Compiler Design
编 译 器 构 造 实 验

Lab 11：Project-3

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xianweiz.github.io

DCS292, 4/28/2022

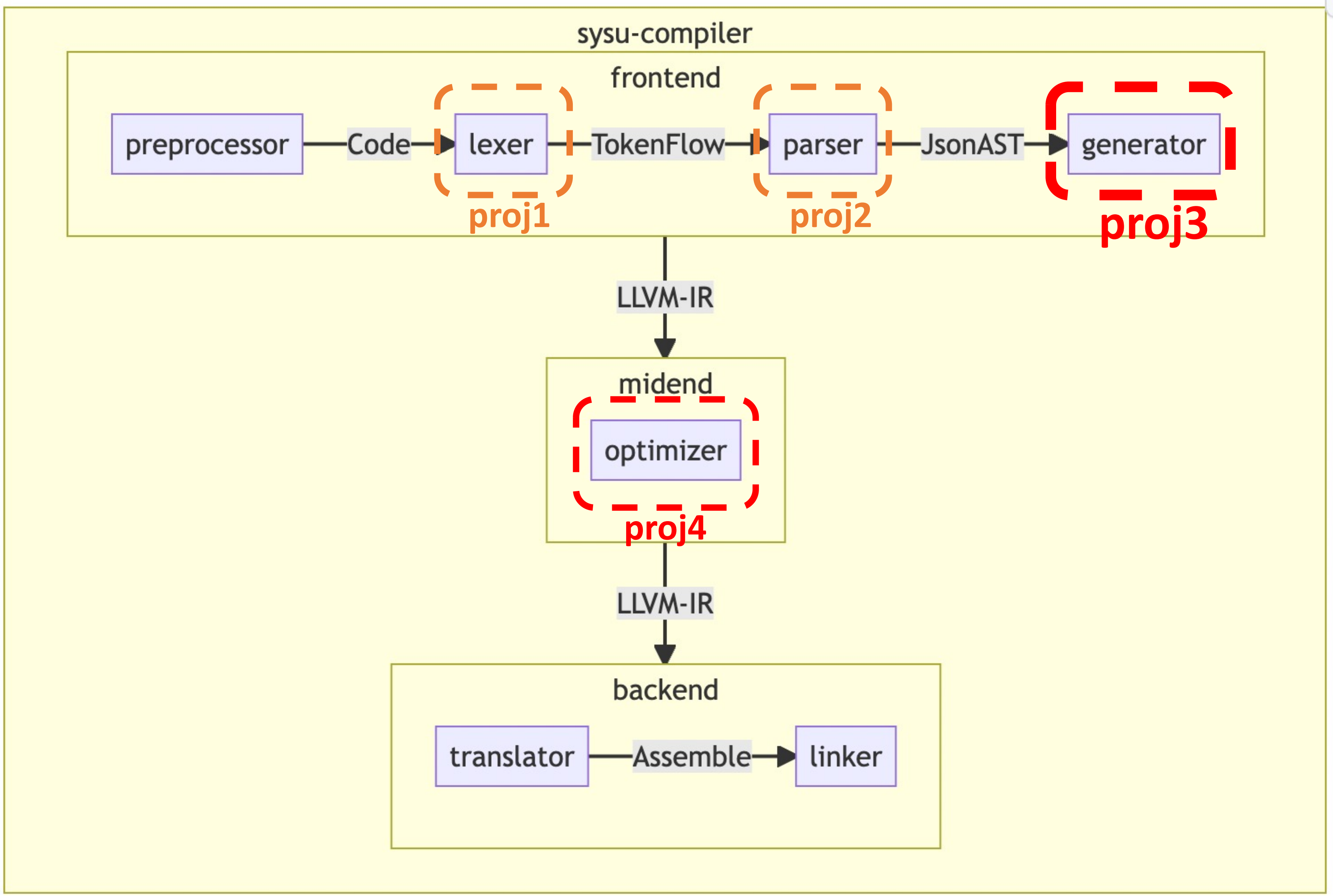
Project 3: What?

- 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?

