Using LLVM For Program Transformation

ANDREW RUEF
UNIVERSITY OF MARYLAND
COMPUTER SCIENCE

LLVM Overview

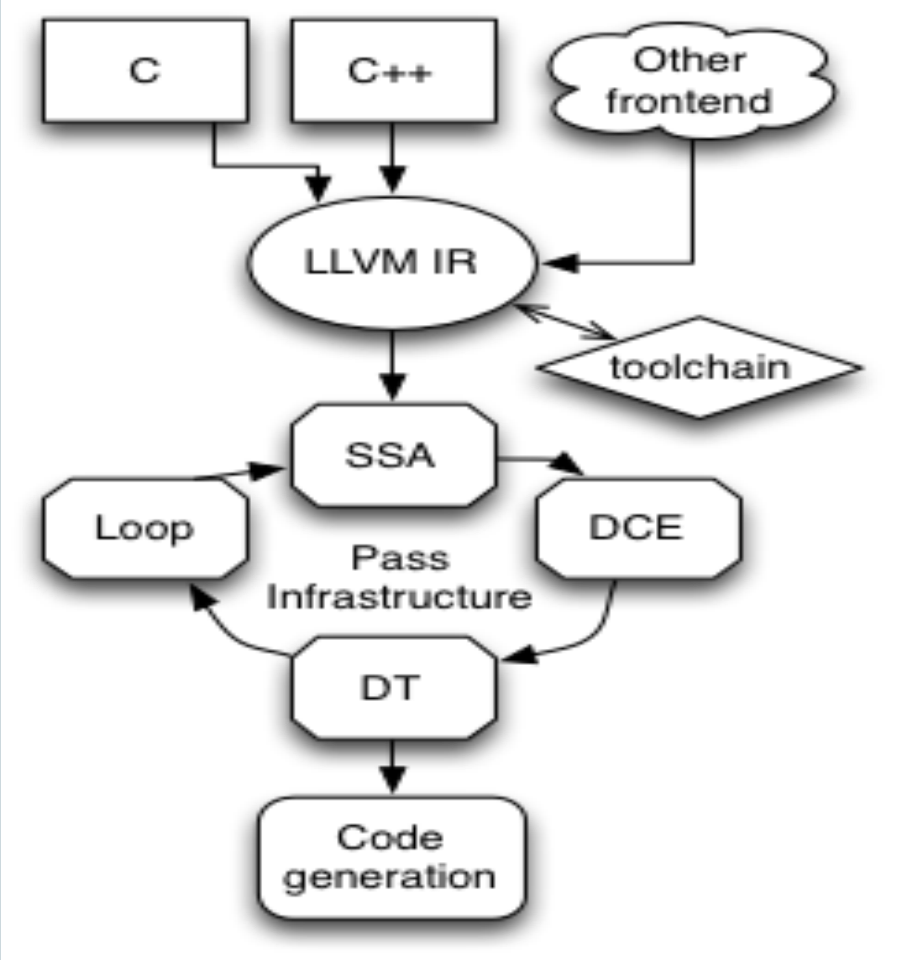
- Research project at UIUC
- Modular compiler tool chain
- Integrated in many open source and commercial projects
- Licensed under an open-source license

Introduction

Components of LLVM

- Mid-level compiler Intermediate Representation (IR)
- C/C++ compiler frontend (clang)
- Target-specific (X86, ARM, etc) code generators

- Divide between ‘clang’ and ‘LLVM’
- Clang is a C/C++ compiler with an LLVM backend
- LLVM is ‘everything else’



Todays Agenda

- We’ll talk about existing LLVM tools
- We’ll do a few demos using those tools
- We’ll talk about how to build tools on top of LLVM
- We’ll build two analysis tools
- We’ll look at a program re-writing tool

Lab: Where we're going

- **clang** – C language frontend, translates C into LLVM bitcode
- **opt** – Analyze and transform LLVM bitcode
- **llc** – Code generator for LLVM bitcode to native code

Lab: Commands to run

```
$ clang –c –emit-llvm –o test.bc test.c
$ opt –O1 –o test.bc test.bc
$ llc –o test.s test.bc
$ gcc –o test test.s
```

Lab: What just happened?

- Full translation of C program to executable program
- At each stage we can look at what the compiler infrastructure is doing
  - C to un-optimized bitcode
  - Optimized bitcode
  - Machine code
  - Executable
- Very good blog post on the life of an LLVM instruction http://eli.thegreenplace.net/2012/11/24/life-of-an-instruction-in-llvm/

LLVM Intermediate Representation

Lab: Find Non-Constant Format String

- Condition to check for:
  - Any time the first parameter to printf, sprintf (others?) is non-constant, alert for potential security badness
- Can we statically detect this in LLVM IR?

