The LLVM Compiler System

LLVM: Low Level Virtual Machine

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Bossa International Conference
on Open Source, Mobile Internet and Multimedia
March 12, 2007

LLVM Talk Overview

- The LLVM Approach to Compilers
- The LLVM C/C++/ObjC Compiler
- Optimizing OpenGL with LLVM
- Using LLVM with Scripting Languages

Open Source Compiler Technology

- "Scripting" Language Interpreters: Python, Ruby, Perl, Javascript, etc
  - Traditionally interpreted at runtime, used by highly dynamic languages
- Java and .NET Virtual Machines
  - Run time compilation for any language that can target the JVM
- GCC: C/C++/ObjC/Ada/FORTRAN/Java Compiler
  - Static optimization and code generation at build time

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OSS Compiler Technology Strengths 1/2

- Scripting/Dynamic Language Strengths:
  - Interpreters are extremely portable and small (code size)
  - Many interesting advanced compilation models (pypy, Parrot, jrubyc, etc)
  - Dynamic languages are very expressive and powerful

- Java Virtual Machine Strengths:
  - JVM bytecode is portable, JVMs available for many systems
  - Many languages can be compiled to JVM
  - Provides runtime/JIT optimization, high level optimizations

OSS Compiler Technology Strengths 2/2

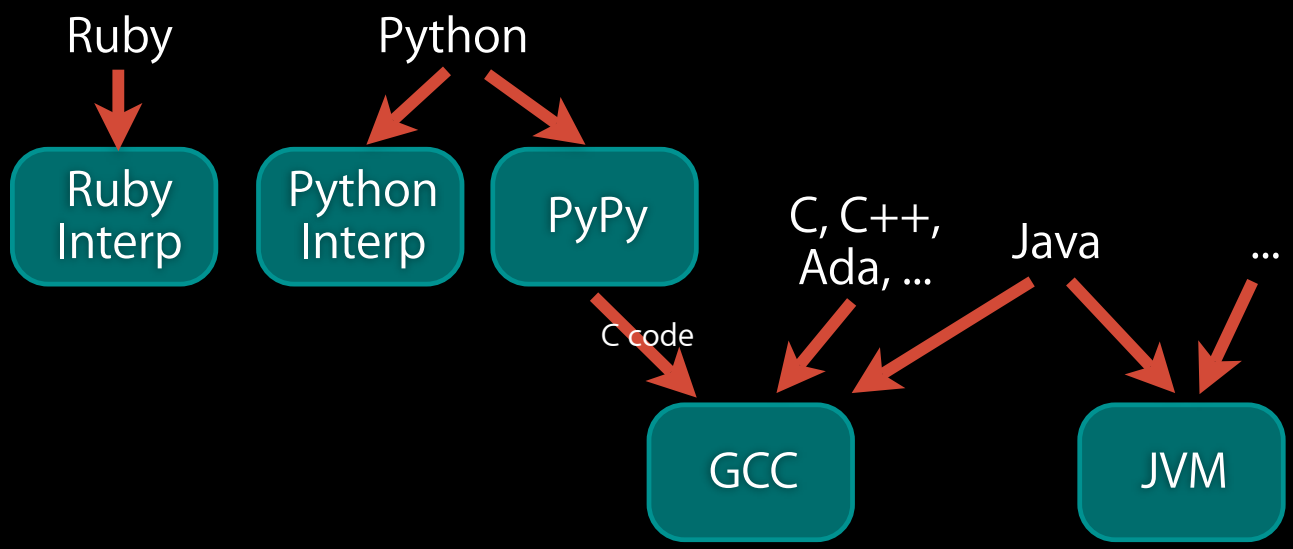
- GCC Strengths:
  - Support for important languages like C/C++
    - Other projects can emit C/C++ code and compile with GCC
  - Good code generation/optimization
  - Supports many different CPUs

- Common strengths:
  - Each has a **large and vibrant community**!
  - We support tons of existing code written in many languages!

With so many strengths, what could be wrong?

