Lecture 6
More on the LLVM Compiler

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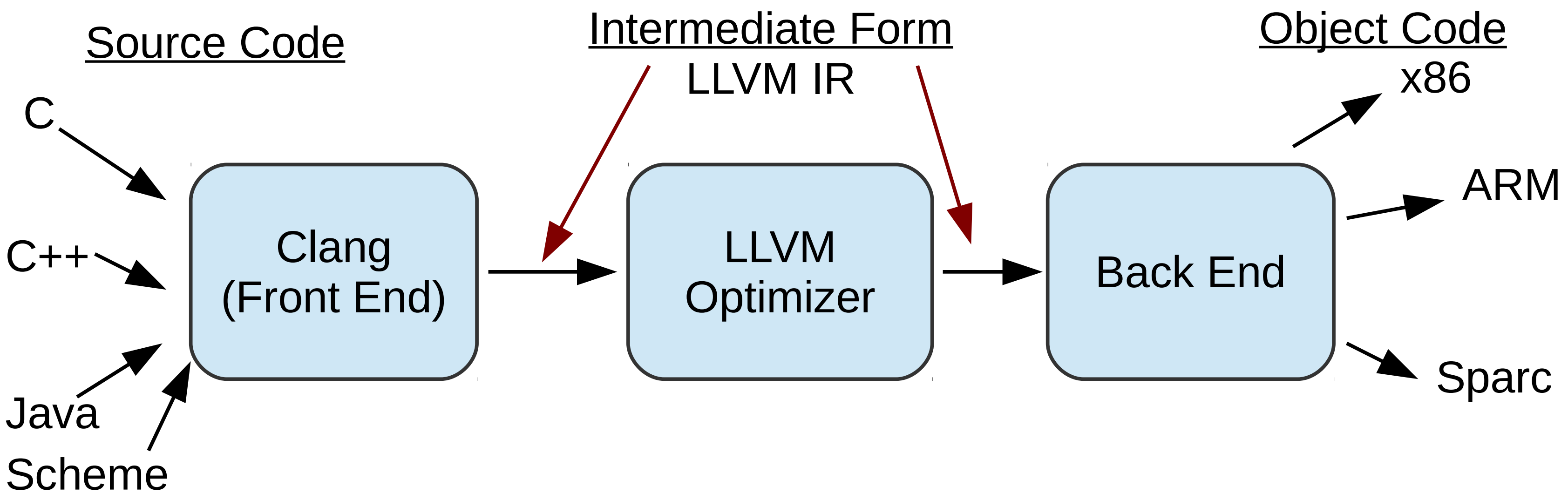
Thanks to Luke Zarko and Gabe Weisz for some content

Outline

- **Understanding and Navigating the LLVM IR**
- **Writing Passes**
  - Changing the LLVM IR
- **Using Passes**
- **Useful Documentation**

Understanding the LLVM IR



- **Recall that LLVM uses an intermediate representation for intermediate steps**
  - Used for all steps between the front end (translating from source code) and the back end (translating to machine code)
  - Language- and mostly target-independent form
    - Target dictates alignment and pointer sizes in the IR, little else

Understanding the LLVM IR - Processing Programs

- **Iterators for modules, functions, blocks, and uses**
  - Use these to access nearly every part of the IR data structure

- **There are functions to inspect data types and constants**

- **Many classes have dump() member functions that print information to standard error**
  - In GDB, use `p obj->dump()` to print the contents of that object

Navigating the LLVM IR - Iterators

- **Module::iterator**
  - Modules are the large units of analysis
  - Iterates through the functions in the module
- **Function::iterator**
  - Iterates through a function's basic blocks
- **BasicBlock::iterator**
  - Iterates through the instructions in a basic block
- **Value::use_iterator**
  - Iterates through **uses** of a value
  - Recall that instructions are treated as values
- **User::op_iterator**
  - Iterates over the operands of an instruction (the “user” is the instruction)
  - Prefer to use convenient accessors defined by many instruction classes

Navigating the LLVM IR - Hints on Using Iterators

- **Be very careful about modifying any part of the object iterated over during iteration**
  - Can cause unexpected behavior
- **Use ++i rather than i++ and pre-compute the end**
  - Avoid problems with iterators doing unexpected things while you are iterating
  - Especially for fancier iterators
- **There is overlap among iterators**
  - E.g., `InstIterator` walks over all instructions in a function, overlapping range of `Function::iterator` and `BasicBlock::iterator`
- **Most iterators automatically convert a pointer to the appropriate object type**
  - Not all: `InstIterator` does not

