvm::FunctionType::get(llvm::Type::getInt32Ty(TheContext), {}, false),
        llvm::Function::ExternalLinkage, TheName, &TheModule);

  if (!TheFunction)
    return nullptr;

  // Create a new basic block to start insertion into.
  auto BB = llvm::BasicBlock::Create(TheContext, "entry", TheFunction);
  llvm::IRBuilder<> Builder(BB);

  if (auto RetVal = llvm::ConstantInt::get(
          TheContext, /* i32 3(decimal) */ llvm::APInt(32, "3", 10))) {
    // Finish off the function.
    Builder.CreateRet(RetVal);

    // Validate the generated code, checking for consistency.
    llvm::verifyFunction(*TheFunction);

    return TheFunction;
  }

  // Error reading body, remove function.
  TheFunction->eraseFromParent();
  return nullptr;
}
```

用于保存全局的状态，在多线程执行的时候，可以每个线程一个LLVMContext，避免竞争

LLVM IR程序的顶层结构

创建一个函数，并指派给Module

参数：类型

参数：链接方式、函数名、该函数待插入的模块

“ExternalLinkage”表示该函数可能定义于当前模块之外，且/或可以被当前模块之外的函数调用。

int main()

为创建的Function添加Basic Block

使用IRBuilder插入指令到BB

return 3

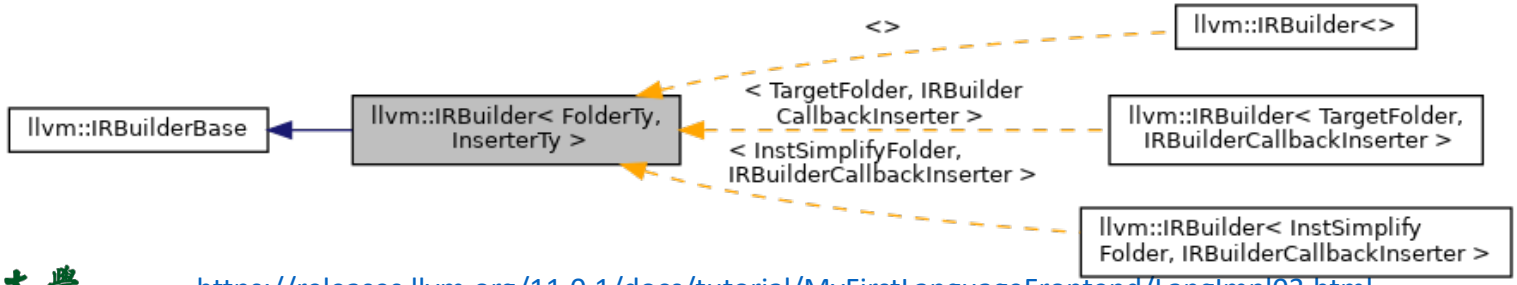
返回值指令语句

https://releases.llvm.org/11.0.1/docs/tutorial/MyFirstLanguageFrontend/LangImpl03.html
https://llvm.org/docs/tutorial/MyFirstLanguageFrontend/LangImpl03.html

https://github.com/arcsysu/SYsU-lang/blob/main/generator/generator.cc

