Introduction to the LLVM Compiler Infrastructure

Chris Lattner
Apple Computer
clattner@apple.com

Gelato ICE 2006
April 25, 2006

LLVM Talk Overview

- Introducing LLVM
- Building a Static Compiler with LLVM Components
- LLVM Code Representation (IR)
- GCC + LLVM Integration
- Itanium Code Generator Status
- (more) Q&A

What is a Compiler?

A tool that inspects and manipulates a representation of programs

- Examples:
  - Traditional C compiler (gcc), Java JIT compiler (hotspot), system assembler (as), system linker (ld), IDEs (Xcode), refactoring tools, ...
- Intentionally a very broad definition

LLVM is not a compiler

What is a Compiler Infrastructure?

- Provides modular & **reusable components** for building compilers
  - Components are ideally language/target independent
- **Reduces the time & cost** to construct a particular compiler
  - A new compiler = glue code plus any components not available
- Allows components to be **shared across different compilers**
  - Improvements made to one compiler benefits the others
- Allows choice of the **right component for the job**
  - Does not force the use of "one true register allocator" or scheduler

LLVM is a compiler infrastructure
llvm-gcc is a compiler

What is the LLVM Compiler Infrastructure?

Low Level Virtual Machine

- A well-defined Intermediate Representation (IR) for programs
  - Language independent, target independent, easy to use
- Many high-quality libraries (components) with clean interfaces!
  - Optimizations, analyses, modular code generator, JIT compiler, accurate GC, profiling, debugging, X86/PPC/IA64/SPARC/Alpha code generators, link time optimization, IPA/IPO…
- Tools built from the libraries:
  - Aggressive optimizing C/C++/ObjC compiler, automated compiler debugger, compiler driver, modular optimizer, LLVM JIT...

This all exists and works today!

Building a Static Compiler with LLVM Components

Example of a Simple Static Compiler

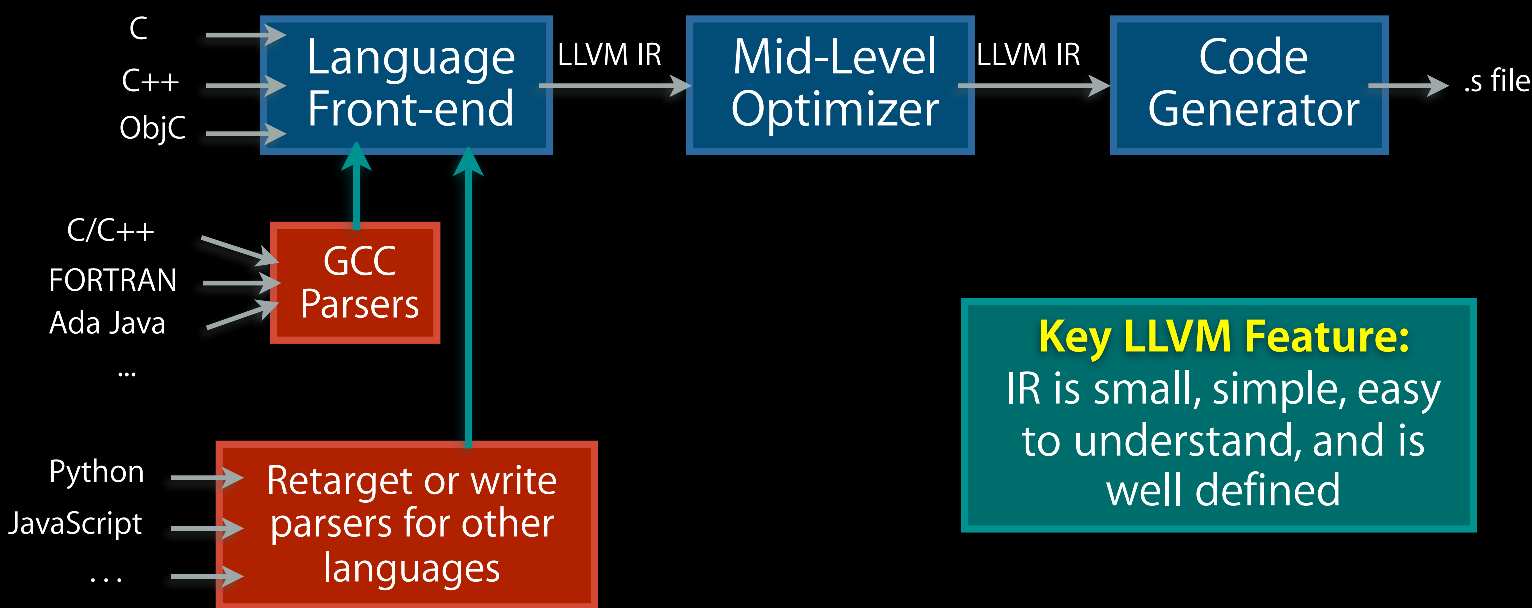
- Standard compiler organization, which uses LLVM as midlevel IR:
  - Language specific front-end lowers code to LLVM IR
  - Language/target independent optimizers improve code
  - Code generator converts LLVM code to target (e.g. IA64) code