Understanding the LLVM IR - Interpreting An Instruction

- **The Instruction class has several subclasses, for various types of operations**
  - E.g., LoadInst, StoreInst, AllocaInst, CallInst, BranchInst
  - Use the dyn_cast<> operator to check to see if the instruction is of the specified type
    - If so, returns a pointer to it
    - If not, returns a null pointer
    - For example,

```
if (AllocationInst *AI = dyn_cast<AllocationInst>(Val)) {
  // ... If we get here, *AI is an alloca instruction
}
```

- **Several classifications of instructions:**
  - Terminator instructions, binary instructions, bitwise binary instructions, memory instructions, and other instructions

Understanding the LLVM IR - Terminator Instructions

- **Every BasicBlock must end with a terminator instruction**
  - Terminator instructions can only go at the end of a BB
- **`ret`, `br`, `switch`, `indirectbr`, `invoke`, `resume`, and `unreachable`**
  - `ret` - return control flow to calling function
  - `br`, `switch`, `indirectbr` - transfer control flow to another BB in the same function
  - `invoke` - transfers control flow to another function

Understanding the LLVM IR - Binary Instructions

- **Binary operations do most of the computation in a program**
  - Handle nearly all of the arithmetic
- **Two operands of the same type; result value has same type**
- **E.g., 'add', 'fadd', 'sub', 'fsub', 'mul', 'fmul', 'udiv', 'sdiv', 'fdiv'**
  - 'f' indicates floating point, 's' indicates signed, 'u' indicates unsigned
- **Bitwise binary operations**
  - Frequently used for optimizations
  - Two operands of the same type; one result value of the same type

Understanding the LLVM IR - Memory Instructions

- **LLVM IR does not represent memory locations (SSA)**
  - Instead, uses named locations
- **alloca**
  - Allocates memory on the stack frame of the current function, reclaimed at return
- **load -** Reads from memory, often in a location named by a previous alloca
- **store-** Writes to memory, often in a location named by a previous alloca
- **For example:**

```
%ptr = alloca i32                  ; yields {i32*}:ptr
store i32 3, i32* %ptr             ; stores 3 in the location named by %ptr
%val = load i32* %ptr              ; yields {i32}:val = i32 3
```

- **getelementptr**
  - gets the address of a sub-element of an aggregate data structure (derived type)

Understanding the LLVM IR - SSA

- **LLVM uses Static Single Assignment (SSA) to represent memory**
  - More on SSA later in the class
- **May produce “phi” instructions**
  - First instruction(s) in a BB
  - Give the different potential values for a variable, depending on which block preceded this one
- **Arbitrary/unlimited number of abstract “registers”**
  - Actual register use is determined at a lower level - target dependent
  - Can use as many as you want
  - Really, they are stack locations or SSA values

Understanding the LLVM IR - Instructions as Values

- **SSA representation means that an Instruction is treated as the same as the Value it produces**
- **Values start with % or @**
  - % indicates a local variable
  - @ indicates a global variable
  - Instructions that produce values can be named
- **%foo = inst in the LLVM IR just gives a name to the instruction in the syntax**

Understanding the LLVM IR - Types in the LLVM IR

- **Strong type system enables some optimizations without additional analysis**
- **Primitive Types**
  - Integers (iN of N bits, N from 1 to 2^{23}-1), Floating point (half, float, double, etc.)
  - Others (x86mmx, void, etc.)
- **Derived Types**
  - Arrays ([# elements (>= 0) x element type])
  - Functions (returntype (paramlist))
  - Pointers (type*, type addrspace(N)*)
  - Vectors (<# elements (> 0) x element type])
  - Structures({ typelist })
- **All derived types of a particular “shape” are considered the same**
  - Does not matter if same-shaped types have different names
  - LLVM may rename them

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Writing Passes - Changing the LLVM IR

- **`eraseFromParent()`**
  - Remove the instruction from basic block, drop all references, delete
- **`removeFromParent()`**
  - Remove remove the instruction from basic block
  - Use if you will re-attach the instruction
  - Does not drop references (or clear the use list), so if you don't re-attach it Bad Things will happen
- **`moveBefore/insertBefore/insertAfter` are also available**
- **`ReplaceInstWithValue` and `ReplaceInstWithInst` are also useful to have**

Writing Passes - Analysis Passes vs. Optimization Passes

- **Two Major kinds of passes:**
  - Analysis: provide information (Like FunctionInfo)
  - Transform: modify the program (Like LocalOpts)
- **getAnalysisUsage method**
  - Defines how this pass interacts with other passes
  - For example,

```
// A pass that modifies the program, but does not modify the CFG
// The pass requires the LoopInfo pass
void LICM::getAnalysisUsage(AnalysisUsage &AU) const {
    AU.setPreservesCFG();
    AU.addRequired<LoopInfo>();
}
```

  - setPreservesAll - used in analysis pass that does not modify the program

Writing Passes - Correctness

- **When you modify code, be careful not to change the meaning!**
  - For our assignments, and in most situations, you want the effect of the code to be the same as before you altered it
- **Think about multi-threaded correctness**
- **You can change the meaning of code while you are modifying the code within your pass, but you should restore the meaning before the pass finishes**
- **You need to check for correctness on your own, because LLVM has very limited built-in correctness checking**

