The LLVM Compiler Framework and Infrastructure

Chris Lattner
lattner@cs.uiuc.edu

Vikram Adve
vadve@cs.uiuc.edu

http://llvm.cs.uiuc.edu/

LCPC Tutorial: September 22, 2004

Acknowledgements

UIUC Contributors:

- Tanya Brethour
- Misha Brukman
- Cameron Buschardt
- John Criswell
- Alkis Evlogimenos
- Brian Gaeke
- Ruchira Sasanka
- Anand Shukla
- Bill Wendling

External Contributors:

- Henrik Bach
- Nate Begeman
- Jeff Cohen
- Paolo Invernizzi
- Brad Jones
- Vladimir Merzliakov
- Vladimir Prus
- Reid Spencer

Funding:

This work is sponsored by the NSF Next Generation Software program through grants EIA-0093426 (an NSF CAREER award) and EIA-0103756. It is also supported in part by the NSF Operating Systems and Compilers program (grant #CCR-9988482), the NSF Embedded Systems program (grant #CCR-0209202), the MARCO/DARPA Gigascale Systems Research Center (GSRC), IBM through the DARPA-funded PERCS project, and the Motorola University Partnerships in Research program.

LLVM Compiler System

- **The LLVM Compiler Infrastructure**
  - Provides reusable components for building compilers
  - Reduce the time/cost to build a new compiler
  - Build static compilers, JITs, trace-based optimizers, ...
- **The LLVM Compiler Framework**
  - End-to-end compilers using the LLVM infrastructure
  - C and C++ are robust and aggressive:
    - Java, Scheme and others are in development
  - Emit C code or native code for X86, Sparc, PowerPC

Chris Lattner – **lattner@cs.uiuc.edu**

Three primary LLVM components

- **The LLVM *Virtual Instruction Set***
  - The common language- and target-independent IR
  - Internal (IR) and external (persistent) representation
- **A collection of well-integrated libraries**
  - Analyses, optimizations, code generators, JIT compiler, garbage collection support, profiling, …
- **A collection of tools built from the libraries**
  - Assemblers, automatic debugger, linker, code generator, compiler driver, modular optimizer, …

Chris Lattner – **lattner@cs.uiuc.edu**

Tutorial Overview

- Introduction to the running example
- LLVM C/C++ Compiler Overview
  - High-level view of an example LLVM compiler
- The LLVM Virtual Instruction Set
  - IR overview and type-system
- LLVM C++ IR and important API's
  - Basics, PassManager, dataflow, ArgPromotion
- Important LLVM Tools
  - opt, code generator, JIT, test suite, bugpoint
- Example applications of LLVM

Running example: arg promotion

Consider use of by-reference parameters:

```
int callee(const int &X) {
  return X+1;
}
int caller() {
  return callee(4);
}
```

compiles to

```
int callee(const int *X) {
  return *X+1;    // memory load
}
int caller() {
  int tmp;        // stack object
  tmp = 4;        // memory store
  return callee(&tmp);
}
```

We want:

```
int callee(int X) {
  return X+1;
}
int caller() {
  return callee(4);
}
```

✓Eliminated load in callee

✓Eliminated store in caller

✓Eliminated stack slot for 'tmp'

Chris Lattner – **lattner@cs.uiuc.edu**

Why is this hard?

- **Requires interprocedural analysis:**
  - Must change the prototype of the callee
  - Must update all call sites → we must **know** all callers
  - What about callers outside the translation unit?
- **Requires alias analysis:**
  - Reference could alias other pointers in callee
  - Must know that loaded value doesn't change from function entry to the load
  - Must know the pointer is not being stored through
- **Reference might not be to a stack object!**