Algorithm For Detection

- Visit every call instruction in the program
- Ask if that call instruction is a format-string accepting routine
- If it is, retrieve the first parameter
- If the first parameter is not a constant global, raise an alert

Structure of Provided Driver

- Very basic driver that uses a PassManager
- Reads in LLVM bitcode and runs the VarPrintf pass on it
- Produce bitcode file using `clang –c –emit-llvm`
- Using the driver might seem clunky, this is easier than integrating with opt
- The pass can later be integrated with opt

Building the drivers

```
$ cd tutorial
$ mkdir build
$ cd build
$ cmake –DLLVM_ROOT=/usr/local ..
$ make
```

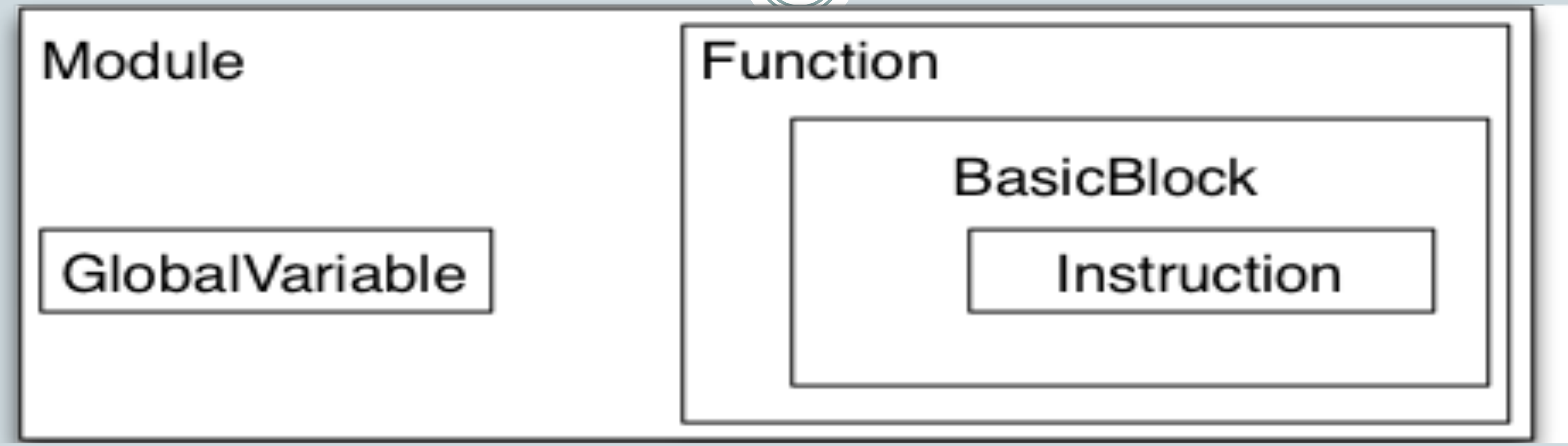
CMake

- CMake is a “meta make”
  - Why? Why not
- CMake generates your build environment
  - Makefiles
  - XCode solution
  - Visual Studio solution
- CMake has its own build specification system for describing building code
  - It might be saner than what you are used to
- LLVM can be built with cmake or automake/ autoconf

LLVM Intermediate Representation

- Language allows for expression of computation
- Instructions produce unique values
- Collection of statements:
  - `%5 = add nsw i32 %3, %4`
    - `%N – a value`
    - `add – a binary instruction`
    - `nsw – no signed wrap`
- The language is Static Single Assignment (SSA)
- Values defined by statements are never re-defined

Hierarchy of the Language



- A compilation unit is a Module, contains functions
- A function is a Function, contains basic blocks
- A basic block is a BasicBlock, contains instructions
- An instruction is an Instruction
- Instructions can contain operands, each is a Value
- All of the above, except Module, is a Value

Types

- No implicit casting in LLVM IR, all values must be explicitly converted
- All values have a static type
- Integers are specified at arbitrary bitwidth
  - i1, i2, i3, … , i32, … i398
- Floating point types
- Derived types specify arrays, vectors, functions pointers, structures
  - Structures have types like `{i32, i32, i8}`
  - Pointers have types like “pointer to i32”