OSS Compiler Technology Weaknesses 1/2

- Common Problem:
  - The tools only work together at a **very coarse grain**



  - Each arrow/box is a completely separate project from the others
    - Very little sharing (e.g.) between ruby and python interpreter
  - Advanced optimizer projects don't share code (e.g. jrubyc vs shedskin)

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OSS Compiler Technology Weaknesses 2/2

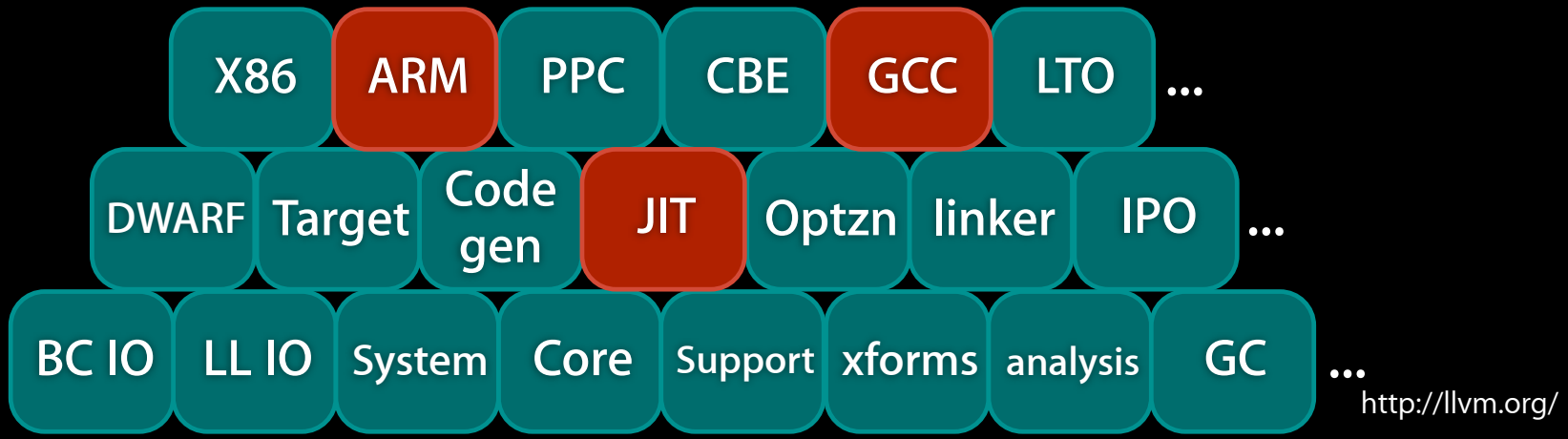
- Scripting Language Weaknesses:
  - Efficient execution: poor "low level" performance, memory use
- Java Virtual Machine Weaknesses:
  - Must use all of JVM or none of it: GC, JIT, class library, etc
  - Forced to mold your language into the Java object model
  - Huge memory footprint and startup time
- GCC Weaknesses:
  - Old code-base and architecture: Very steep learning curve
  - Doesn't support modern compiler techniques (JIT, cross file optimization)
  - Slow compile times

Each approach has mostly disjoint strengths and weaknesses!

LLVM Compiler Vision and Approach

- Basic mission: **build a set of modular compiler components** that:
  - ... implement aggressive and modern techniques
  - ... integrate well with each other
  - ... have few dependencies on each other
  - ... are language- and target-independent where possible
  - ... integrate closely with existing tools where possible

- **Second: Build compilers that use these components**



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Value of a library-based approach

- **Reduces the time & cost** to construct a particular compiler
  - A new compiler = glue code plus any components not yet available
- Components are **shared across different compilers**
  - Improvements made for one compiler benefits the others
- Allows choice of the **right component for the job**
  - Don't force "one true register allocator", scheduler, or optimization order

- Examples:
  - Initial bringup of llvm-gcc4 took 2-3 months (GCC is very complex!)
    - Required building "GCC tree to LLVM" converter
    - Including support for many targets, aggressive optimizations, etc
  - First OpenGL JIT built in two weeks:
    - Required building "OpenGL to LLVM" converter
    - Replaced existing JIT, much better optimizations and performance

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

Example Client: llvm-gcc4

C/C++/ObjC/...

Standard GCC 4.x Design

- Standard compiler organization: front-end, optimizer, codegen
  - Parser and front-ends work with language-specific "trees"
  - Optimizers use trees in "GIMPLE" form, modern SSA techniques, etc.
  - RTL code generator use antiquated compiler algorithms/data structures