Chris Lattner – **lattner@cs.uiuc.edu**

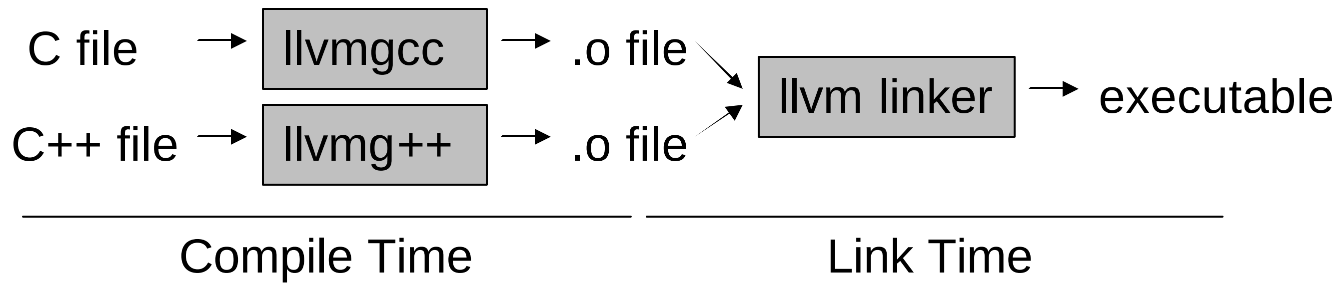
Tutorial Overview

- **Introduction to the running example**
- **LLVM C/C++ Compiler Overview**
  - High-level view of an example LLVM compiler
- **The LLVM Virtual Instruction Set**
  - IR overview and type-system
- **LLVM C++ IR and important API's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**
  - opt, code generator, JIT, test suite, bugpoint
- **Example applications of LLVM**

Chris Lattner – **lattner@cs.uiuc.edu**

The LLVM C/C++ Compiler

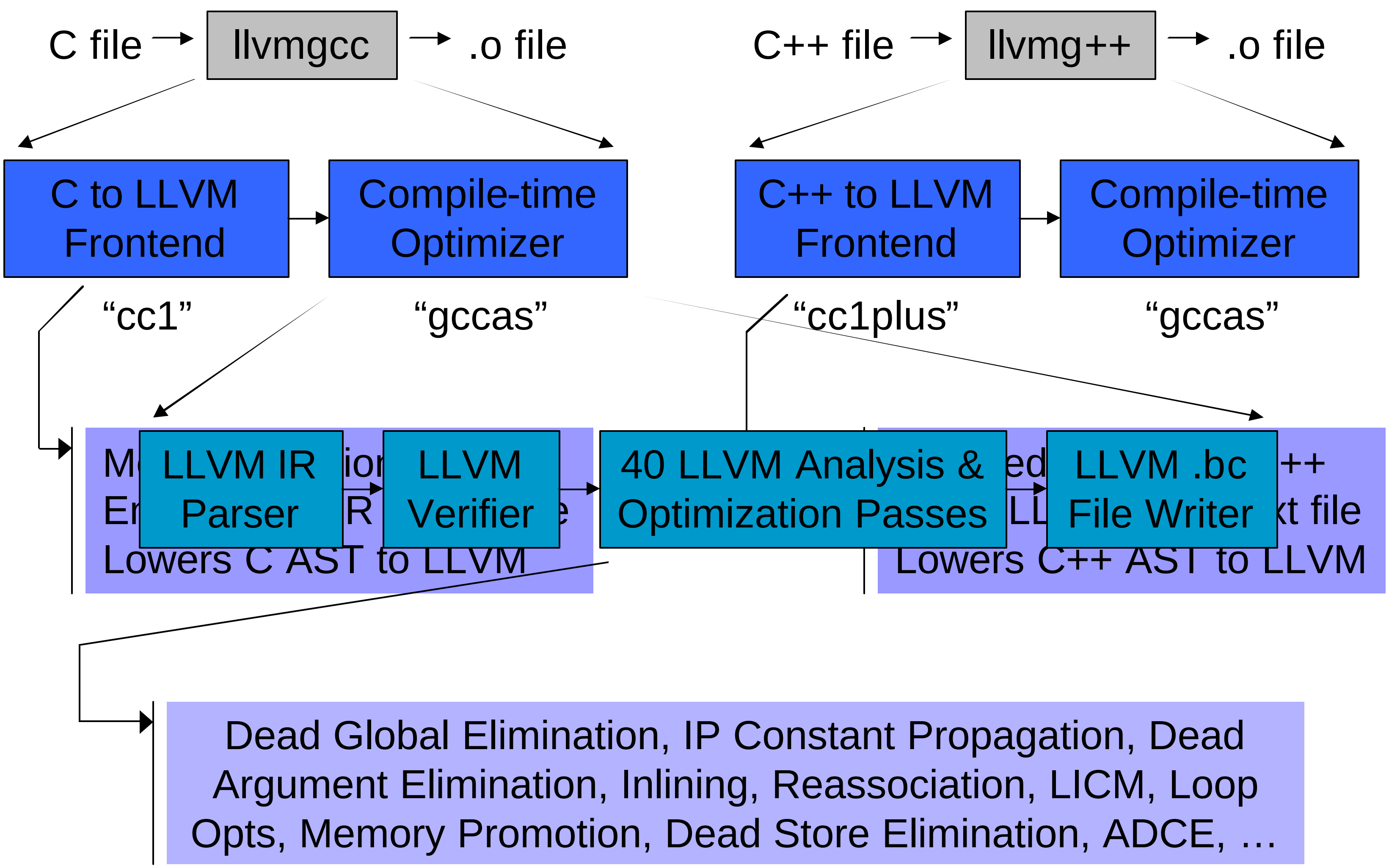
- **From the high level, it is a standard compiler:**
  - Compatible with standard makefiles
  - Uses GCC 3.4 C and C++ parser