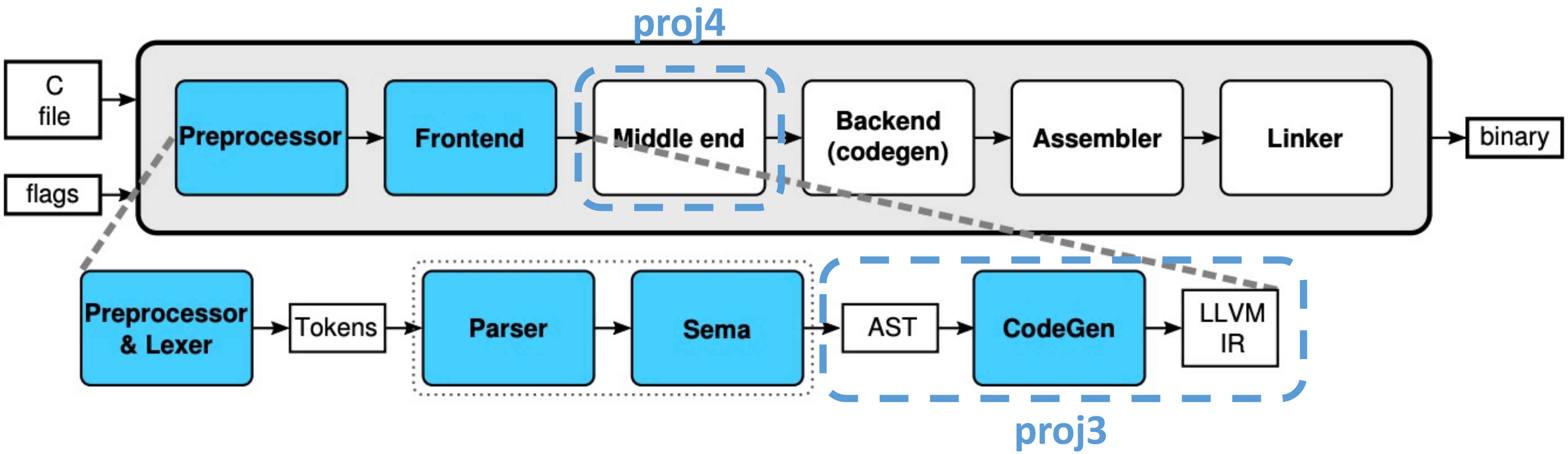
- 实现
  - $vim parser/generator.cc
- 编译
  - $cmake --build ~/sysu/build -t install
    - 输出：~/sysu/build/generator
- 运行
  - (export PATH=~/sysu/bin:$PATH \ CPATH=~/sysu/include:$CPATH \ LIBRARY_PATH=~/sysu/lib:$LIBRARY_PATH \ LD_LIBRARY_PATH=~/sysu/lib:$LD_LIBRARY_PATH && clang -E tester/functional/000_main.sysu.c | <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?



https://github.com/arcsysu/SYsU-lang

CodeGen[中间代码生成]

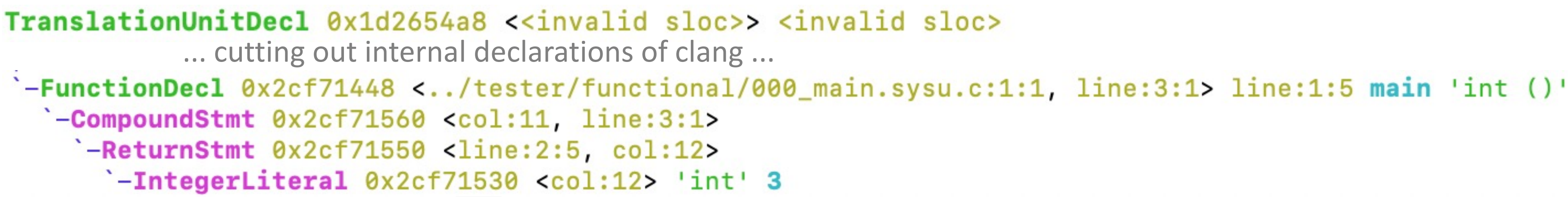


- Not to be confused with LLVM CodeGen! (which generates machine code)
- Uses AST visitors, IRBuilder, and TargetInfo
  - AST visitors
    - RecursiveASTVisitor for visiting the full AST
    - StmtVisitor for visiting Stmt and Expr
    - TypeVisitor for Type hierarchy