Many compilers (e.g. GCC) follow this model.

http://llvm.org/

Front-end options for this compiler

- Front-ends are truly separate from optimizer & codegen
  - Can use front-end AST's that are tailored to the source language
  - Optimizer & Codegen improvements benefit all front-ends
  - Front-ends generate debug info and include it in the IR

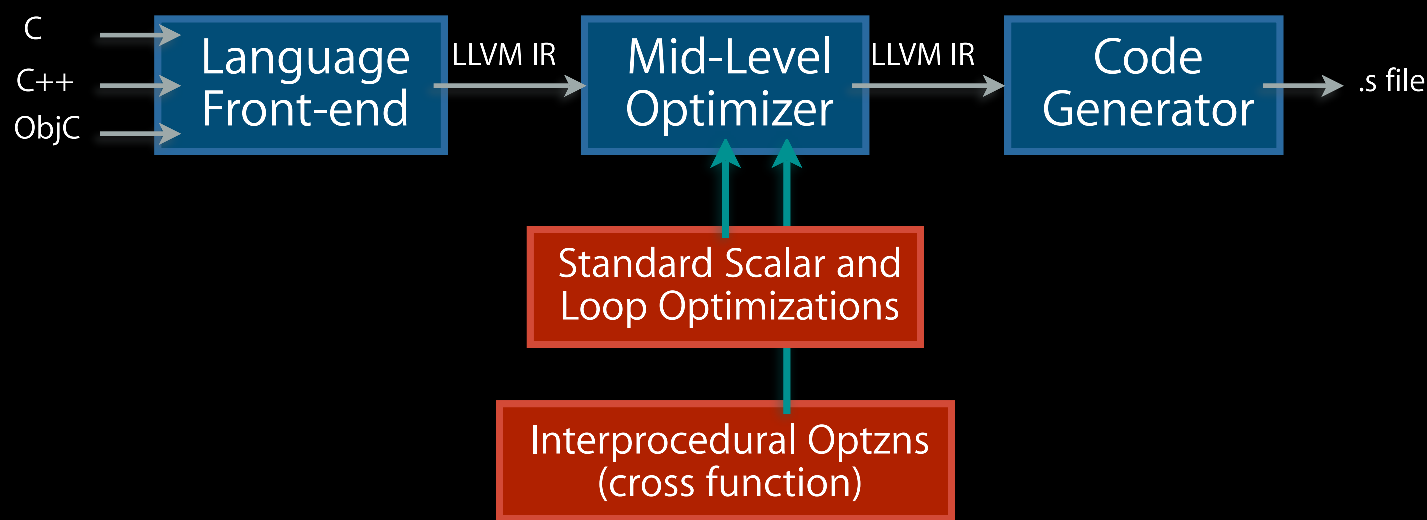


Key LLVM Feature:
