Lecture 2
Overview of the LLVM Compiler

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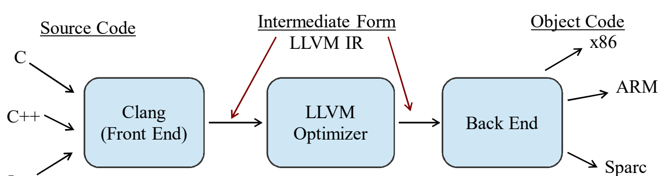
LLVM Compiler System

The LLVM Compiler Infrastructure
- Provides reusable components for building compilers
- Reduce the time/cost to build a new compiler
- Build different kinds of compilers
- Our homework assignments focus on static compilers
- There are also JITs, trace-based optimizers, etc.

The LLVM Compiler Framework
- End-to-end compilers using the LLVM infrastructure
- Support for C and C++ is robust and aggressive
- Java, Scheme and others are in development
- Emit C code or native code for x86, SPARC, PowerPC

Visualizing the LLVM Compiler System

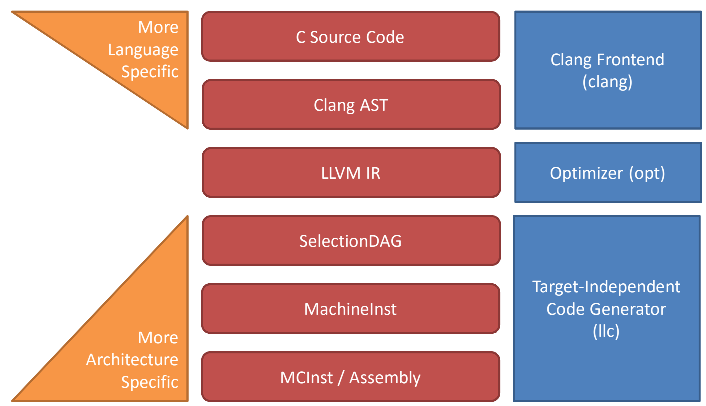


Three-Phase Design

The LLVM Optimizer is a series of "passes"
- **Analysis and optimization passes, run one after another**
- ***Analysis* passes do not change code, *optimization* passes do**

LLVM Intermediate Form is a *Virtual Instruction Set*
- Language- and target-independent form
  - Used to perform the same passes for all source and target languages
- Internal Representation (IR) and external (persistent) representation

LLVM: From Source to Binary



C Source Code

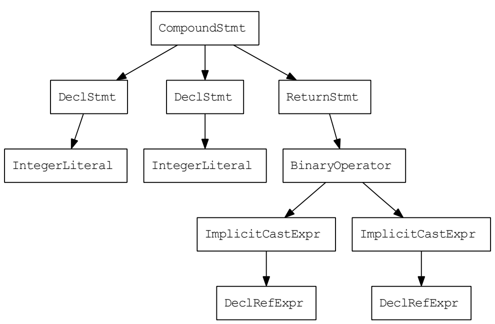
```c
int main() {
    int a = 5;
    int b = 3;
    return a - b;
}
```

Read “Life of an instruction in LLVM”:
http://eli.thegreenplace.net/2012/11/24/life-of-an-instruction-in-llvm

Clang AST

```
TranslationUnitDecl 0xd8185a0 <<invalid sloc>> <invalid sloc>
|-TypedefDecl 0xd818870 <<invalid sloc>> <invalid sloc> implicit __builtin_va_list 'char *'
`-FunctionDecl 0xd8188e0 <example.c:1:1, line:5:1> line:1:5 main 'int ()'
  `-CompoundStmt 0xd818a90 <col:12, line:5:1>
    |-DeclStmt 0xd818998 <line:2:5, col:14>
    | `-VarDecl 0xd818950 <col:5, col:13> col:9 used a 'int' cinit
    |   `-IntegerLiteral 0xd818980 <col:13> 'int' 5
    |-DeclStmt 0xd818a08 <line:3:5, col:14>
    | `-VarDecl 0xd8189c0 <col:5, col:13> col:9 used b 'int' cinit
    |   `-IntegerLiteral 0xd8189f0 <col:13> 'int' 3
    `-ReturnStmt 0xd818a80 <line:4:5, col:16>
      `-BinaryOperator 0xd818a68 <col:12, col:16> 'int' '-'
        |-ImplicitCastExpr 0xd818a48 <col:12> 'int' <LValueToRValue>
        | `-DeclRefExpr 0xd818a18 <col:12> 'int' lvalue Var 0xd818950 'a' 'int'
        `-ImplicitCastExpr 0xd818a58 <col:16> 'int' <LValueToRValue>
          `-DeclRefExpr 0xd818a30 <col:16> 'int' lvalue Var 0xd8189c0 'b' 'int'
```