Note on Integer Types

- There are no signed or unsigned integers
- LLVM views integers as bit vectors
- Frontends destroyed signed/unsigned information
  - Really, C programmers destroyed signed/unsigned information…
- Research prototypes exist that analyze integer wrapping in LLVM IR (http://code.google.com/p/wrapped-intervals/)
- Operations are interpreted as signed or unsigned based on instructions they are used in

Memory Model

- LLVM has a low level view of memory
  - Just a key -> value map
  - Keys are pointer values
  - Values stored in LLVM memory must be integers, floating point, pointers, vectors, structures, or arrays
- LLVM has a concept of creating function-local memory via `alloca`

The Module

- Highest level concept
- Contains a set of global values
  - Global variables
  - Functions

The Function

- Name
- Argument list
- Return type
- Calling convention
- Extends from `GlobalValue`, has properties of linkage visibility

The BasicBlock

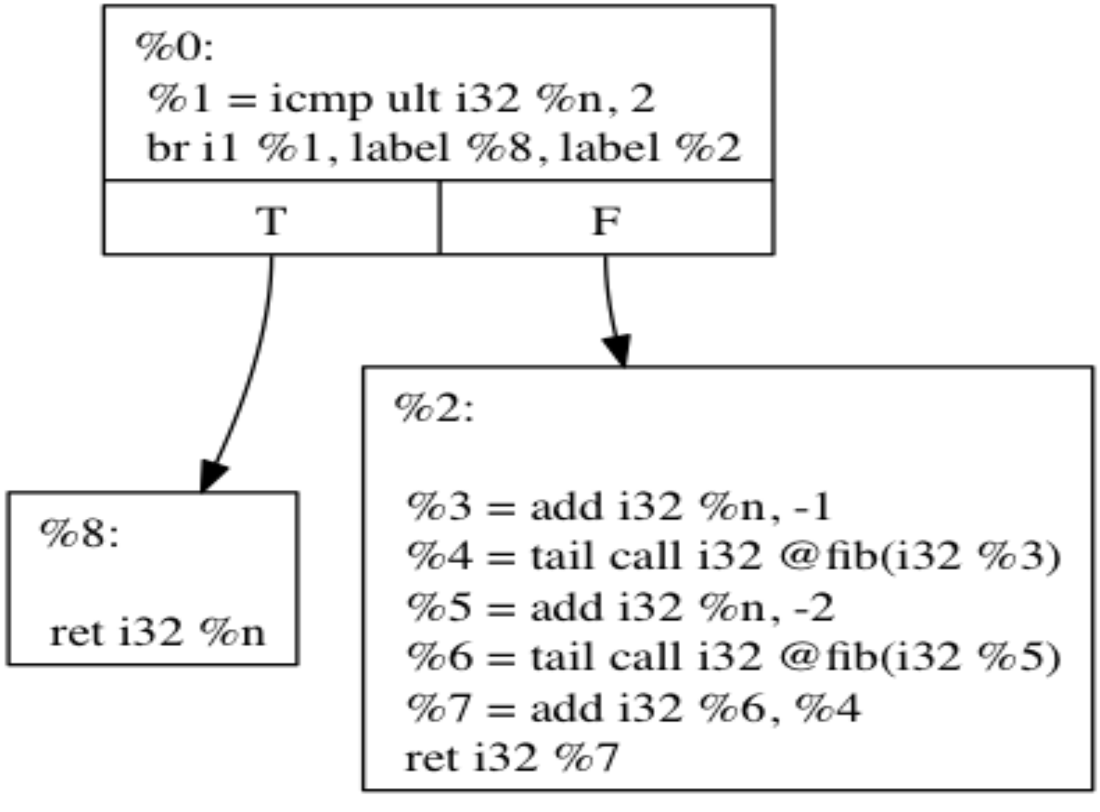
- Contains a list of Instructions
- All BasicBlocks must end in a TerminatorInst
- BasicBlocks descend from values, and are used as values in branching instructions

The Instruction

- Terminator instructions
- Binary instructions
- Bitwise instructions
- Aggregate instructions
- Memory instructions
- Type conversion instructions
- Control and misc instructions