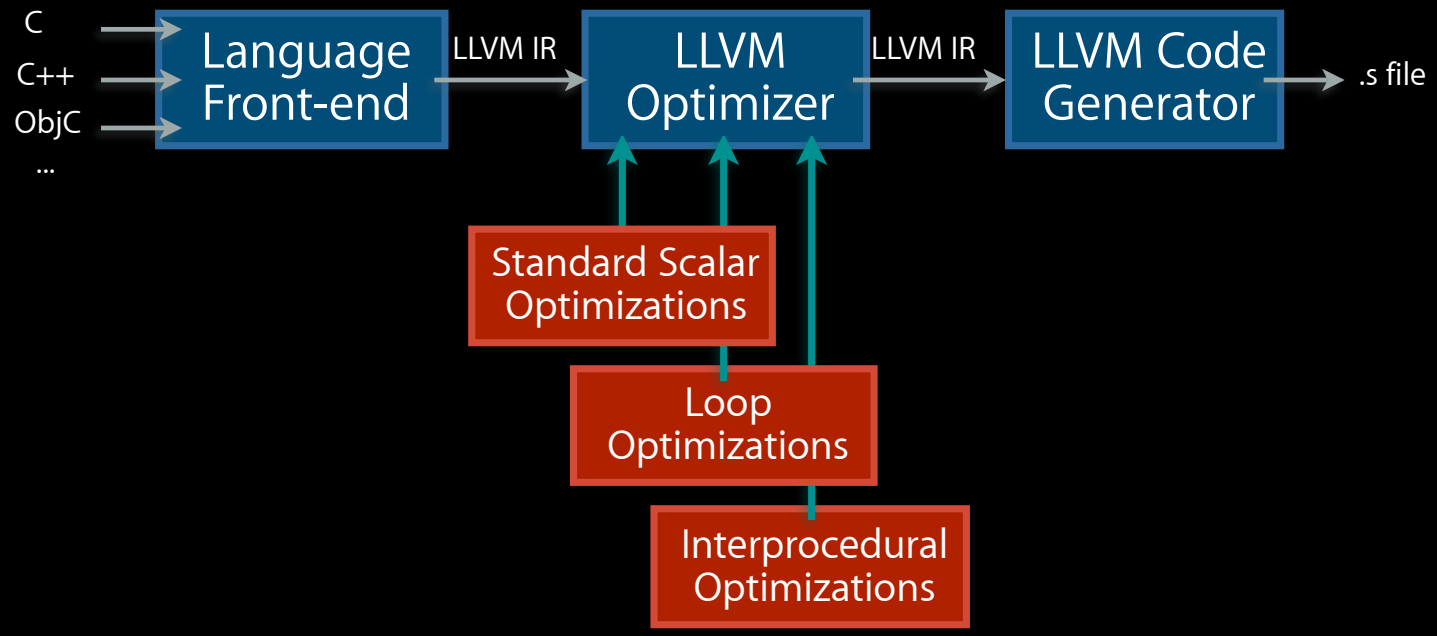
- Pros: Excellent front-ends, support for many processors, defacto standard
- Cons: Very slow, memory hungry, hard to retarget, no JIT, no LTO, no aggressive optimizations, ...

llvm-gcc4 Design

- Use GCC front-end with LLVM optimizer and code generator
  - Reuses parser, runtime libraries, and some GIMPLE lowering
  - Requires a new GCC "tree to llvm" converter