Clang AST



LLVM IR

In-Memory Data Structure

Bitcode (.bc files)

```
42 43 C0 DE   21 0C 00 00
06 10 32 39   92 01 84 0C
0A 32 44 24   48 0A 90 21
18 00 00 00   98 00 00 00
E6 C6 21 1D   E6 A1 1C DA
…
```

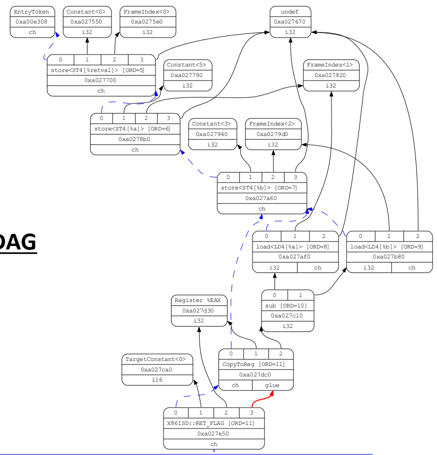
llvm-dis ↔ llvm-asm

Text Format (.ll files)

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %a = alloca i32, align 4
…
```

Bitcode files and LLVM IR text files are **lossless serialization formats**!
We can pause optimization and come back later.

SelectionDAG



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Machine Inst

```
BB#0: derived from LLVM BB %entry
    Live Ins: %EBP
        PUSH32r %EBP<kill>, %ESP<imp-def>, %ESP<imp-use>; flags: FrameSetup
        %EBP<def> = MOV32rr %ESP; flags: FrameSetup
        %ESP<def,tied1> = SUB32ri8 %ESP<tied0>, 12, %EFLAGS<imp-def,dead>; flags: FrameSetup
        MOV32mi %EBP, 1, %noreg, -4, %noreg, 0; mem:ST4[%retval]
        MOV32mi %EBP, 1, %noreg, -8, %noreg, 5; mem:ST4[%a]
        MOV32mi %EBP, 1, %noreg, -12, %noreg, 3; mem:ST4[%b]
        %EAX<def> = MOV32rm %EBP, 1, %noreg, -8, %noreg; mem:LD4[%a]
        %EAX<def,tied1> = ADD32ri8 %EAX<kill,tied0>, -3, %EFLAGS<imp-def,dead>
        %ESP<def,tied1> = ADD32ri8 %ESP<tied0>, 12, %EFLAGS<imp-def,dead>
        %EBP<def> = POP32r %ESP<imp-def>, %ESP<imp-use>
        RETL %EAX
```

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MCInst

```
#BB#0:                          # %entry
pushl    %ebp                   # <MCInst #2191 PUSH32r
                                #  <MCOperand Reg:20>>
movl     %esp, %ebp             # <MCInst #1566 MOV32rr
                                #  <MCOperand Reg:20>
                                #  <MCOperand Reg:30>>
subl     $12, %esp              # <MCInst #2685 SUB32ri8
                                #  <MCOperand Reg:30>
                                #  <MCOperand Reg:30>
                                #  <MCOperand Imm:12>>
movl     $0, -4(%ebp)           # <MCInst #1554 MOV32mi
                                #  <MCOperand Reg:20>
                                #  <MCOperand Imm:1>
                                #  <MCOperand Reg:0>
                                #  <MCOperand Imm:-4>
                                #  <MCOperand Reg:0>
                                #  <MCOperand Imm:0>>
                ....
```

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Assembly

```
main:                     # @main
# BB#0:                    # %entry
          pushl    %ebp
          movl     %esp, %ebp
          subl     $12, %esp
          movl     $0, -4(%ebp)
          movl     $5, -8(%ebp)
          movl     $3, -12(%ebp)
          movl     -8(%ebp), %eax
          addl     $-3, %eax
          addl     $12, %esp
          popl     %ebp
          retl
```

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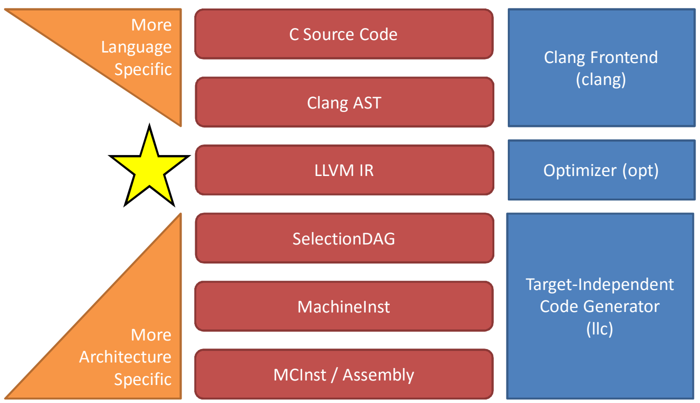
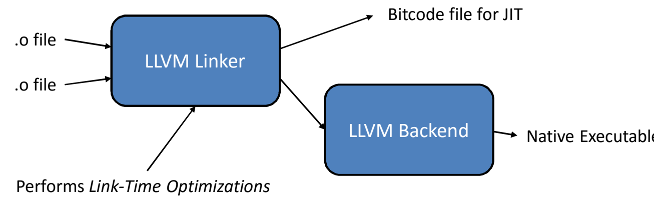
LLVM: From Source to Binary



Linking and Link-Time Optimization



Goals of LLVM Intermediate Representation (IR)

- Easy to produce, understand, and define
- Language- and Target-Independent
- One IR for analysis and optimization
- Supports high- *and* low-level optimization
- Optimize as much as early as possible

LLVM Instruction Set Overview

- Low-level and target-independent semantics
  - RISC-like three address code
  - Infinite virtual register set in SSA form
  - Simple, low-level control flow constructs
  - Load/store instructions with typed-pointers