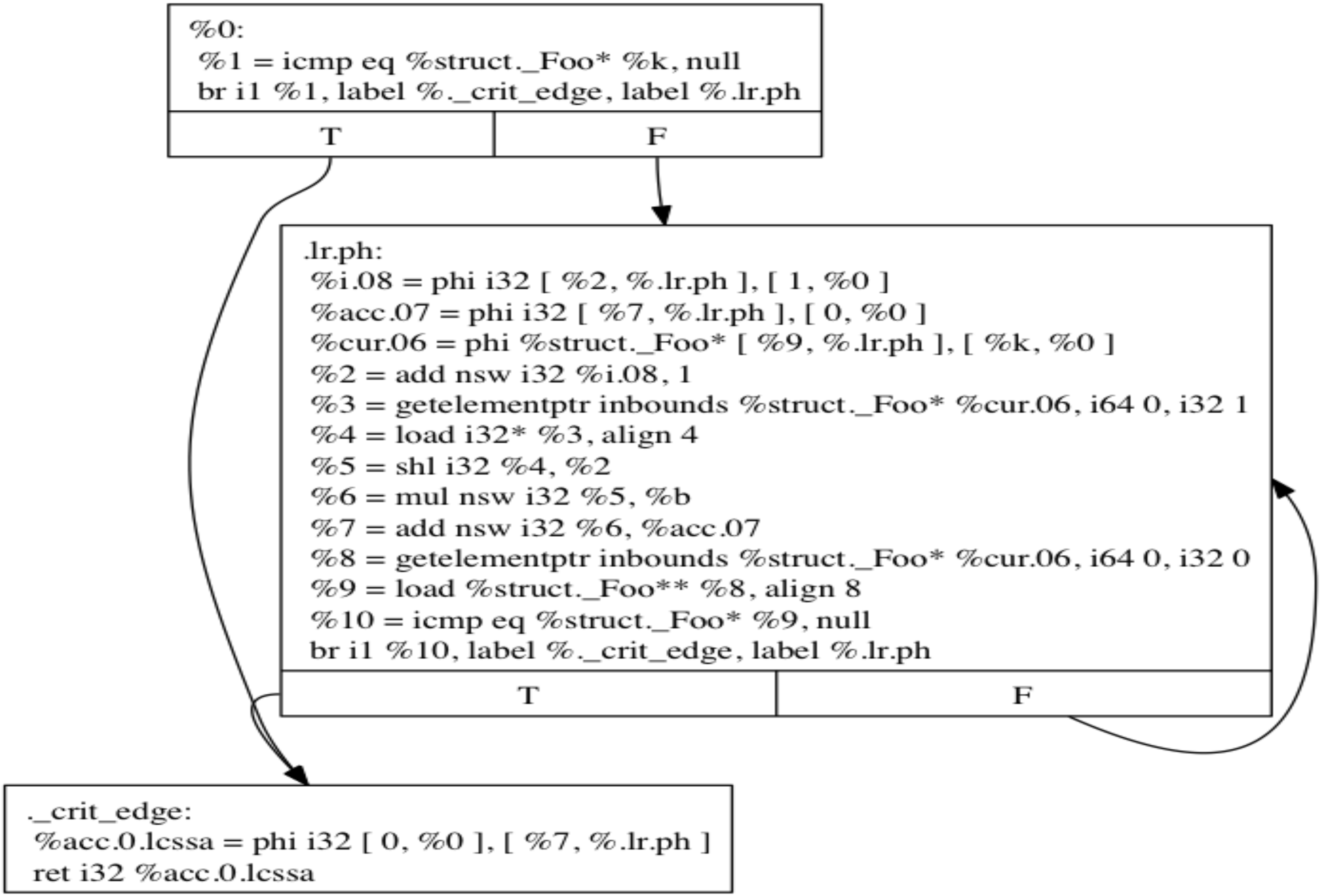
Language By Example

Produced with `opt –dot-cfg –o fib.bc fib.bc` and graphviz



CFG for 'fib' function

Language By Example, Part 2



CFG for 'xform_all' function

Static Single Assignment

- LLVM contains a pass to promote variable-using functions to value-using functions
- Once transformed by this pass, an LLVM module is in SSA form
- Most LLVM analyses and transformations expect to operate on an SSA IR
- SSA allows for Def-Use and Use-Def chain analysis

Simple function

```
int foo(int a, int b) {
  int i = a;
  int j = b;

  return i+j+1;
}
```