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

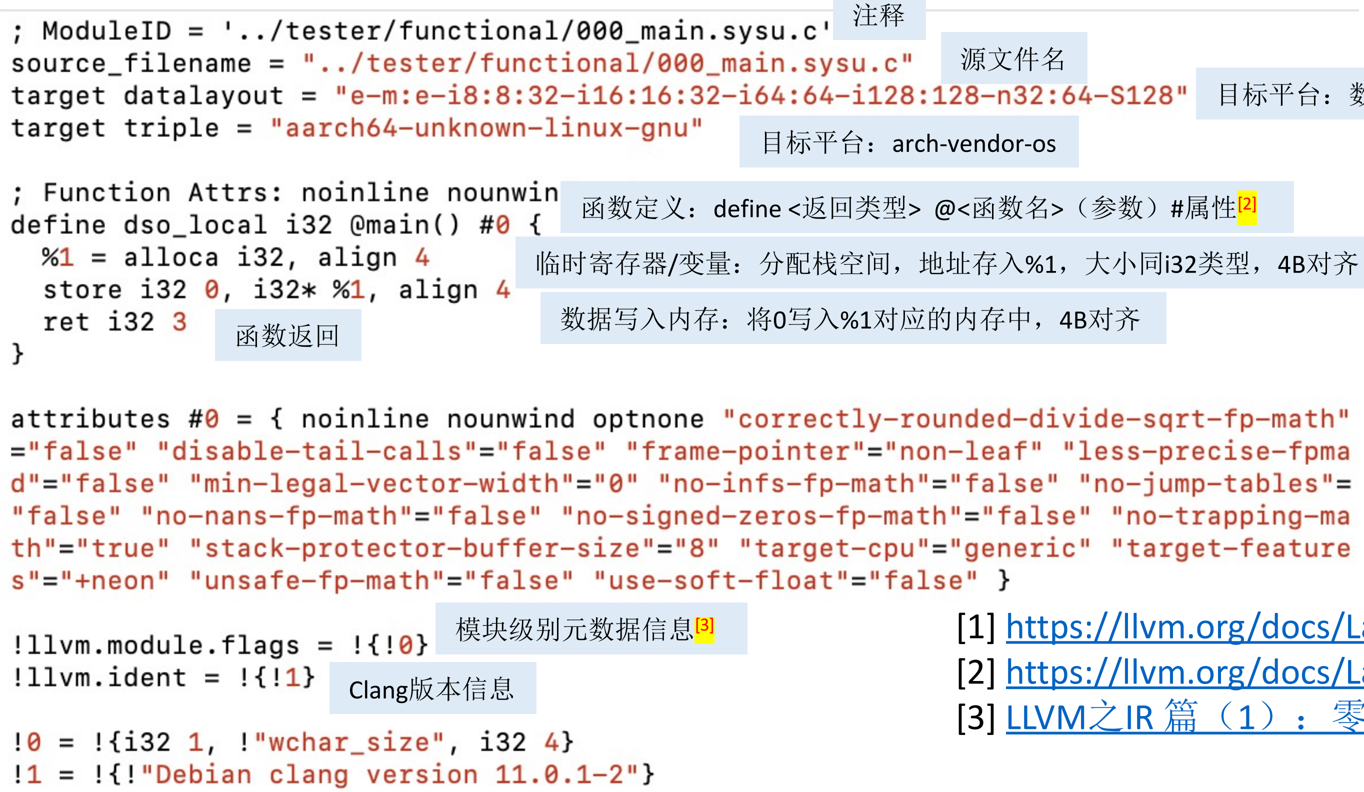
AST → IR: Example

$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 nounwind optnone
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

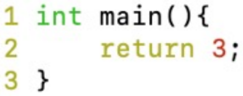
[1] https://llvm.org/docs/LangRef.html#data-layout

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

[3] LLVM之IR 篇（1）：零基础快速入门 LLVM IR

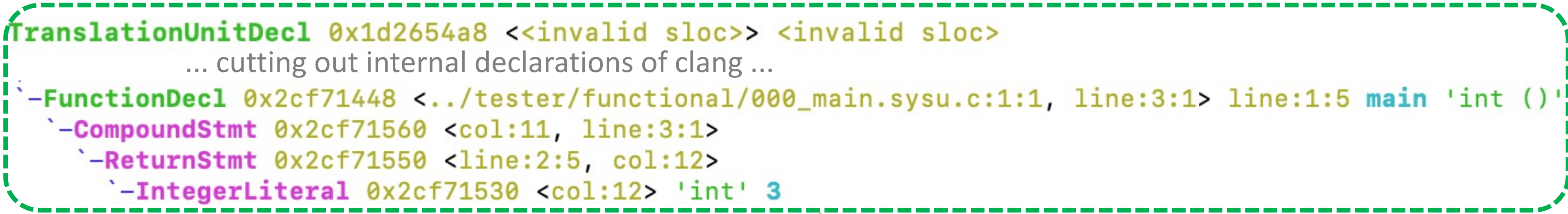
AST → IR: Example (cont.)