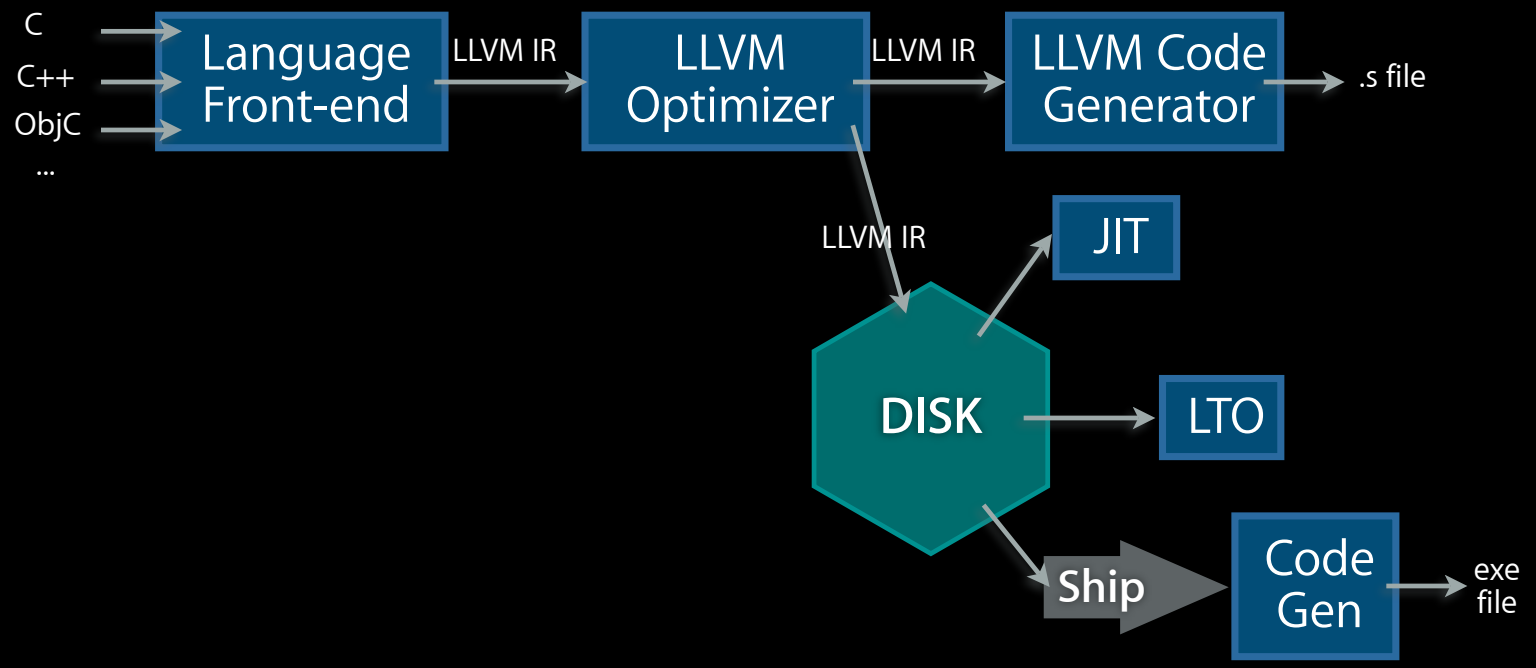
LLVM optimizer features used by llvm-gcc

- Aggressive and fast optimizer built on modern techniques
  - SSA-based optimizer for light-weight (fast) and aggressive xforms
  - Aggressive loop optimizations: unrolling, unswitching, mem promotion, ...
  - Many InterProcedural (cross function) optimizations: inlining, dead arg elimination, global variable optimization, IP constant prop, EH optzn, ...



Other LLVM features used by llvm-gcc

- LLVM Code Generator
  - Modern retargetable code generator, easier to retarget than GCC
- Write LLVM IR to disk for codegen after compile time:
  - link-time, install-time, run-time



Install Time Code Generation

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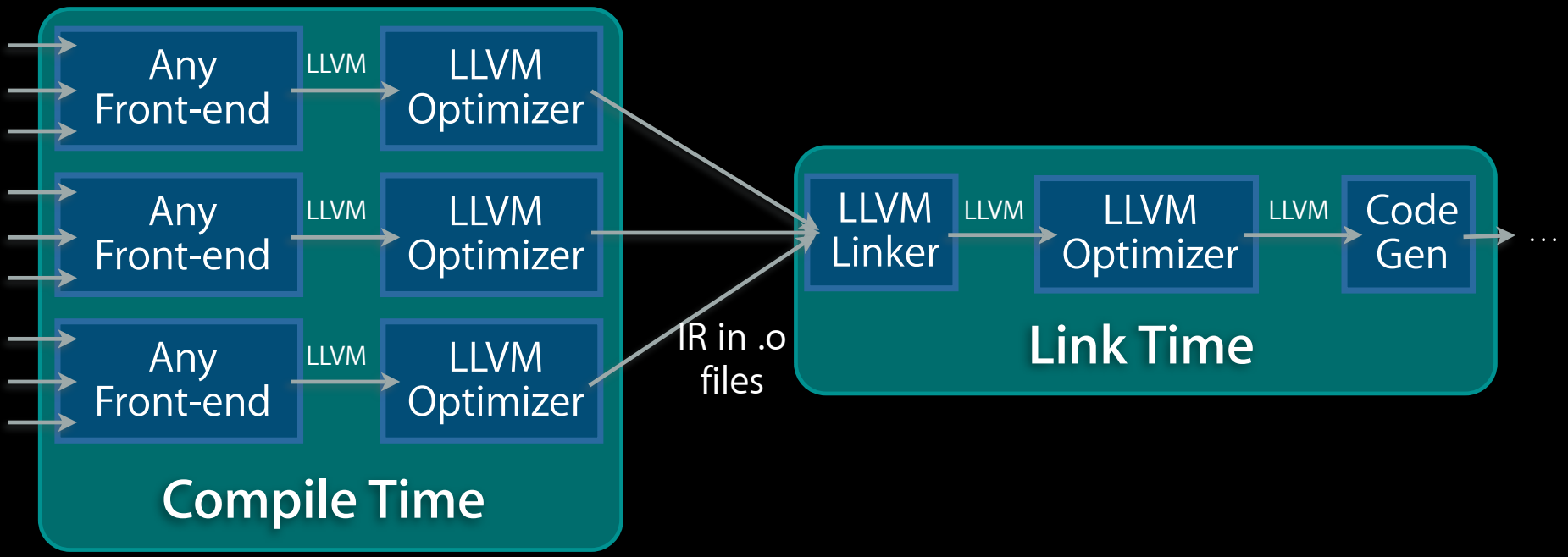
Link-Time Optimization (LTO)