Writing Passes - Module Invariants

- **LLVM has module invariants that should stay the same before and after your pass**
  - Some module invariant examples:
    - Types of binary operator parameters are the same
    - Terminator instructions only at the end of BasicBlocks
    - Functions are called with correct argument types
    - Instructions belong to Basic blocks
    - Entry node has no predecessor
- **You can break module invariants while in your pass, but you should repair them before you finish**
- **opt automatically runs a pass (-verify) to check module invariants**
  - **But it doesn't check correctness in general!**

Writing Passes - Parameters

- **The CommandLine library allows you to add command line parameters very quickly**
  - Conflicts in parameter names won't show up until runtime, since passes are loaded dynamically

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Using Passes

- **For homework assignments, do not use passes provided by LLVM unless instructed to**
  - We want you to implement the passes yourself to understand how they really work
- **For projects, you can use whatever you want**
  - Your own passes or LLVM's passes
- **Some useful LLVM passes follow**

Some Useful Passes - mem2reg transform pass

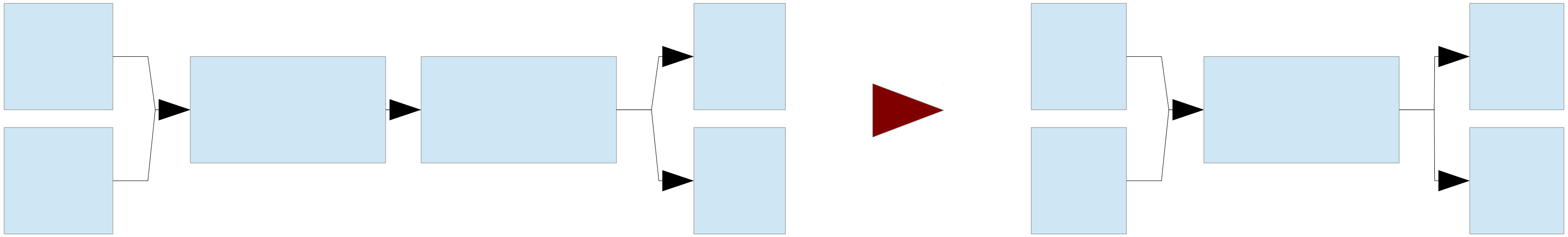
- **If you have alloca instructions that only have loads and stores as uses**
  - Changes them to register references
  - May add SSA features like “phi” instructions
- **Sometimes useful for simplifying IR**
  - Confuses easily

Some Useful Passes - Loop information (-loops)

- **llvm/Analysis/LoopInfo.h**
- **Reveals:**
  - The basic blocks in a loop
  - Headers and pre-headers
  - Exit and exiting blocks
  - Back edges
  - “Canonical induction variable”
  - Loop Count

Some Useful Passes - Simplify CFG (-simplifycfg)

- **Performs basic cleanup**
  - Removes unnecessary basic blocks by merging unconditional branches if the second block has only one predecessor



  - Removes basic blocks with no predecessors
  - Eliminates phi nodes for basic blocks with a single predecessor
  - Removes unreachable blocks

Some Useful Passes

- **Scalar Evolution (-scalar-evolution)**
  - Tracks changes to variables through nested loops
- **Target Data (-targetdata)**
  - Gives information about data layout on the target machine
  - Useful for generalizing target-specific optimizations
- **Alias Analyses**
  - Several different passes give information about aliases
  - E.g., does *A point to the same location as *B?
  - If you know that different names refer to different locations, you have more freedom to reorder code, etc.

Other Useful Passes

- **Liveness-based dead code elimination**
  - Assumes code is dead unless proven otherwise
- **Sparse conditional constant propagation**
  - Aggressively search for constants
- **Correlated propagation**
  - Replace select instructions that select on a constant
- **Loop invariant code motion**
  - Move code out of loops where possible
- **Dead global elimination**
- **Canonicalize induction variables**
  - All loops start from 0
- **Canonicalize loops**
  - Put loop structures in standard form

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Some Useful LLVM Documentation

- **LLVM Programmer's Manual**
  - http://llvm.org/docs/ProgrammersManual.html
- **LLVM Language Reference Manual**
  - http://llvm.org/docs/LangRef.html
- **Writing an LLVM Pass**
  - http://llvm.org/docs/WritingAnLLVMPass.html
- **LLVM's Analysis and Transform Passes**
  - http://llvm.org/docs/Passes.html
- **LLVM Internal Documentation**
  - http://llvm.org/docs/doxygen/html/
  - May be easier to search the internal documentation from the http://llvm.org front page