Source



```c
int main(){
    return 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 ()'
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    `-ReturnStmt 0x2cf71550 <line:2:5, col:12>
      `-IntegerLiteral 0x2cf71530 <col:12> 'int' 3
```
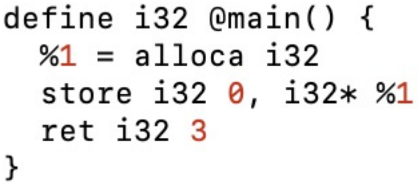
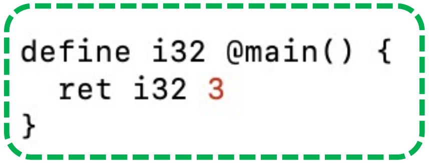

IR



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



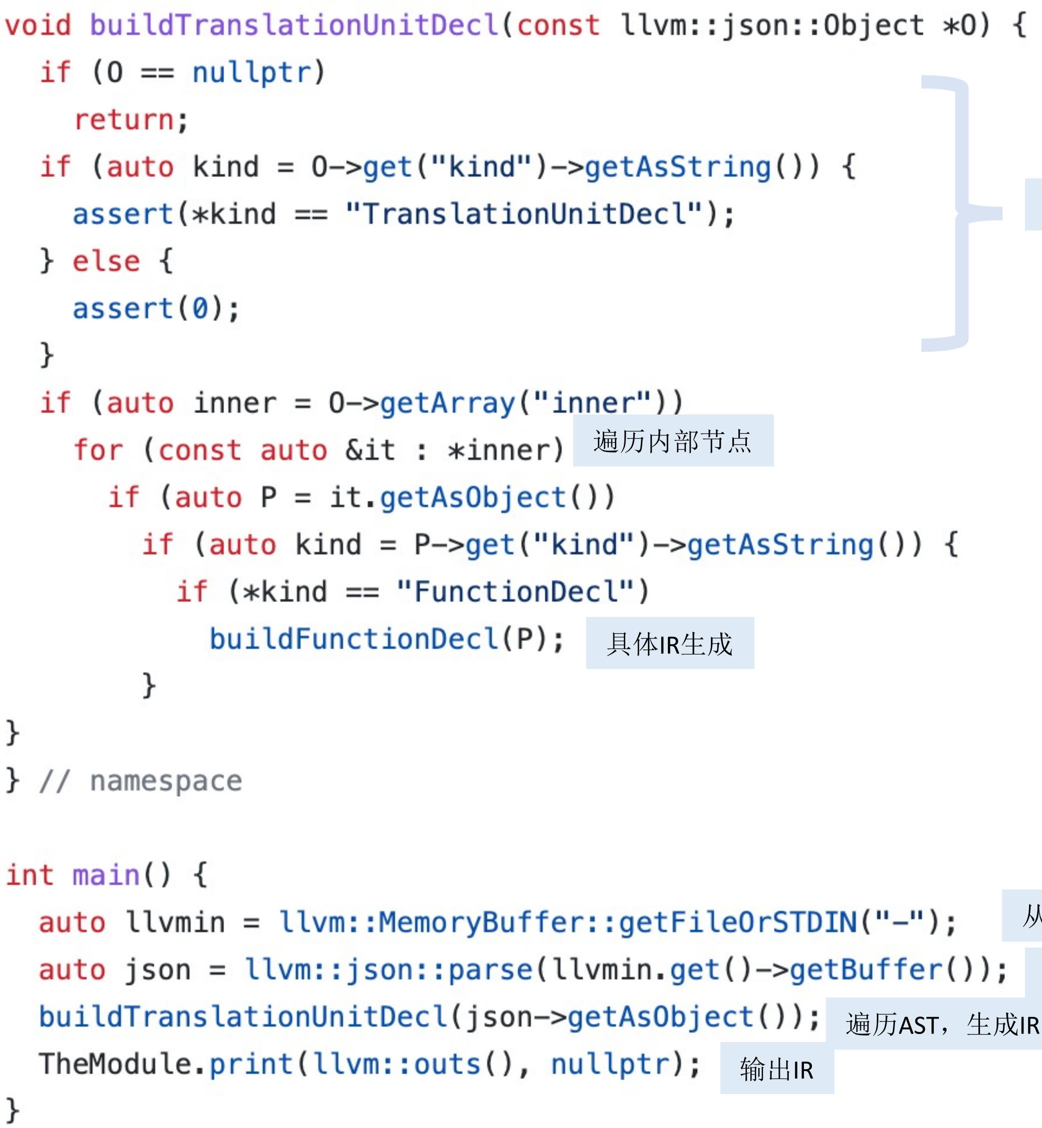
```llvm
define i32 @main() {
  ret i32 3
}
```

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

https://mukulrathi.com/create-your-own-programming-language/llvm-ir-cpp-api-tutorial/