- Link-time is a natural place for interprocedural optimizations
  - Cross-module optimization is natural and trivial (no makefile changes)
  - LLVM is safe with partial programs (dynamically loaded code, libraries, etc)
  - LTO has been available since LLVM 1.0!



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Example Client: OpenGL JIT

OpenGL Vertex/Pixel Shaders

OpenGL Pixel/Vertex Shaders

- Small program, provided at run-time, to be run on each vertex/pixel:
  - Written in one of a few high-level graphics languages (e.g. GLSL)
  - Executed millions of times, extremely performance sensitive
- Ideally, these are executed on the graphics card:
  - What if hardware doesn't support some feature? (e.g. laptop gfx)
    - **Interpret or JIT on main CPU**

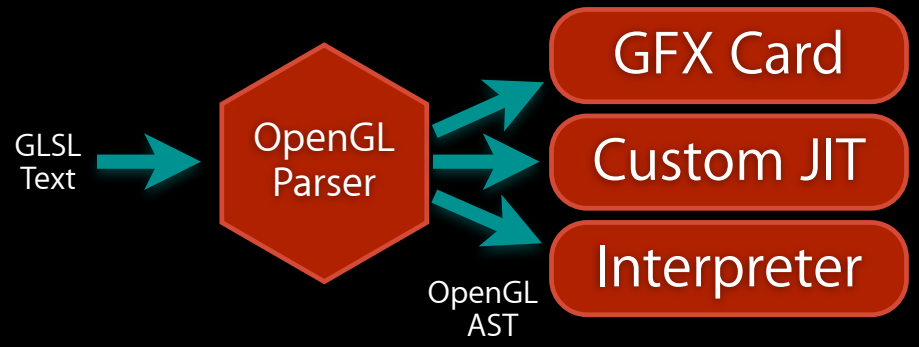
```
void main() {
 vec3 ecPosition = vec3(gl_ModelViewMatrix * gl_Vertex);
 vec3 tnorm      = normalize(gl_NormalMatrix * gl_Normal);
 vec3 lightVec   = normalize(LightPosition - ecPosition);
 vec3 reflectVec = reflect(-lightVec, tnorm);
 vec3 viewVec    = normalize(-ecPosition);
 float diffuse   = max(dot(lightVec, tnorm), 0.0);
 float spec      = 0.0;
 if (diffuse > 0.0) {
     spec = max(dot(reflectVec, viewVec), 0.0);
     spec = pow(spec, 16.0);
 }
 LightIntensity = DiffuseContribution * diffuse +
                  SpecularContribution * spec;
 MCposition     = gl_Vertex.xy;
 gl_Position    = ftransform();
}
```

GLSL Vertex Shader

Traditional OpenGL Impl - Before LLVM

- Custom JIT for X86-32 and PPC-32:
  - Very simple codegen: Glued chunks of Altivec or SSE code
  - Little optimization across operations (e.g. scheduling)
  - Very fragile, hard to understand and change (hex opcodes)

- OpenGL Interpreter:
  - JIT didn't support all OpenGL features: fallback to interpreter
  - Interpreter was very slow, 100x or worse than JIT



OpenGL JIT built with LLVM Components

- At runtime, build LLVM IR for program, optimize, JIT:
  - Result supports any target LLVM supports
  - Generated code is as good as an optimizing static compiler
- Other LLVM improvements to optimizer/codegen improves OpenGL
- Key question: How does the "OpenGL to LLVM" stage work?