Pre-SSA

```
define i32 @foo(i32 %a, i32 %b) nounwind uwtable ssp {
entry:
  %a.addr = alloca i32, align 4
  %b.addr = alloca i32, align 4
  %i = alloca i32, align 4
  %j = alloca i32, align 4
  store i32 %a, i32* %a.addr, align 4
  store i32 %b, i32* %b.addr, align 4
  %0 = load i32* %a.addr, align 4
  store i32 %0, i32* %i, align 4
  %1 = load i32* %b.addr, align 4
  store i32 %1, i32* %j, align 4
  %2 = load i32* %i, align 4
  %3 = load i32* %j, align 4
  %add = add nsw i32 %2, %3
  %add1 = add nsw i32 %add, 1
  ret i32 %add1
}
```

Post-SSA

```
define i32 @foo(i32 %a, i32 %b) nounwind
uwtable ssp {
entry:
  %add = add nsw i32 %a, %b
  %add1 = add nsw i32 %add, 1
  ret i32 %add1
}
```

The Phi-Node

- To support conditional assignments, we introduce an imaginary function
- Phi defines a value and accepts a list of tuples as an argument
- Each tuple is a (BasicBlock * Value)
- Interpret the phi node as defining a value conditionally based on the previous basic block

Phi node example

```
int foo(int a, int b) {
  int r;

  if( a > b )
    r = a;
  else
    r = b;

  return r;
}
```

Phi node example, pre SSA

```
define i32 @foo(i32 %a, i32 %b) nounwind uwtable ssp {
entry:
  %a.addr = alloca i32, align 4
  %b.addr = alloca i32, align 4
  %r = alloca i32, align 4
  store i32 %a, i32* %a.addr, align 4
  store i32 %b, i32* %b.addr, align 4
  %0 = load i32* %a.addr, align 4
  %1 = load i32* %b.addr, align 4
  %cmp = icmp sgt i32 %0, %1
  br i1 %cmp, label %if.then, label %if.else

if.then:
  %2 = load i32* %a.addr, align 4
  store i32 %2, i32* %r, align 4
  br label %if.end

if.else:
  %3 = load i32* %b.addr, align 4
  store i32 %3, i32* %r, align 4
  br label %if.end

if.end:
  %4 = load i32* %r, align 4
  ret i32 %4
}
```

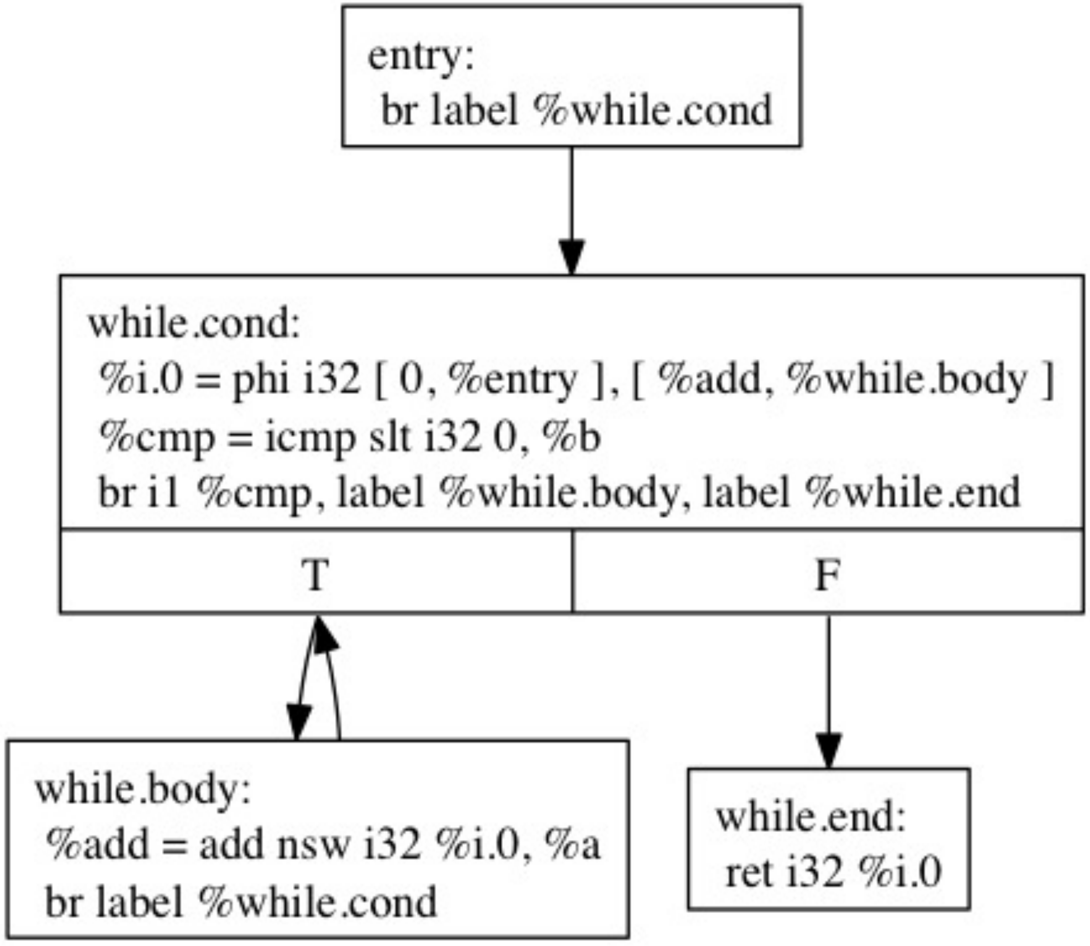
Phi node example, post SSA

```
define i32 @foo(i32 %a, i32 %b) nounwind uwtable ssp
{
entry:
  %cmp = icmp sgt i32 %a, %b
  br i1 %cmp, label %if.then, label %if.else

if.then: br label %if.end

if.else: br label %if.end

if.end: %r.0 = phi i32 [ %a, %if.then ], [ %b,
%if.else ]
  ret i32 %r.0
}
```