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

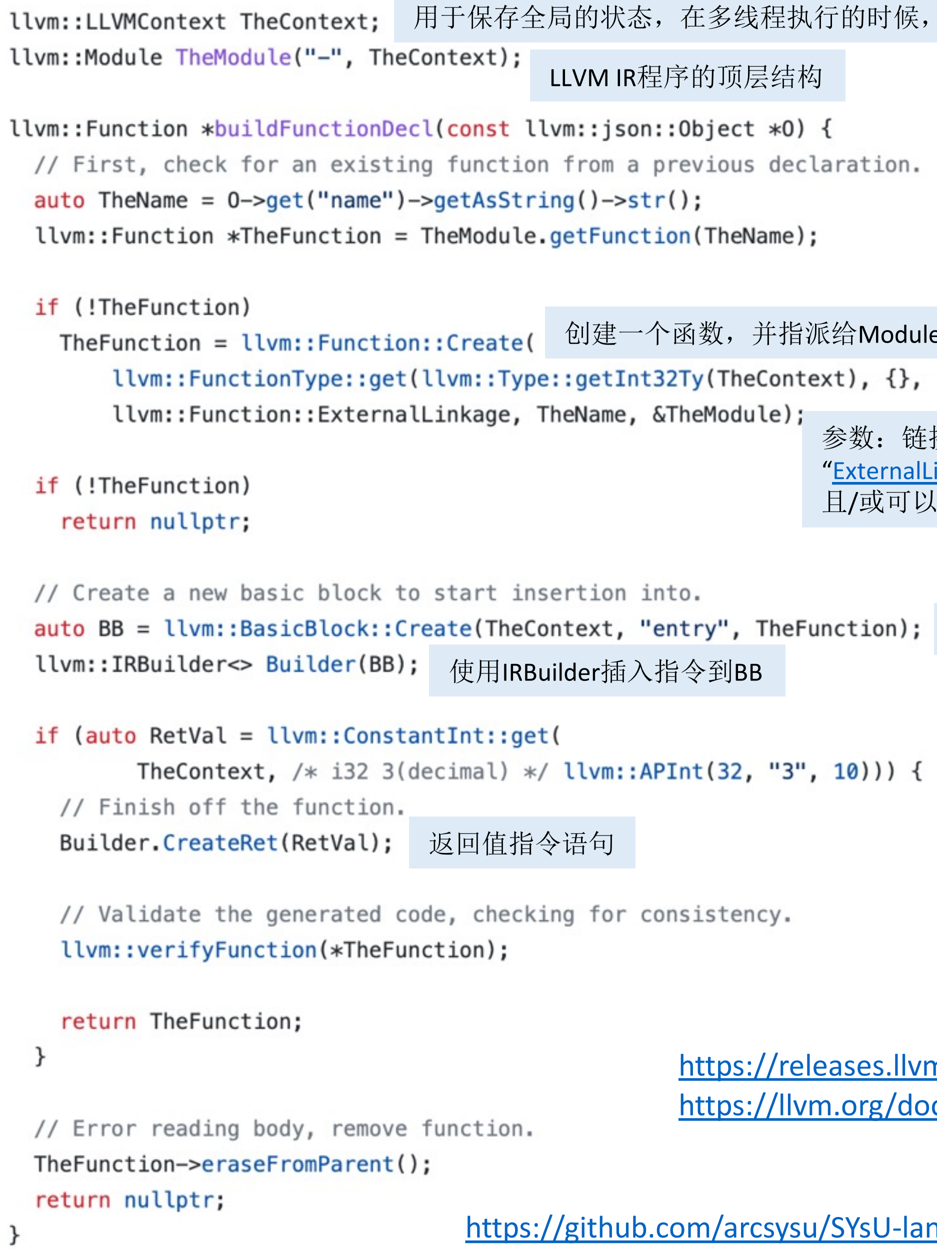
解析为JSON格式

遍历AST，生成IR

输出IR

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

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

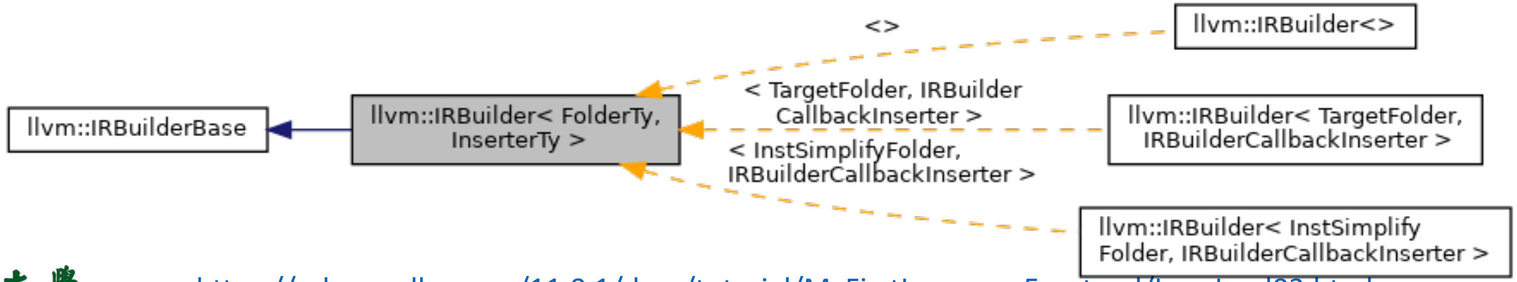
返回值指令语句

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

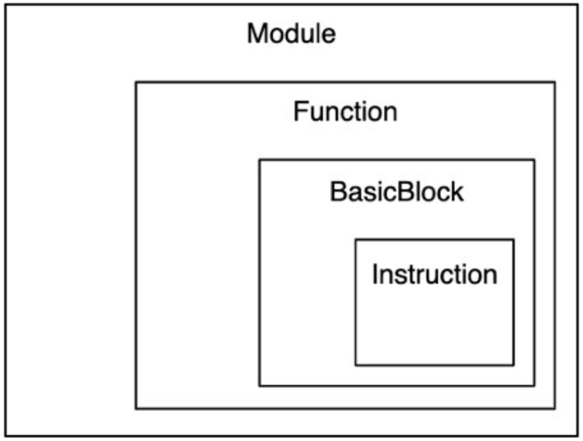
Variables in codegen[相关变量]