Structure of an Interpreter

- Simple opcode-based dispatch loop:

```
while (...) {
  ...
  switch (cur_opcode) {
  case dotproduct:      result = opengl_dot(lhs, rhs); break;
  case texturelookup: result = opengl_texlookup(lhs, rhs); break;
  case ...
```

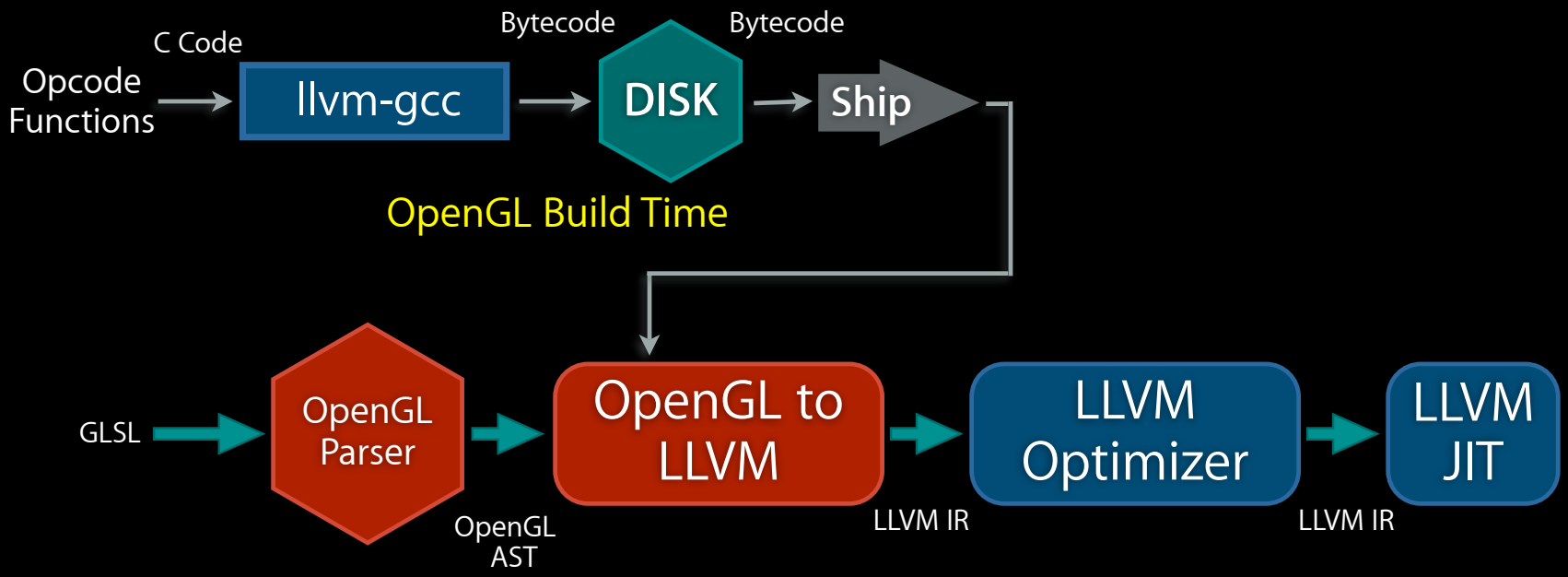
- One function per operation, written in C:

```
double opengl_dot(vec3 LHS, vec3 RHS) {
  #ifdef ALTIVEC
    ... altivec intrinsics ...
  #elif SSE
    ... sse intrinsics ...
  #else
    ... generic c code ...
  #endif
}
```

Key Advantage of an Interpreter:
Easy to understand and debug, easy to write each operation (each operation is just C code)

- In a high-level language like GLSL, each op can be hundreds of LOC

OpenGL to LLVM Implementation



- At OpenGL build time, compile each opcode to LLVM bytecode:
  - Same code used by the interpreter: easy to understand/change/optimize

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OpenGL to LLVM: At runtime

1. Translate OpenGL AST into LLVM call instructions: one per operation
2. Use the LLVM inliner to inline opcodes from precompiled bytecode
3. Optimize/codegen as before


```
...
vec3 viewVec = normalize(-ecPosition);
float diffuse = max(dot(lightVec, tnorm), 0.0);
 ...
```

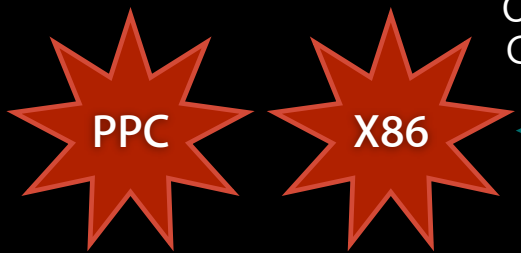
OpenGL to LLVM

```
 ...
%tmp1 = call opengl_negate(ecPosition)
%viewVec = call opengl_normalize(%tmp1);
%tmp2 = call opengl_dot(%lightVec, %tnorm)
%diffuse = call opengl_max(%tmp2, 0.0);
 ...
```