- **Distinguishing features:**
  - Uses LLVM optimizers, not GCC optimizers
  - .o files contain LLVM IR/bytecode, not machine code
  - Executable can be bytecode (JIT'd) or machine code

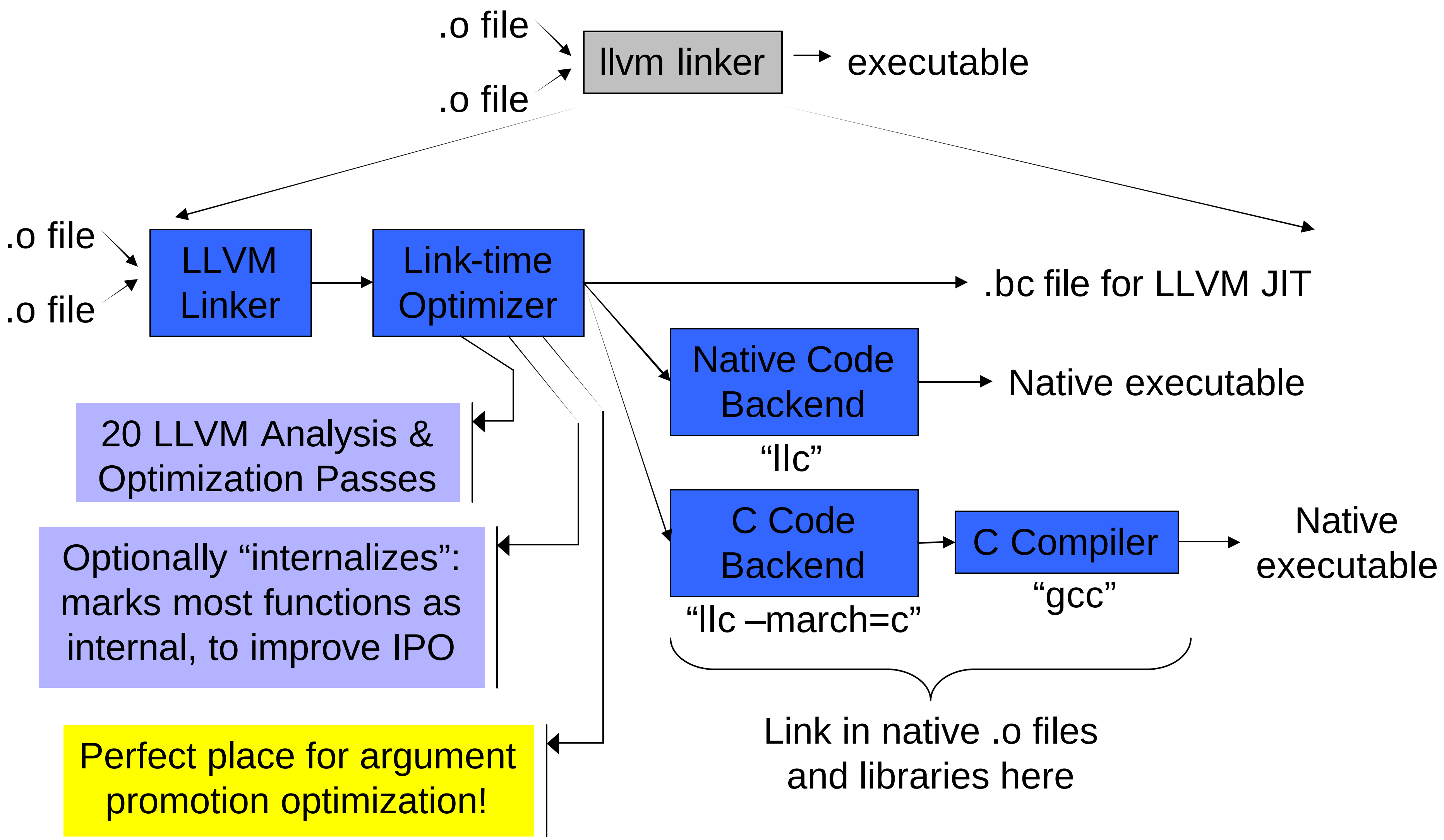
Chris Lattner – **lattner@cs.uiuc.edu**

Looking into events at compile-time



Chris Lattner – **lattner@cs.uiuc.edu**

Looking into events at link-time



Chris Lattner – **lattner@cs.uiuc.edu**

Goals of the compiler design

- **Analyze and optimize as early as possible:**
  - Compile-time opts reduce modify-rebuild-execute cycle
  - Compile-time optimizations reduce work at link-time (by shrinking the program)
- **All IPA/IPO make an open-world assumption**
  - Thus, they all work on libraries and at compile-time
  - "Internalize" pass enables "whole program" optzn
- **One IR (without lowering) for analysis & optzn**
  - Compile-time optzns can be run at link-time too!
  - The same IR is used as input to the JIT

IR design is the key to these goals!

Tutorial Overview

- **Introduction to the running example**
- **LLVM C/C++ Compiler Overview**
  - High-level view of an example LLVM compiler
- **The LLVM Virtual Instruction Set**
  - IR overview and type-system
- **LLVM C++ IR and important API's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**
  - opt, code generator, JIT, test suite, bugpoint
- **Example applications of LLVM**

Chris Lattner – **lattner@cs.uiuc.edu**

Goals of LLVM IR

- **Easy to produce, understand, and define!**
- **Language- and Target-Independent**
  - AST-level IR (e.g. ANDF, UNCOL) is not very feasible
    - Every analysis/xform must know about 'all' languages
- **One IR for analysis and optimization**
  - IR must be able to support aggressive IPO, loop opts, scalar opts, … high- ***and*** low-level optimization!
- **Optimize as much as early as possible**
  - Can't postpone everything until link or runtime