- **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

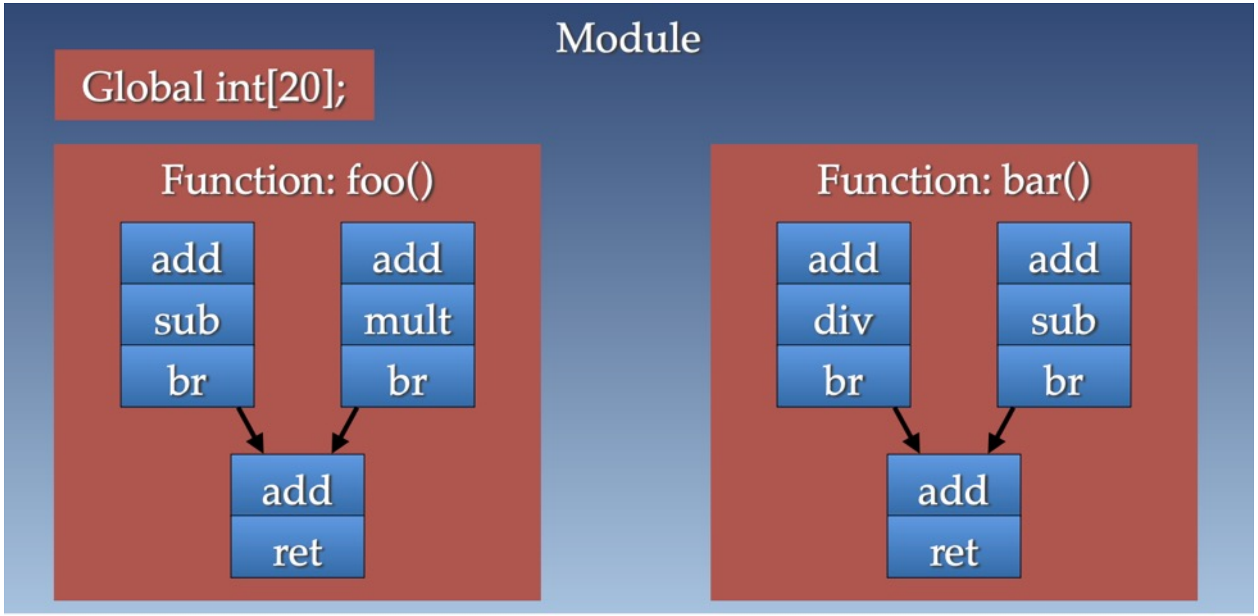

llvm::IRBuilderBase
llvm::IRBuilder< FolderTy, InserterTy >
<>
llvm::IRBuilder<>
< TargetFolder, IRBuilder CallbackInserter >
llvm::IRBuilder< TargetFolder, IRBuilderCallbackInserter >
< InstSimplifyFolder, IRBuilderCallbackInserter >
llvm::IRBuilder< InstSimplify Folder, IRBuilderCallbackInserter >