LLVM Inliner

```
 ...
%tmp1 = sub <4 x float> <0,0,0,0>, %ecPosition
%tmp3 = shuffle <4 x float> %tmp1, ...;
%tmp4 = mul <4 x float> %tmp3, %tmp3
 ...
```

Optimize, Codegen



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Benefits of this approach

- Key features of this approach:
  - Each opcode is written/debugged for a simple interpreter, in standard C
    - Retains all advantages of an interpreter: debugability, understandability, etc
    - Easy to make algorithmic changes to opcodes
  - OpenGL runtime is independent of opcode implementation
  - LLVM provides high performance: optimizations, regalloc, scheduling, etc

- Continuing benefits of using LLVM:
  - Support for new platforms for free
  - LLVM codegen continues to improve as it is used by other projects (e.g. llvm-gcc)
  - OpenGL group doesn't maintain their own JIT!

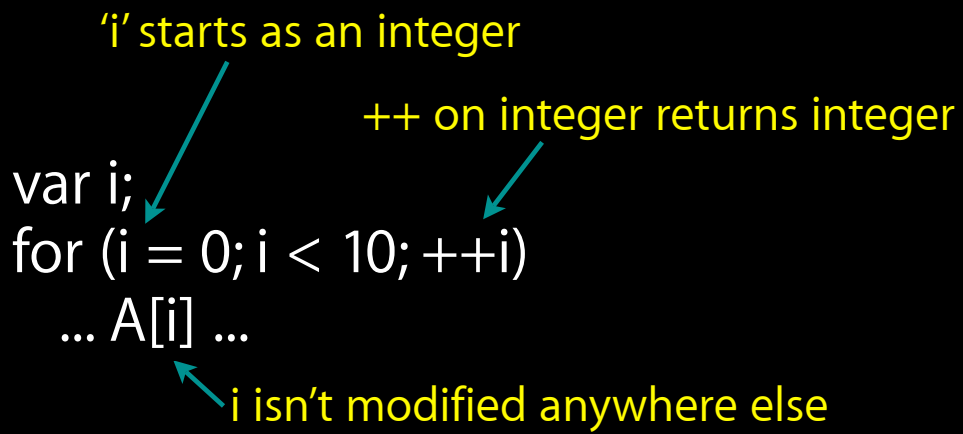
Example Client: a Scripting Language

Loosely based on "pypy" Python Compiler

LLVM and Dynamic Languages

- Dynamic languages are very different than C:
  - Extremely polymorphic, reflective, dynamically extensible
  - Standard compiler optzns don't help much if "+" is a dynamic method call

- Observation: in many important cases, dynamism is eliminable
  - Solution: Use dataflow and static analysis to infer types:



  - We proved "i" is always an integer: change its type to integer instead of object
  - Operations on "i" are now not dynamic
    - Faster, can be optimized by LLVM (e.g. loop unrolling)

Advantages and Limitations of Static Analysis

- Works on unmodified programs in scripting languages:
  - No need for user annotations, no need for sub-languages
- Many approaches for doing the analysis (with cost/benefit tradeoffs)
- Most of the analyses could work with many scripting languages:
  - Parameterize the model with info about the language operations
- Limitation: cannot find all types in general!
  - That's ok though, the more we can prove, the faster it goes