IR is small, simple, easy to understand, and is well defined

llvm-gcc currently uses the GCC 4.0.1 parsers

Optimizer options for this compiler

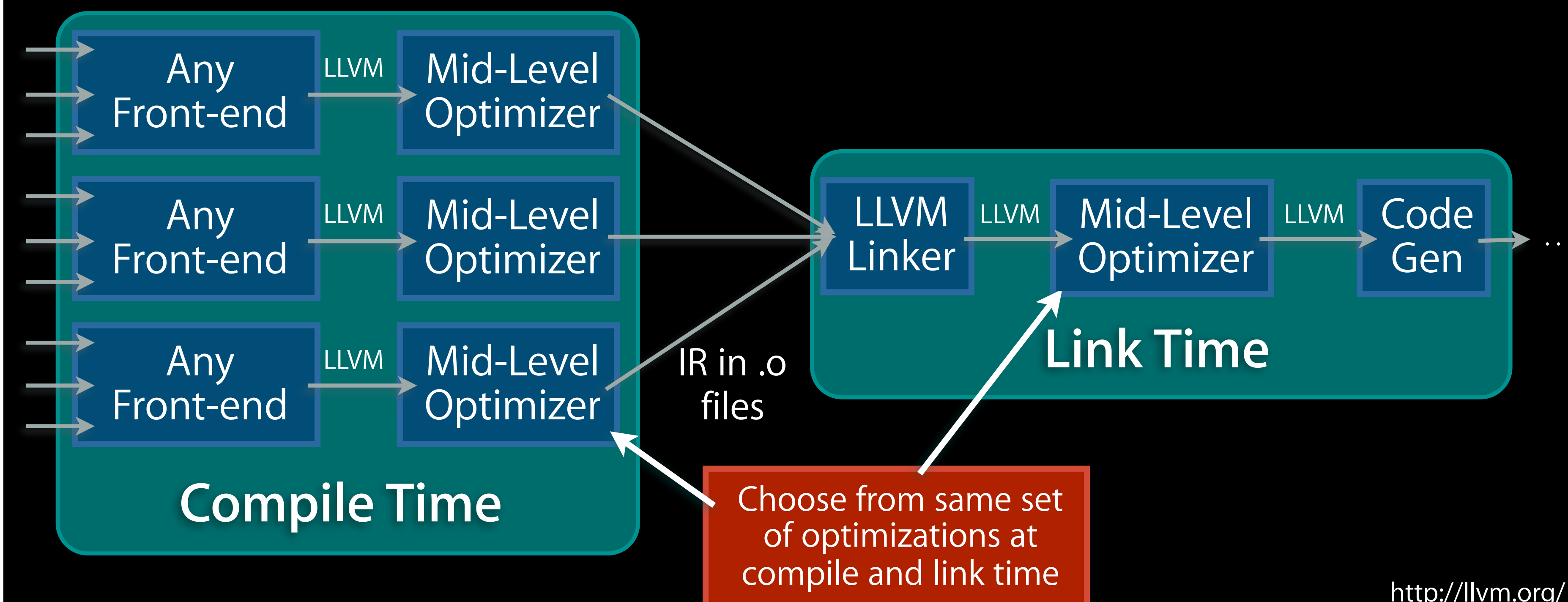
- Optimizer is solely concerned with semantics of LLVM IR
  - Optimizer & Codegen only know LLVM, not all source languages
  - LLVM includes IP framework and aggressive IP optimizations
  - LLVM uses a modern and light-weight (fast) SSA-based optimizer