  - No lowering in the IR!

Chris Lattner – **lattner@cs.uiuc.edu**

LLVM Instruction Set Overview #1

- **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
- **IR has text, binary, and in-memory forms**

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

```
loop:
  %i.1 = phi int [ 0, %bb0 ], [ %i.2, %loop ]
  %AiAddr = getelementptr float* %A, int %i.1
  call void %Sum(float %AiAddr, %pair* %P)
  %i.2 = add int %i.1, 1
  %tmp.4 = setlt int %i.1, %N
  br bool %tmp.4, label %loop, label %outloop
```

LLVM Instruction Set Overview #2

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

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

```
loop:
  %i.1 = phi int [ 0, %bb0 ], [ %i.2, %loop ]
  %AiAddr = getelementptr float* %A, int %i.1
  call void %Sum(float %AiAddr, %pair* %P)
  %i.2 = add int %i.1, 1
  %tmp.4 = setlt int %i.1, %N
  br bool %tmp.4, label %loop, label %outloop
```

LLVM Type System Details

- **The entire type system consists of:**
  - Primitives: void, bool, float, ushort, opaque, …
  - Derived: pointer, array, structure, function
  - No high-level types: type-system is language neutral!

- **Type system allows arbitrary casts:**
  - Allows expressing weakly-typed languages, like C
  - *Front-ends can implement safe languages*
  - *Also easy to define a type-safe subset of LLVM*

See also: `docs/LangRef.html`

Lowering source-level types to LLVM

- **Source language types are lowered:**
  - Rich type systems expanded to simple type system
  - Implicit & abstract types are made explicit & concrete
- **Examples of lowering:**
  - References turn into pointers: `T&` → `T*`
  - Complex numbers: `complex float` → `{ float, float }`
  - Bitfields: `struct X { int Y:4; int Z:2; }` → `{ int }`
  - Inheritance: `class T : S { int X; }` → `{ S, int }`
  - Methods: `class T { void foo(); }` → `void foo(T*)`
- **Same idea as lowering to machine code**