Variables in codegen[相关变量]

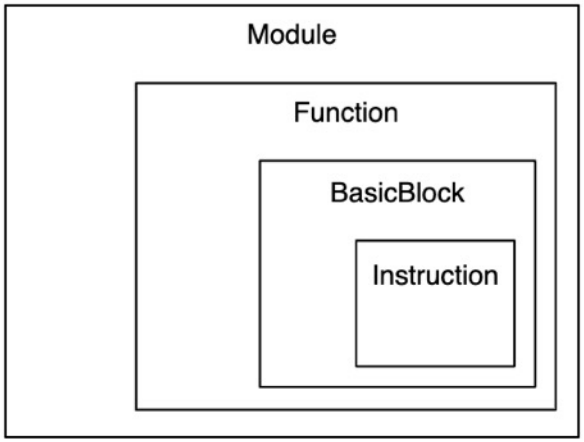
- **TheContext**: an opaque object that owns a lot of core LLVM data structures, such as the type and constant value tables
- **TheModule**: an LLVM construct that contains functions and global variables
  - In many ways, it is the top-level structure that the LLVM IR uses to contain code
- **Builder**: a helper object that makes it easy to generate LLVM instructions
  - Instances of the IRBuilder class template keep track of the current place to insert instructions and has methods to create new instructions

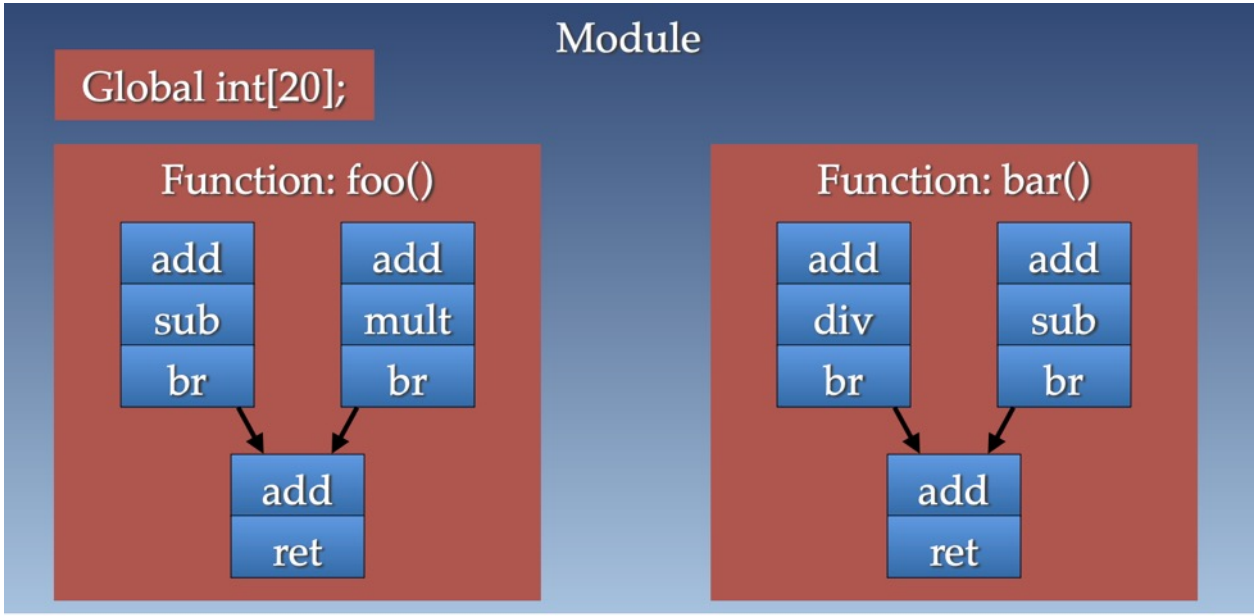


https://releases.llvm.org/11.0.1/docs/tutorial/MyFirstLanguageFrontend/LangImpl03.html
https://releases.llvm.org/8.0.0/docs/tutorial/LangImpl03.html

IR Overview

- Each assembly/bitcode file is a Module
- Each **Module** is comprised of
  - Global variables
  - A set of **Function**s which consists of
    - A set of **Basic Block**s
      - Which is further comprised of a set of **Instruction**s





https://cs.rochester.edu/u/ejohns48/secdev19/secdev20-llvm-tutorial-version4_copy.pdf

Visualize IR[可视化]

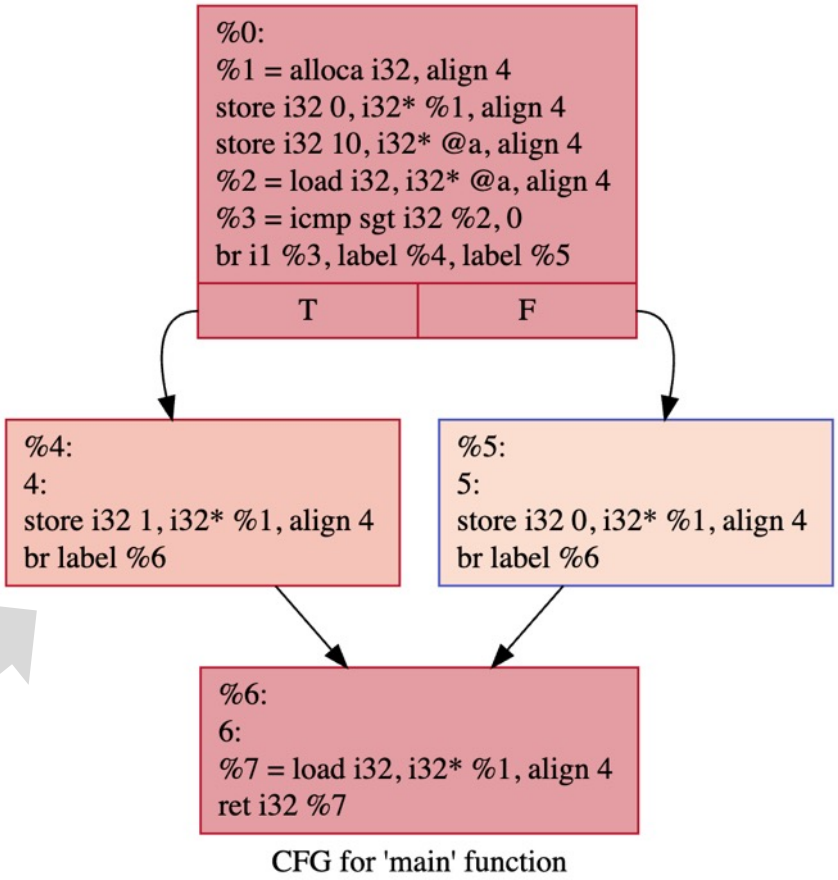
- $clang -emit-llvm -S ../tester/functional/027_if2.sysu.c