http://llvm.org/

Link-Time Optimization

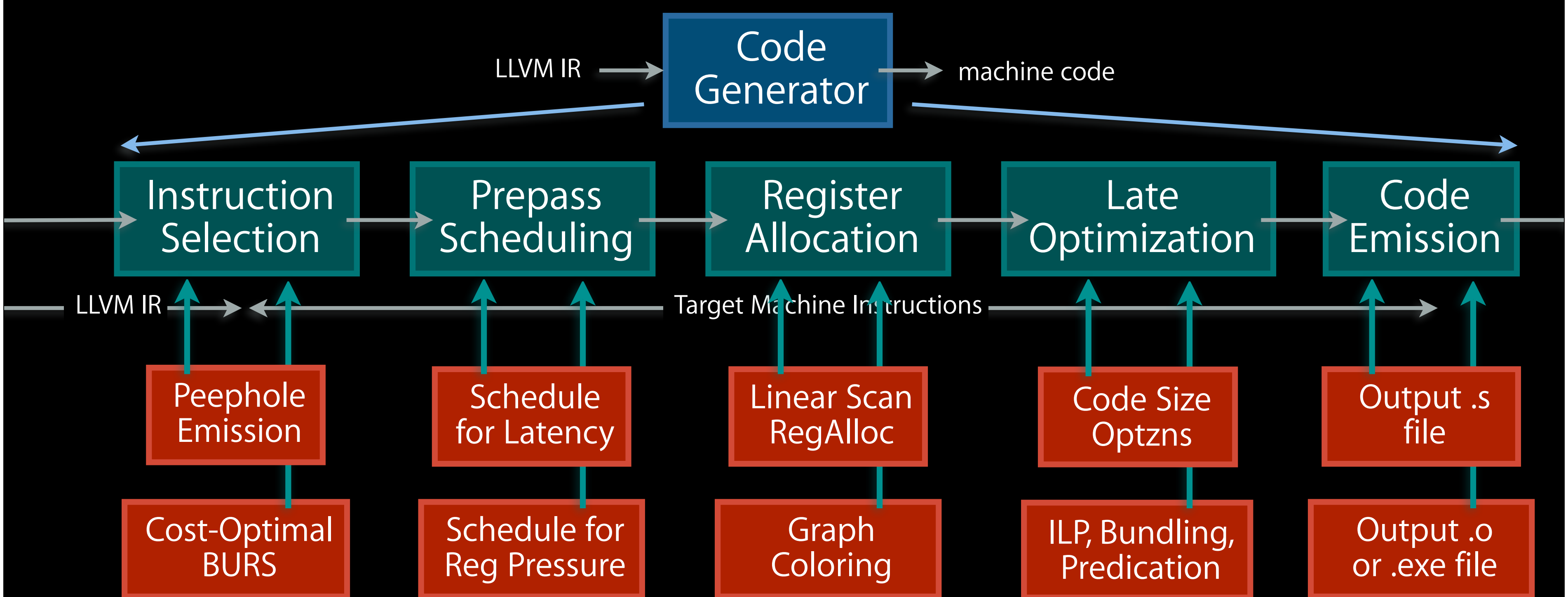
- Link-time is a natural place for interprocedural optimizations
  - Cross-module optzn is natural and trivial (no makefile changes)
  - All optimizations respect limitations of incomplete programs
    - e.g. building an app with missing libraries, building a library, etc...
  - LTO has been available since LLVM 1.0!



http://llvm.org/

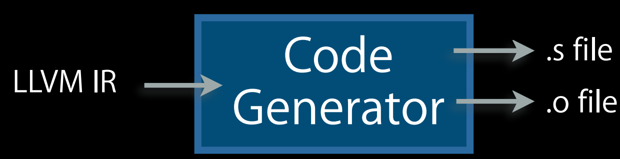
CodeGen options for this compiler

- The LLVM code generator is modern and modular:
  - Modern: maintains SSA form until register allocation
  - Modular: choose components based on compiler constraints
    - e.g. Itanium port uses a PQS, could use more aggressive scheduler
  - Fast: Representation is similar to the “compressed RTL” GCC proposal



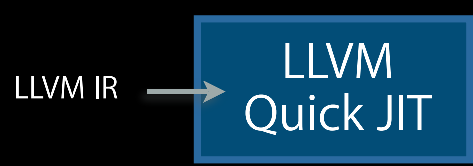
CodeGen choices this compiler

- Portable IR provides flexibility for many different ways to codegen
- Note: IR can have symbols stripped, like machine code
  - ... LLVM IR does not suffer from Java/C#'s "easy to decompile" problem