Chris Lattner – **lattner@cs.uiuc.edu**

LLVM Program Structure

- **Module contains Functions/GlobalVariables**
  - Module is unit of compilation/analysis/optimization
- **Function contains BasicBlocks/Arguments**
  - Functions roughly correspond to functions in C
- **BasicBlock contains list of instructions**
  - Each block ends in a control flow instruction
- **Instruction is opcode + vector of operands**
  - All operands have types
  - Instruction result is typed

Chris Lattner – **lattner@cs.uiuc.edu**

Our example, compiled to LLVM

```
int callee(const int *X) {
  return *X+1;   // load
}
int caller() {
  int T;         // on stack
  T = 4;         // store
  return callee(&T);
}
```

```
internal int %callee(int* %X) {
  %tmp.1 = load int* %X
  %tmp.2 = add int %tmp.1, 1
  ret int %tmp.2
}
int %caller() {
  %T = alloca int
  store int 4, int* %T
  %tmp.3 = call int %callee(int* %T)
  ret int %tmp.3
}
```

Linker "internalizes" most functions in most cases

Chris Lattner – **lattner@cs.uiuc.edu**

Our example, desired transformation

```
internal int %callee(int* %X) {
  %tmp.1 = load int* %X
  %tmp.2 = add int %tmp.1, 1
  ret int %tmp.2
}
int %caller() {
  %T = alloca int
  store int 4, int* %T
  %tmp.3 = call int %callee(int* %T)
  ret int %tmp.3
}
```

```
internal int %callee(int %X.val) {
  %tmp.2 = add int %X.val, 1
  ret int %tmp.2
}
int %caller() {
  %T = alloca int
  store int 4, int* %T
  %tmp.1 = load int* %T
  %tmp.3 = call int %callee(%tmp.1)
  ret int %tmp.3
}
```

```
int %caller() {
  %tmp.3 = call int %callee(int 4)
  ret int %tmp.3
}
```

Other transformation (-mem2reg) cleans up the rest

Chris Lattner – **lattner@cs.uiuc.edu**

Tutorial Overview

- **Introduction to the running example**
- **LLVM C/C++ Compiler Overview**
  - High-level view of an example LLVM compiler
- **The LLVM Virtual Instruction Set**
  - IR overview and type-system
- **LLVM C++ IR and important API's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**
  - opt, code generator, JIT, test suite, bugpoint
- **Example applications of LLVM**

Chris Lattner – **lattner@cs.uiuc.edu**

LLVM Coding Basics

- **Written in modern C++, uses the STL:**
  - Particularly the vector, set, and map classes
- **LLVM IR is almost all doubly-linked lists:**
  - Module contains lists of Functions & GlobalVariables
  - Function contains lists of BasicBlocks & Arguments
  - BasicBlock contains list of Instructions
- **Linked lists are traversed with iterators:**

```
Function *M = …
for (Function::iterator I = M->begin(); I != M->end(); ++I) {
  BasicBlock &BB = *I;
  ...
```

See also: docs/ProgrammersManual.html

Chris Lattner – **lattner@cs.uiuc.edu**

LLVM Pass Manager

- **Compiler is organized as a series of 'passes':**
  - Each pass is one analysis or transformation
- **Four types of Pass:**
  - ModulePass: general interprocedural pass
  - CallGraphSCCPass: bottom-up on the call graph
  - FunctionPass: process a function at a time
  - BasicBlockPass: process a basic block at a time
- **Constraints imposed (e.g. FunctionPass):**
  - FunctionPass can only look at "current function"
  - Cannot maintain state across functions

See also: `docs/WritingAnLLVMPass.html`

Chris Lattner – **lattner@cs.uiuc.edu**

Services provided by PassManager

- **Optimization of pass execution:**
  - Process a function at a time instead of a pass at a time
  - Example: If F, G, H are three functions in input pgm: “FFFFGGGGHHHH” not “FGHFGHFGHFGH”
  - Process functions in parallel on an SMP (future work)
- **Declarative dependency management:**
  - Automatically fulfill and manage analysis pass lifetimes
  - Share analyses between passes when safe:
    - e.g. “DominatorSet live unless pass modifies CFG”
- **Avoid boilerplate for traversal of program**

See also: `docs/WritingAnLLVMPass.html`

Chris Lattner – **lattner@cs.uiuc.edu**

Pass Manager + Arg Promotion #1/2

- **Arg Promotion is a CallGraphSCCPass:**
  - Naturally operates bottom-up on the CallGraph
    - Bubble pointers from callees out to callers

```
24: #include "llvm/CallGraphSCCPass.h"
47: struct SimpleArgPromotion : public CallGraphSCCPass {
```