```
@a = dso_local global i32 0, align 4

define dso_local i32 @main() {
  %1 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  store i32 10, i32* @a, align 4
  %2 = load i32, i32* @a, align 4
  %3 = icmp sgt i32 %2, 0
  br i1 %3, label %4, label %5

4:
  store i32 1, i32* %1, align 4
  br label %6

5:
  store i32 0, i32* %1, align 4
  br label %6

6:
  %7 = load i32, i32* %1, align 4
  ret i32 %7
}
```

$opt -dot-cfg 027_if2.sysu.ll [→ .main.dot]

```
digraph "CFG for 'main' function" {
        label="CFG for 'main' function";

        Node0x2a784a90 [shape=record,color="#b70d28ff", style=filled, fillcolor="#b
70d2870",label="{%0:\l  %1 = alloca i32, align 4\l  store i32 0, i32* %1, align 4\l
  store i32 10, i32* @a, align 4\l  %2 = load i32, i32* @a, align 4\l  %3 = icmp sg
t i32 %2, 0\l  br i1 %3, label %4, label %5\l|{<s0>T|<s1>F}}"];
        Node0x2a784a90:s0 -> Node0x2a784c70;
        Node0x2a784a90:s1 -> Node0x2a784cc0;
        Node0x2a784c70 [shape=record,color="#b70d28ff", style=filled, fillcolor="#e
8765c70",label="{%4:\l4:                                                \l  store i
32 1, i32* %1, align 4\l  br label %6\l}"];
        Node0x2a784c70 -> Node0x2a784e50;
        Node0x2a784cc0 [shape=record,color="#3d50c3ff", style=filled, fillcolor="#f
7b39670",label="{%5:\l5:                                                \l  store i
32 0, i32* %1, align 4\l  br label %6\l}"];
        Node0x2a784cc0 -> Node0x2a784e50;
        Node0x2a784e50 [shape=record,color="#b70d28ff", style=filled, fillcolor="#b
70d2870",label="{%6:\l6:                                                \l  %7 = lo
ad i32, i32* %1, align 4\l  ret i32 %7\l}"];
}
```

http://viz-js.com/



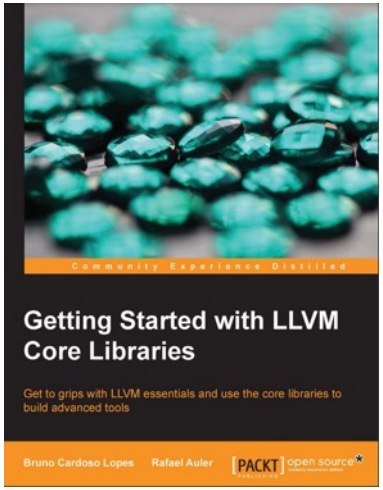
CFG for 'main' function

More …

- $(export PATH=~/sysu/bin:$PATH \ CPATH=~/sysu/include:$CPATH \ LIBRARY_PATH=~/sysu/lib:$LIBRARY_PATH \ LD_LIBRARY_PATH=~/sysu/lib:$LD_LIBRARY_PATH && clang -E tester/functional/000_main.sysu.c | <THE_PARSER> | sysu-generator)