Phi node example 2

```
int aa(int a, int b) {
  int i = 0;
  int k = 0;
  while( k < b) {
    i += a;
  }

  return i;
}
```

LLVM CFG



CFG for 'aa' function

The GetElementPtr instruction

- An instruction so frequently misunderstood, it has its own documentation page about how it is misunderstood
- Frequently abbreviated as GEP
- GEP instructions compute offsets from pointer bases
  - Similar to 'lea' instructions in X86 assembler
- GEP instructions are type aware
  - Asking for 'the 5th field' of a pointer to structure operand will 'do the right thing'

Well-Formed LLVM

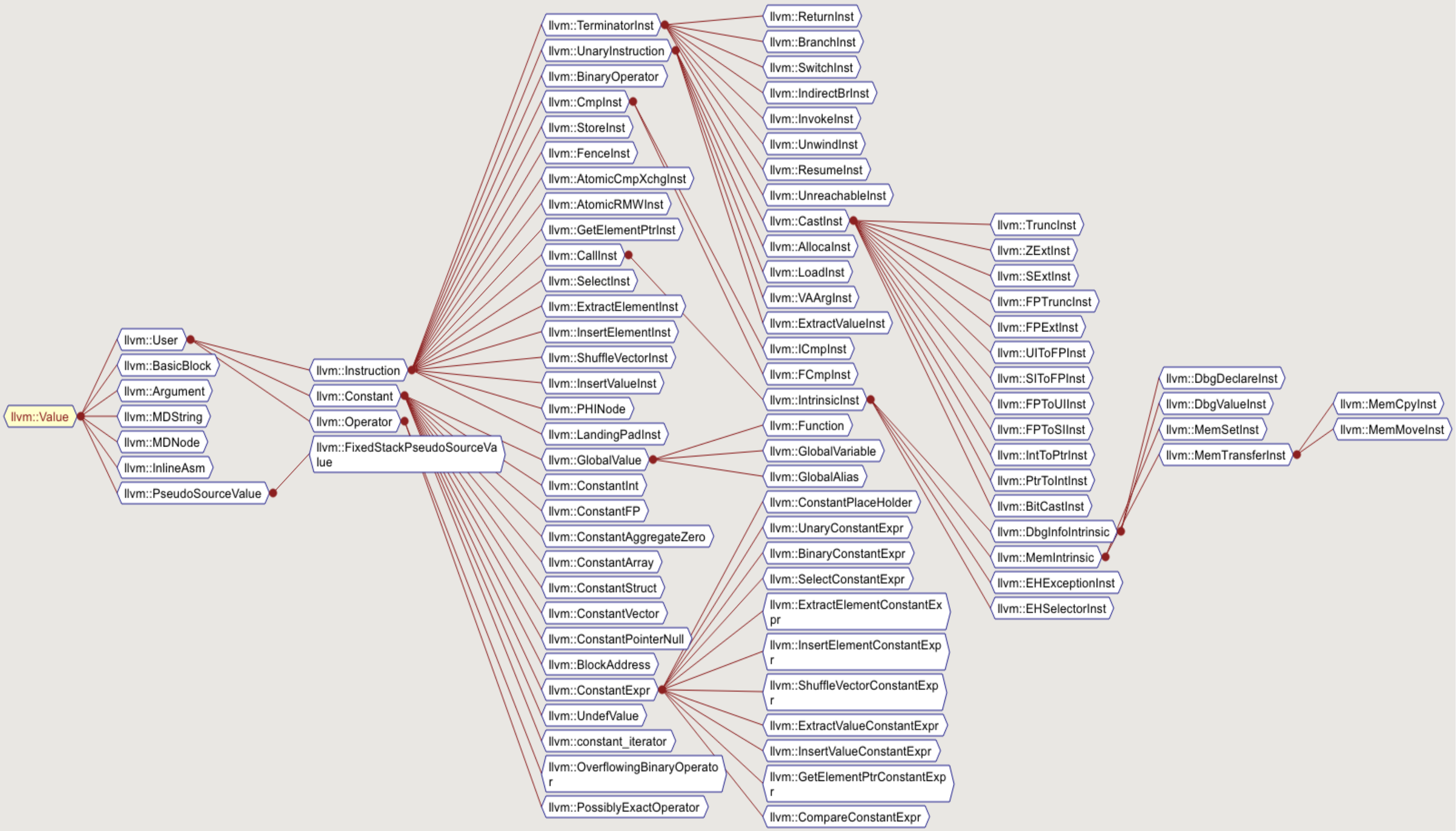
- There are specific rules as to what constitutes "Well-Formed" LLVM
  - Phi-nodes dominate their uses
  - Instruction arguments are defined before use
  - All blocks end in a terminator
  - All branch targets are defined values
- There is an automatic verification pass that will alert when IR is not well formed