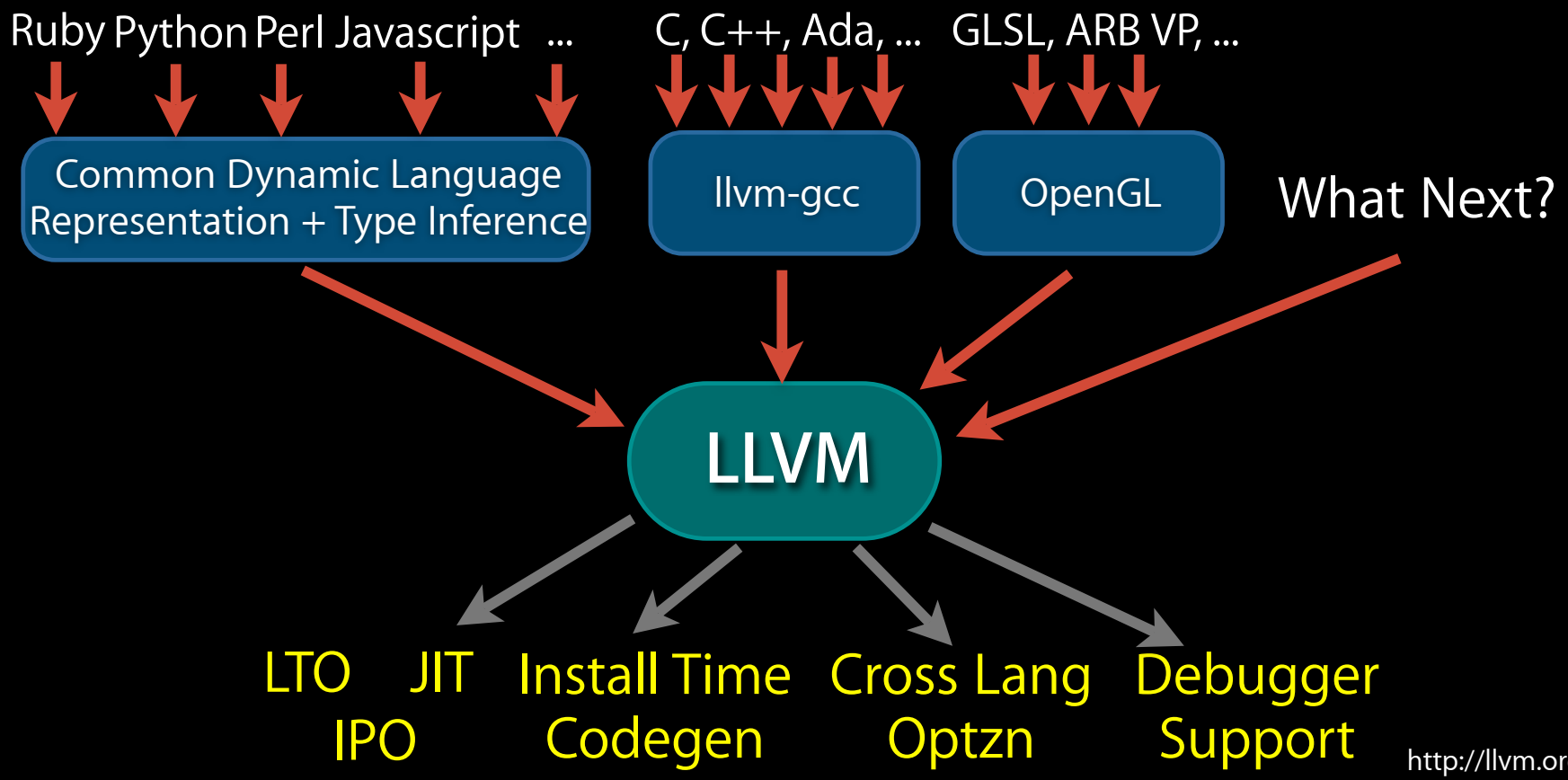
Scripting Language Performance

- Ahead-of-Time Compilation provides:
  - Reduced memory footprint (no ASTs in memory)
  - Eliminate (if no 'eval') or reduce use of interpreter at runtime (save code size)
  - Much better performance if type inference is successful
- JIT compilation provides:
  - Full support for optimizing eval'd code (e.g. json objects in javascript)
  - Runtime "type profiling" for speculative optimizations

- LLVM provides:
  - Both of the above, with one language -> llvm translator
  - Install-time codegen
  - Continuously improving set of optimizations and targets
  - Ability to inline & optimize code from different languages
    - inline your runtime library into the client code?

Call for help!

- OSS community needs to unite work on various scripting languages
  - Common module to represent/type infer an arbitrary dynamic language
- Who will provide this? pypy? parrot? llvm itself someday ("hlvm")?



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LLVM Summary

- LLVM is a set of modular compiler components:
  - LLVM can be used for many things other than simple static compilers!
  - LLVM can be used to make a great static compiler! (llvm-gcc)
- LLVM components are language- and target-independent:
  - Does not force use of JIT, GC, or a particular object model
  - Code from different languages can be linked together and optimized
- LLVM provides aggressive functionality and is industrial strength:
  - Interprocedural optimization, link-time, install-time optimization today!
  - LLVM has compiled and optimized millions of lines of code
- LLVM 2.0 due out in May:
  - Huge number of new features, codegen improvements
  - Full ARM support, contributed by INdT, enhanced by Apple

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