  - S0: get AST
    - $clang -cc1 -ast-dump=json ../tester/functional/000_main.sysu.c > ast.json
  - S1: gen IR
    - $cat ast.json | ~/sysu/build/generator/sysu-generator
- Execute the IR file[1]: $lli *.ll*
  - Result: $echo $?
- Further compile the IR file: $clang *.ll* [-o ./a.out]
  - $(export PATH=~/sysu/bin:$PATH CPATH=~/sysu/include:$CPATH LIBRARY_PATH=~/sysu/lib:$LIBRARY_PATH LD_LIBRARY_PATH=~/sysu/lib:$LD_LIBRARY_PATH && clang -lsysy -lsysu *.ll* [-o ./a.out])
- Translate to bitcode file[2]: $llvm-as *.ll* [-o *.bc]
  - Reverse: $llvm-dis *.bc -o *.ll
  - Further compile the bitcode[3]: $llc –march=x86 *.bc -o out.x86*

[1] https://www.llvm.org/docs/CommandGuide/lli.html
[2] https://www.llvm.org/docs/CommandGuide/llvm-as.html
[3] https://www.llvm.org/docs/CommandGuide/llc.html

参考资料



LLVM Tutorial: Table of Contents

Kaleidoscope: Implementing a Language with LLVM

My First Language Frontend with LLVM Tutorial

This is the "Kaleidoscope" Language tutorial, showing how to implement a si

- 1. Kaleidoscope: Kaleidoscope Introduction and the Lexer
- 2. Kaleidoscope: Implementing a Parser and AST
- 3. Kaleidoscope: Code generation to LLVM IR
- 4. Kaleidoscope: Adding JIT and Optimizer Support
- 5. Kaleidoscope: Extending the Language: Control Flow
- 6. Kaleidoscope: Extending the Language: User-defined Operators
- 7. Kaleidoscope: Extending the Language: Mutable Variables
- 8. Kaleidoscope: Compiling to Object Code
- 9. Kaleidoscope: Adding Debug Information
- 10. Kaleidoscope: Conclusion and other useful LLVM tidbits

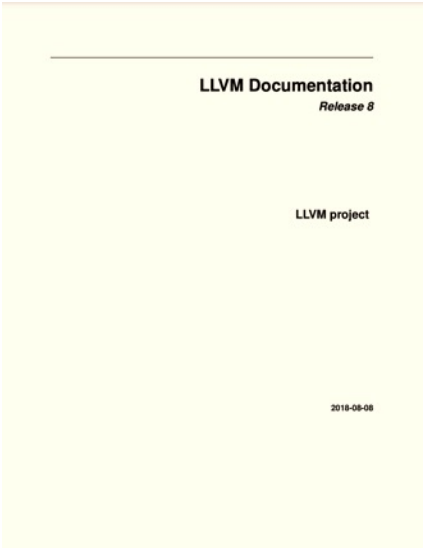
https://llvm.org/docs/tutorial/

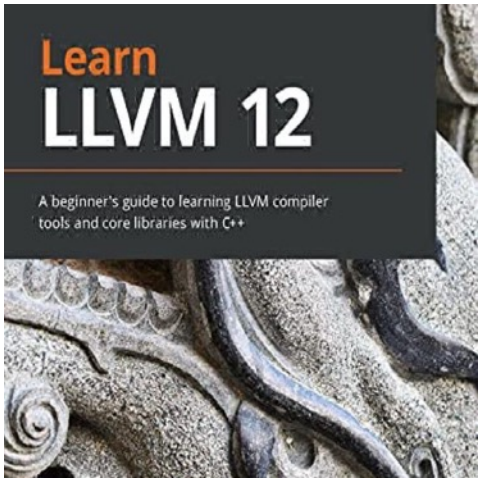
LLVM COMPILER INFRASTRUCTURE

LLVM Home | Documentation »

https://llvm.org/docs/

https://faculty.sist.shanghaitech.edu.cn/faculty/songfu/course/spring2018/CS131/llvm.pdf





https://github.com/xiaoweiChen/Learn-LLVM-12

https://bcain-llvm.readthedocs.io/_/downloads/llvm/en/latest/pdf/