C++ API

Value Hierarchy

- Value has a very rich class hierarchy
- LLVM API allows the manipulation of every Value
- Any degree of transformation is possible

Value class hierarchy



Everything From Value

- Every item contained in a Module inherits from Value
- This allows for some useful APIs
  - Def-Use / Use-Def iteration
  - Replace any Value with another Value
  - Sub
- Allows for classification
  - Instructions can be UnaryInstructions or BinaryInstructions
  - GlobalValues can be Functions or GlobalVariables

LLVM Context

- Frequent argument to LLVM API functions
- These can normally be retrieved from a Value via `getContext`
  - There is also a `getGlobalContext`
- The same LLVMContext should always be used across code that interacts with the same Values
  - LLVM objects are created in a specific context and are unique by pointer values
  - For example, type objects can be pointer-compared for equality between types of different instructions

Run Time Type Information

- An evil C++ concept
- If you have a function that accepts a parameter of an abstract class and it could be one of any specific implementations, how to choose?
- "Normal" C++ methods
  - `dynamic_cast<T>` and friends
- Compiler stores information about object types off to the side so that it can be used at run-time

LLVM and Run Time Type Information

- The LLVM codebase implements its own RTTI for LLVM objects
  - When writing passes, you use LLVM specific helpers
  - `isa<T>` - True or false if pointer/reference is of type T
  - `cast<T>` - "Checked cast", asserts on failure if not type T
  - `dyn_cast<T>` - unchecked cast, null if not type T
- The project advises you not to use big chains of these to approximate 'match' from ML
- Instead they give you a Visitor pattern (yay)
- You might find these insufficient (or distasteful)

Common Patterns

- "Iterate over BasicBlock in a Function"
  - Use begin(), end() iterators of Function
- "Iterate over Instructions in a Function"
  - Use `inst_iterator`
- "Iterate over Def-Use chains"
  - Use `use_begin, use_end`

InstVisitor

- Pattern to avoid giant blocks of

```
if(T *n = dyn_cast<T>(foo))
```

- Inherit from InstVisitor class and define a visitTInst method
- Could work for your purposes
- Could confuse control flow even more