Traditional Compiler

Portability to New Architectures



Fast Developer Debug-Compile-Run cycle

http://llvm.org/

More Aggressive Applications of LLVM

Run-time code generation

Efficient implementation of mini languages: Dynamically translate language to LLVM, then JIT compile.

```
<script type="text/javascript">
function myfunction() {
    compute(15)
}
</script>
```

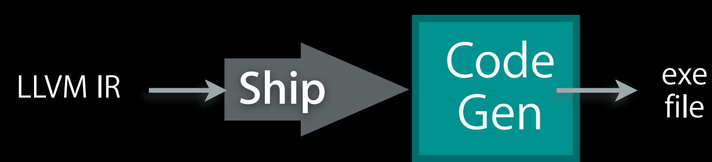
Dynamic Code Specialization

Good for long-running computations with "dynamic constants." Use LLVM to specialize run-time constants into the code, then optimize based on them.

```
for (i = 0; i < ARCHnodes; i++)
  for (j = 0; j < 3; j++)
    disp[disptplus][i][j] *= - Exc.dt * Exc.dt;
```

Install-time Code Generation

Tune apps for the specific architecture at the end-user site



Vendor provides code generator?

"Old binaries scheduled for new chips"

The LLVM Code Representation (IR)

Requirements on the LLVM IR

- IR must be usable through much of the compiler:
  - Produced by front-ends, consumed by code generator
- It must be language- and target-independent:
  - Including mixing of source languages within the same LLVM file
  - Allows cross-language analysis and optimization
  - Can still perform target-specific optimizations on it
- It must host a wide variety of optimizations and analyses:
  - Standard scalar optimizations (e.g. common subexpr elimination)
  - Loop optimizations (e.g. LICM, unrolling, unswitching, ...)
  - Interprocedural (e.g. inlining, arg promotion, IP-SCCP, global var opt)
  - Must support both high- and low-level optimization

Design Approach of the LLVM IR

- Design IR as a typed **Virtual Instruction Set**
  - Operations are low-level instructions in CFG
  - Language- & target- independent semantics

```
%X = load int* %Ptr
%Y = add int %X, 1
%C = setlt int %Y, 10
br %C, label %Dest
```

- IR is designed with three isomorphic formats:
  - In memory IR - for the compiler to work on
  - On-disk compressed binary IR - Interchange format
  - On-disk text - Compiler debugging, inspection

- IR has a clean/simple design:
  - Small memory footprint, fast to manipulate
  - Easy to understand (and well specified/documented)

http://llvm.org/docs/LangRef.html

LLVM IR Features

- Basic features:
  - Light-weight design, efficient and easy to understand
  - Scalars values are always in SSA form, memory never is
  - IR is fully typed and types are rigorously checked for consistency
  - Explicit array/struct accesses, supports alias/dependence analysis
  - Full support for vector/SIMD datatypes and operations
  - Full support for GCC-style inline assembly

- Minor features:
  - Exceptions are explicit in CFG, not an on-the-side datastructure
  - Includes support for Accurate Garbage Collection
  - IR is easily extensible with intrinsic functions
  - Supports custom calling conventions (required for guaranteed tail calls)

Example LLVM Tool: Bugpoint

Automatically reduce optimizer/codegen ICEs, miscompilations, and JIT failures

- Simple idea: binary search for bug
  - Figure out which pass (out of 60+) is causing the problem
  - Figure out what (code) input to the pass demonstrates the problem
- For a compiler crash:
  - Binary search pass list. Run previous passes to get its input.
  - Split up program, eliminate pieces not required for ICE
- For a miscompilation:
  - Run program with designated input to determine if it works
  - Split program, optimize/codegen half, link together, run.
- Can reduce 100K LOC program to a single basic block in 5 mins