```
for (i = 0; i < N; i++)
        Sum(&A[i], &P);
```

```
loop:                              ; preds = %bb0, %loop
%i.1 = phi i32 [ 0, %bb0 ], [ %i.2, %loop ]
%AiAddr = getelementptr float* %A, i32 %i.1
call void @Sum(float %AiAddr, %pair* %P)
%i.2 = add i32 %i.1, 1
%exitcond = icmp eq i32 %i.1, %N
br i1 %exitcond, label %outloop, label %loop
```

LLVM Instruction Set Overview (continued)

- High-level information exposed in the code
  - Explicit dataflow through SSA form (more later in the class)
  - Explicit control-flow graph (even for exceptions)
  - Explicit language-independent type-information
  - Explicit typed pointer arithmetic
  - Preserves array subscript and structure indexing

```
for (i = 0; i < N; i++)
        Sum(&A[i], &P);
```

```
loop:                              ; preds = %bb0, %loop
%i.1 = phi i32 [ 0, %bb0 ], [ %i.2, %loop ]
%AiAddr = getelementptr float* %A, i32 %i.1
call void @Sum(float %AiAddr, %pair* %P)
%i.2 = add i32 %i.1, 1
%exitcond = icmp eq i32 %i.1, %N
br i1 %exitcond, label %outloop, label %loop
```

Nice syntax for calls is preserved

Lowering Source-Level Types to LLVM

- Source language types are *lowered*:
  - Rich type systems expanded to **simple types**
  - Implicit & abstract types are made explicit & concrete
- Examples of lowering:
  - Reference turn into pointers: T& -> T*
  - Complex numbers: complex flaod -> {float, float}
  - Bitfields: struct X { int Y:4; int Z:2; } -> { i32 }
- The entire type system consists of:
  - **Primitives**: label, void, float, integer, …
    - Arbitrary bitwidth integers (i1, i32, i64, i1942652)
  - **Derived**: pointer, array, structure, function (unions get turned into casts)
  - No high-level types
- Type system allows arbitrary casts

Example Function in LLVM IR

```
int main() {
  int a = 5;
  int b = 3;
  return a - b;
}
```

clang →

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %a = alloca i32, align 4
  %b = alloca i32, align 4
  store i32 0, i32* %retval
  store i32 5, i32* %a, align 4
  store i32 3, i32* %b, align 4
  %0 = load i32* %a, align 4
  %1 = load i32* %b, align 4
  %sub = sub nsw i32 %0, %1
  ret i32 %sub
}
```

Explicit stack allocation

Explicit Loads and Stores

Explicit Types

Example Function in LLVM IR

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %a = alloca i32, align 4
  %b = alloca i32, align 4
  store i32 0, i32* %retval
  store i32 5, i32* %a, align 4
  store i32 3, i32* %b, align 4
  %0 = load i32* %a, align 4
  %1 = load i32* %b, align 4
  %sub = sub nsw i32 %0, %1
  ret i32 %sub
}
```

mem2reg →

```
define i32 @main() #0 {
entry:
  %sub = sub nsw i32 5, 3
  ret i32 %sub
}
```

Not always possible: Sometimes stack operations are too complex

LLVM Instruction Hierarchy

LLVM Instructions <--> Values

```
int main() {
   int x;
   int y = 2;
   int z = 3;
   x = y+z;
   y = x+z;
   z = x+y;
}
```

clang + no m2r

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %x = alloca i32, align 4
  %y = alloca i32, align 4
  %z = alloca i32, align 4
  store i32 0, i32* %retval
  store i32 1, i32* %x, align 4
  store i32 2, i32* %y, align 4
  store i32 3, i32* %z, align 4
  %0 = load i32* %y, align 4
  %1 = load i32* %z, align 4
  %add = add nsw i32 %0, %1
  store i32 %add, i32* %x, align 4
  ...
```