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



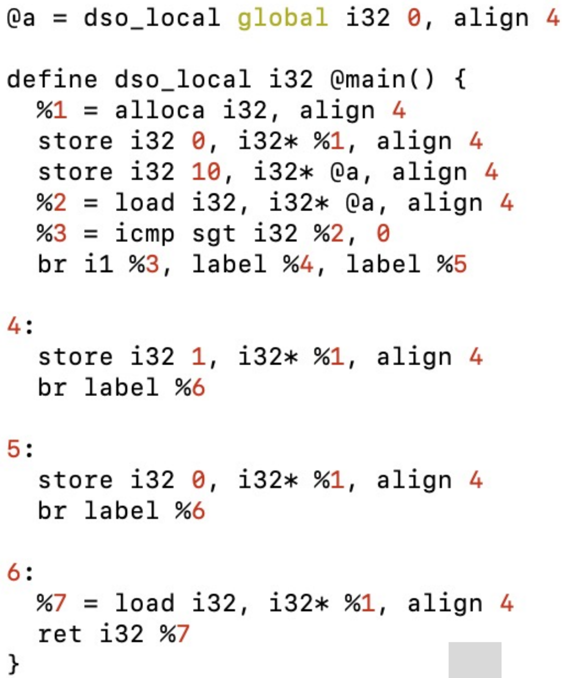
- Each assembly/bitcode file is a Module
- Each **Module** is comprised of
  - Global variables
  - A set of **Functions** which consists of
    - A set of **Basic Blocks**
      - Which is further comprised of a set of **Instructions**



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

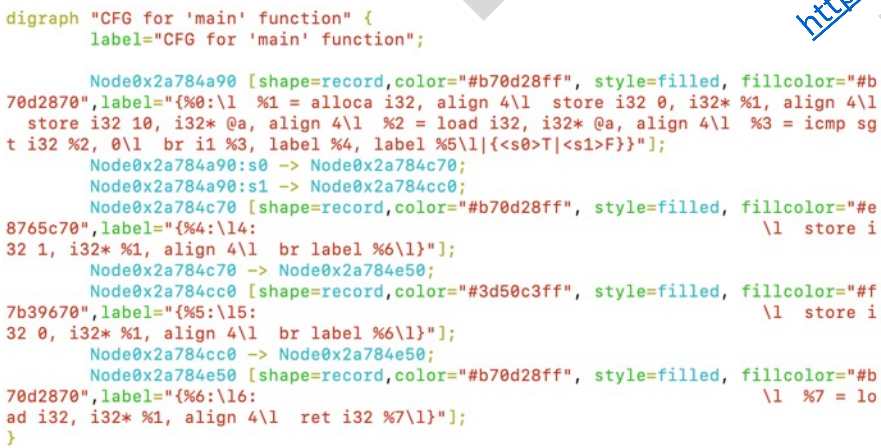
Visualize IR[可视化]