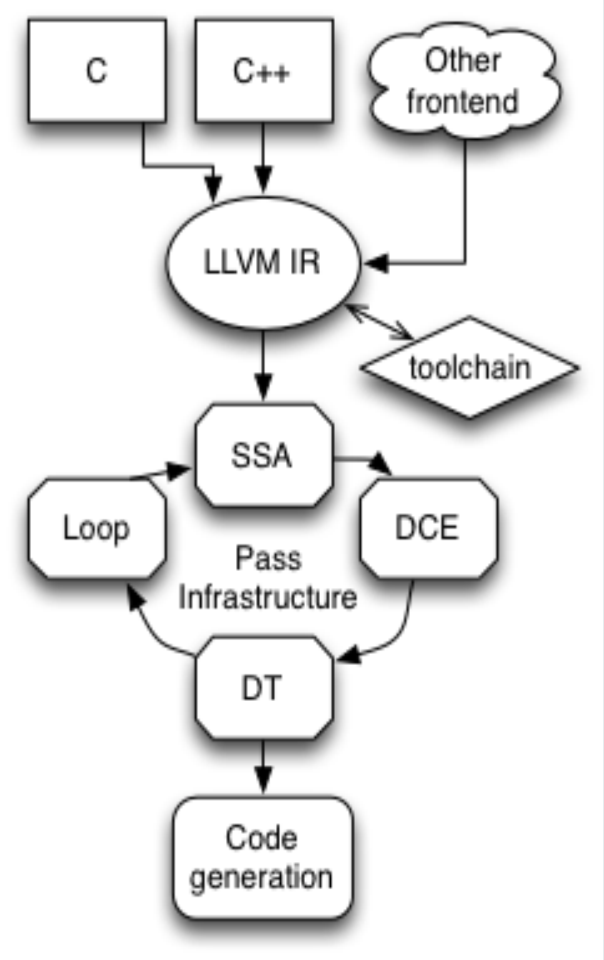
Including LLVM In Your Project

- `llvm-config` – executable that will provide useful info about the installed LLVM
- Provide paths to headers, library files, etc
- If LLVM is built with Cmake, it will add a FindLLVM.cmake to your /usr/share
- Compiling your code with –fno-rtti will probably be required
- If you compiled LLVM yourself, you can pass LLVM_REQUIRES_RTTI to cmake
- Needed if combining boost and llvm

Passes and transformations

Passes

- In the previous lab, we wrote a pass
- Compiling is the act of passing over and analyzing/transforming IR
- Most things that happen in LLVM happen in the context of a pass
- Passes can have complicated actions



Pass Dependencies

- Passes can depend on the output of other passes
  - Analysis passes for alias analysis
- Passes note their dependencies on other passes
  - By overriding the `getAnalysisUsage` method
- PassManager figures out the dependency graph
  - It also attempts to optimize the traversal of the graph
- Each Pass returns a bool, PassManager runs until everyone stops

Pass Manager

- PassManager performs dependency maintenance
  - Note that PassManager invocations could be multi-threaded!
  - Importance of multiple LLVMContexts
- PassManager also performs optimizations of pass ordering
- PassManager defines different kinds of Passes that can be run
- ModulePass – Run on entire module
- FunctionPass – Run on individual functions
- BasicBlockpass – Run on individual basic blocks

Pass Rules

- Non-analysis passes should not ‘remember’ any information about a function or basic block
- Analysis passes should remember some information
  - Otherwise why run them
- Transformation passes should be idempotent

Lab: Escape Analysis

- If a variable is allocated on the local stack, a pointer to that variable should not outlive the stack
- This could happen if a pointer to a local is returned or assigned to a global
- clang currently includes a check for this, but the check is kind of busted

Algorithm For Escape Analysis

- Populate a set of values that escape the function via return or store
- Traverse the set checking for `alloca`-ed values in the Values descending from the escapes

Structure of Provided Driver

- Driver is laid out similarly to before
- Collection of tests are included

Projects built on LLVM

- Google AddressSanitizer/ThreadSanitizer
  - http://code.google.com/p/address-sanitizer/
- Utah Integer Overflow Checker
  - http://embed.cs.utah.edu/ioc/
- Emscripten, LLVM to Javascript
  - https://github.com/kripken/emscripten/wiki
- Dagger, decompilation from x86 to LLVM
  - http://llvm.org/devmtg/2013-04/bougacha-slides.pdf

Important LLVM subprojects

- poolalloc – field-sensitive, context-sensitive alias analysis
- lldb – llvm debugger
- klee – symbolic execution for LLVM

- FreeBSD compiles with clang, soon will switch to building exclusively with clang

Conclusion

- LLVM enables powerful transformations
- Includes an “industry grade” C/C++ frontend
  - clang is default compiler on OSX, supported by Apple
  - Can compile much of Linux userspace
- Well defined Intermediate Language
- Modular and pluggable framework for analysis and transformation

Project Documentation

- Good documentation online
  - http://www.llvm.org/docs
- Documentation covers many aspects of the LLVM project
  - Programmers manual details finer points of the C++ API
  - Language reference is ultimate source for language details and semantics
- Relatively responsive IRC channel on OFTC
- Active and responsive mailing list