LLVM Instructions <--> Values

```
int main() {
   int x;
   int y = 2;
   int z = 3;
   x = y+z;
   y = x+z;
   z = x+y;
}
```

clang + mem2reg

```
; Function Attrs: nounwind
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 3
  %add1 = add nsw i32 %add, 3
  %add2 = add nsw i32 %add, %add1
  ret i32 0
}
```

Instruction I: %add1 = add nsw i32 %add, 3

Operand 1 Operand 2

You can't "get" %add1 from Instruction I.
Instruction serves as the Value %add1.

LLVM Instructions <--> Values

```
int main() {
   int x;
   int y = 2;
   int z = 3;
   x = y+z;
   y = x+z;
   z = x+y;
}
```

clang + mem2reg

```
; Function Attrs: nounwind
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 3
  %add1 = add nsw i32 %add, 3
  %add2 = add nsw i32 %add, %add1
  ret i32 0
}
```

Instruction I: %add1 = add nsw i32 %add, 3

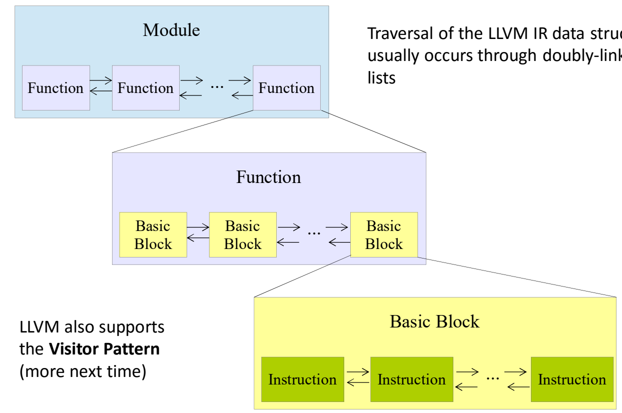
outs() << *(I.getOperand(0)); ⟶ "%add = add nsw i32 2, 3"

outs() << *(I.getOperand(0)->getOperand(0)); ⟶ "2"

Only makes sense for an SSA Compiler

LLVM Program Structure

- Module **contains** Functions and GlobalVariables
  - Module is a unit of analysis, compilation, and optimization
- Function **contains** BasicBlocks and Arguments
  - Functions roughly correspond to functions in C
- BasicBlock **contains a** list of Instructions
  - Each block ends in a control flow instruction
- Instruction **is an** opcode + vector of operands



Traversal of the LLVM IR data structure usually occurs through doubly-linked lists

LLVM also supports the **Visitor Pattern** (more next time)

LLVM Pass Manager

- **Compiler is organized as a series of "passes":**
  - Each pass is an analysis or transformation
  - Each pass can depend on results from previous passes
- **Six useful types of passes:**
  - BasicBlockPass: iterate over basic blocks, in no particular order
  - CallGraphSCCPass: iterate over SCC's, in bottom-up call graph order
  - FunctionPass: iterate over functions, in no particular order
  - LoopPass: iterate over loops, in reverse nested order
  - ModulePass: general interprocedural pass over a program
  - RegionPass: iterate over single-entry/exit regions, in reverse nested order
- **Passes have different constraints (e.g. FunctionPass):**
  - FunctionPass can only look at the "current function"
  - Cannot maintain state across functions

LLVM Tools

- Basic LLVM Tools
  - llvm-dis: Convert from .bc (IR binary) to .ll (human-readable IR text)
  - llvm-as: Convert from .ll (human-readable IR text) to .bc (IR binary)
  - opt: LLVM optimizer
  - llc: LLVM static compiler
  - lli: LLVM bitcode interpreter
  - llvm-link: LLVM bitcode linker
  - llvm-ar: LLVM archiver
- Some Additional Tools
  - bugpoint - automatic test case reduction tool
  - llvm-extract - extract a function from an LLVM module
  - llvm-bcanalyzer - LLVM bitcode analyzer
  - FileCheck - Flexible pattern matching file verifier
  - tblgen - Target Description To C++ Code Generator

opt: LLVM modular optimizer

- **Invoke arbitrary sequence of passes :**
  - Completely control PassManager from command line
  - Supports loading passes as plugins from *.so files

opt -load foo.so -pass1 -pass2 -pass3 x.bc -o y.bc

- **Passes "register" themselves:**
  - **When you write a pass, you must write the registration**

```
RegisterPass<FunctionInfo> X("function-info",
       "15745: Function Information");
```