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



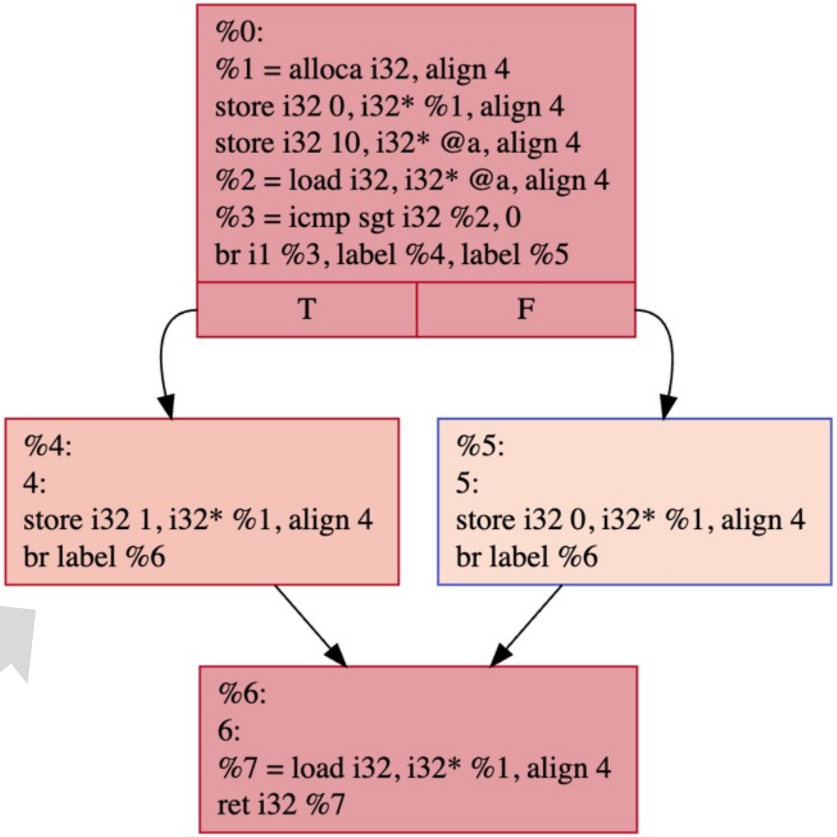
```
@a = dso_local global i32 0, align 4

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/



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

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

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

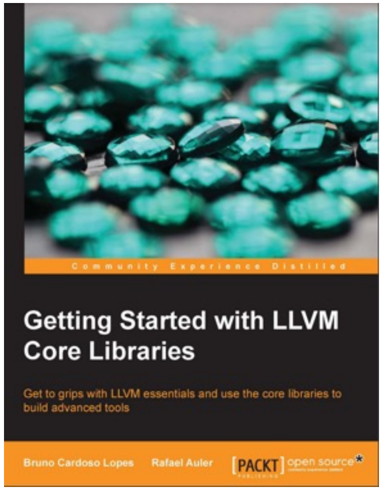
CFG for 'main' function

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 fle[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



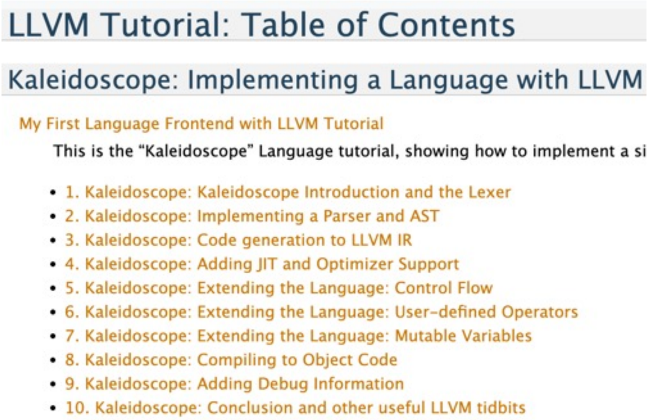
Community Experience Distilled

Getting Started with LLVM Core Libraries

Get to grips with LLVM essentials and use the core libraries to build advanced tools

Bruno Cardoso Lopes Rafael Auler

[PACKT] open source*



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

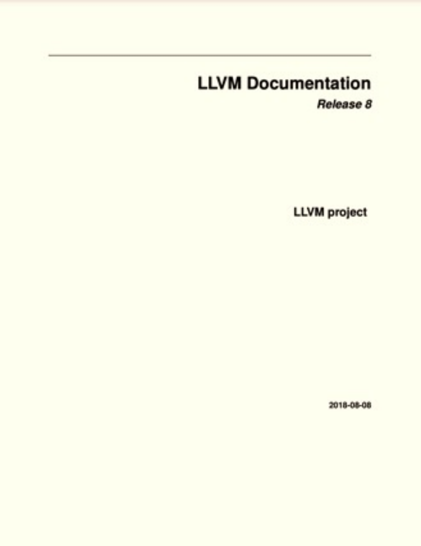
- 1. Kaleidoscope: Kaleidoscope Introduction and the Lexer
- 2. Kaleidoscope: Implementing a Parser and AST
- 3. Kaleidoscope: Code generation to LLVM IR
- 4. Kaleidoscope: Adding JIT and Optimizer Support
- 5. Kaleidoscope: Extending the Language: Control Flow
- 6. Kaleidoscope: Extending the Language: 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 Home | Documentation »

https://llvm.org/docs/

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

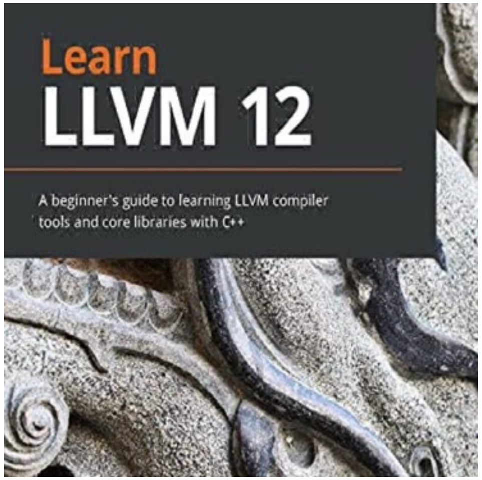


LLVM Documentation

Release 8

LLVM project

2018-08-08



Learn LLVM 12

A beginner's guide to learning LLVM compiler tools and core libraries with C++

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

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