- Simple tool reuses many LLVM libraries, relies on well defined IR

http://llvm.org/docs/Bugpoint.html

LLVM + GCC Integration

LLVM + Apple GCC Integration

- llvm-gcc 4.0 is the 3rd edition of llvm-gcc:
  - Based on Apple GCC 4.0.1 branch
  - GIMPLE to LLVM translation: ~6000 lines of code
  - Tight integration: llvm-gcc links in the LLVM libraries
  - GCC front-ends, LLVM optimizers & code generators
- Current status:
  - Mostly feature complete:
    - Supports C/C++/ObjC/ObjC++, vector support, debug info, has basic inline asm support, most GCC attributes, etc
  - Missing features (as of April 25, 2006):
    - No linker support for transparent IPO yet (exists in llvm-gcc3)
    - C++ Exception Handling (exists in llvm-gcc3)
    - long double and other minor features

LLVM + FSF GCC Integration: Design

- Most likely design point: replace tree-ssa with LLVM, keep RTL
  - Convert from GENERIC to LLVM in frontend
  - Convert from LLVM to RTL in the backend

- Design Advantages:
  - GCC gets LLVM LTO support, a light-weight IR and fast optimizer
  - LLVM is similar to tree-ssa: tree-ssa expertise should transfer well
  - By using the RTL backend, no GCC targets are lost

- Eventually could use native LLVM backends if desired:
  - Enables JIT compiler for Java, faster compiles, direct .o file emission, better codegen, easier porting to new targets
    - ... for the subset of GCC targets that are supported by LLVM

These thoughts are based on my impression of the GCC mailing list discussions, details subject to change!

LLVM + FSF GCC Integration: Progress

- Remaining technical issues to resolve:
  - No LLVM to RTL backend implemented yet
  - Must forward port from Apple 4.0.1 branch to mainline
  - Must implement minor missing features

- Assigning control / Copyright assignment to FSF:
  - Ongoing project!
  - Progress since November:
    - FSF okay's writing IR to disk, LTO proposal is made
    - No more web registration required to download LLVM
    - Official LLVM domain changes from llvm.cs.uiuc.edu to llvm.org
    - Many missing features implemented in LLVM (vector support, target intrinsics, inline asm, debugging, ...)
    - Continuing to work with the copyright clerk and related parties to complete paperwork

LLVM vs LTO for link-time optimization

- LTO advantages over LLVM:
  - LLVM is missing some functionality, has no LLVM-to-RTL backend yet
- LLVM advantages over LTO:
  - LLVM has had IPO support since before tree-ssa was started!
    - LLVM exists, works great, and can be evaluated today
  - LLVM has far more efficient data structures than GCC:
    - LLVM can represent 200K LOC in ~50M, GCC requires multi GB
    - Many projects to fix GCC's mem usage have had limited success
  - Without major changes, LTO cannot link different languages or flags:
    - Langhooks and global flags like -ffast-math are a big problem
  - LTO suffers same class of bugs that IMA does:
    - Linking "GCC trees" is extremely hard to do 100% correctly
    - Cross language linking multiplies the problem many-fold
  - Does not try to solve front-end issues with IPA infrastructure!

LLVM Itanium
Code Generator

LLVM Itanium Backend Status

- Itanium backend developed & maintained by Duraid Madina
  - Progress has been slow, due to lack of time and other commitments

- Current implementation:
  - Basically working, very few miscompilations
  - Missing many simple optimizations
  - Has trivial stop bit insertion, but no bundle aware hazard recognizer
  - No post-pass scheduling, predication, prefetching, modsched, etc
  - ~4000 lines of code (.cpp, .h, .td)

- Generated code is about 50-60% the performance of GCC
- When assembled with IAS, LLVM beats GCC on many programs
  - IAS is an 'optimizing assembler', which does scheduling/bundling

A small investment can go a long way!

LLVM Summary

- LLVM is a modular compiler infrastructure:
  - Primary focus is on providing good interfaces & robust components
  - LLVM can be used for many things other than simple static compilers!
- LLVM provides language- and target-independent components:
  - Does not force use of JIT, GC, or a particular object model
  - Code from different languages can be linked together and optimized
- LLVM is well designed and provides aggressive functionality:
  - Interprocedural optimization, link-time/install-time optimization today!
- LLVM 1.7 was released last week:
  - Huge number of new features, many codegen improvements
  - Give it a try: http://llvm.org/releases/

clattner@apple.com