- **Arg Promotion requires AliasAnalysis info**
  - To prove safety of transformation
    - Works with any alias analysis algorithm though

```
48: virtual void getAnalysisUsage(AnalysisUsage &AU) const {
      AU.addRequired<AliasAnalysis>();        // Get aliases
      AU.addRequired<TargetData>();           // Get data layout
      CallGraphSCCPass::getAnalysisUsage(AU); // Get CallGraph
    }
```


Chris Lattner – lattner@cs.uiuc.edu

Pass Manager + Arg Promotion #2/2

- **Finally, implement `runOnSCC` (line 65):**

```
bool SimpleArgPromotion::
runOnSCC(const std::vector<CallGraphNode*> &SCC) {
  bool Changed = false, LocalChange;
  do {    // Iterate until we stop promoting from this SCC.
    LocalChange = false;
    // Attempt to promote arguments from all functions in this SCC.
    for (unsigned i = 0, e = SCC.size(); i != e; ++i)
      LocalChange |= PromoteArguments(SCC[i]);
    Changed |= LocalChange;   // Remember that we changed something.
  } while (LocalChange);
  return Changed;             // Passes return true if something changed.
}
```

```
static int foo(int ***P) {
  return ***P;
}
```

```
static int foo(int P_val_val_val) {
  return P_val_val_val;
}
```

LLVM Dataflow Analysis

- **LLVM IR is in SSA form:**
  - use-def and def-use chains are always available
  - All objects have user/use info, even functions
- **Control Flow Graph is always available:**
  - Exposed as BasicBlock predecessor/successor lists
  - Many generic graph algorithms usable with the CFG
- **Higher-level info implemented as passes:**
  - Dominators, CallGraph, induction vars, aliasing, GVN, …

See also: `docs/ProgrammersManual.html`

Chris Lattner – **lattner@cs.uiuc.edu**

Arg Promotion: safety check #1/4

#1: Function must be "internal" (aka "static")

```
88: if (!F || !F->hasInternalLinkage()) return false;
```

#2: Make sure address of F is not taken

- In LLVM, check that there are only direct calls using F

```
99: for (Value::use_iterator UI = F->use_begin();
         UI != F->use_end(); ++UI) {
      CallSite CS = CallSite::get(*UI);
      if (!CS.getInstruction()) // "Taking the address" of F.
        return false;
```

#3: Check to see if any args are promotable:

```
114: for (unsigned i = 0; i != PointerArgs.size(); ++i)
       if (!isSafeToPromoteArgument(PointerArgs[i]))
         PointerArgs.erase(PointerArgs.begin()+i);
       if (PointerArgs.empty()) return false; // no args promotable
```

Arg Promotion: safety check #2/4

#4: Argument pointer can only be loaded from:

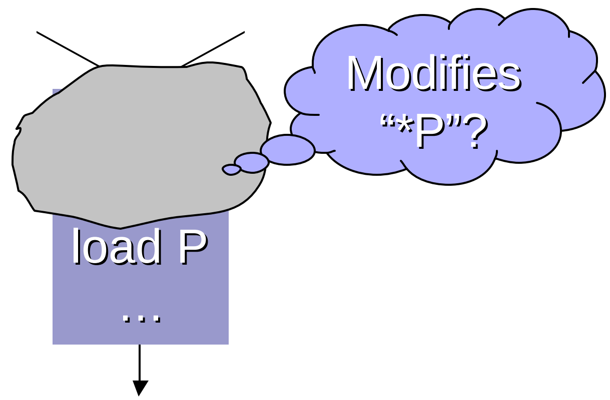
- No stores through argument pointer allowed!

```
// Loop over all uses of the argument (use-def chains).
for (Value::use_iterator UI = Arg->use_begin();
     UI != Arg->use_end(); ++UI) {
  // If the user is a load:
  if (LoadInst *LI = dyn_cast<LoadInst>(*UI)) {
    // Don't modify volatile loads.
    if (LI->isVolatile()) return false;
    Loads.push_back(LI);
  } else {
    return false;  // Not a load.
  }
}
```

Arg Promotion: safety check #3/4

#5: Value of "*P" must not change in the BB

- We move load out to the caller, value cannot change!



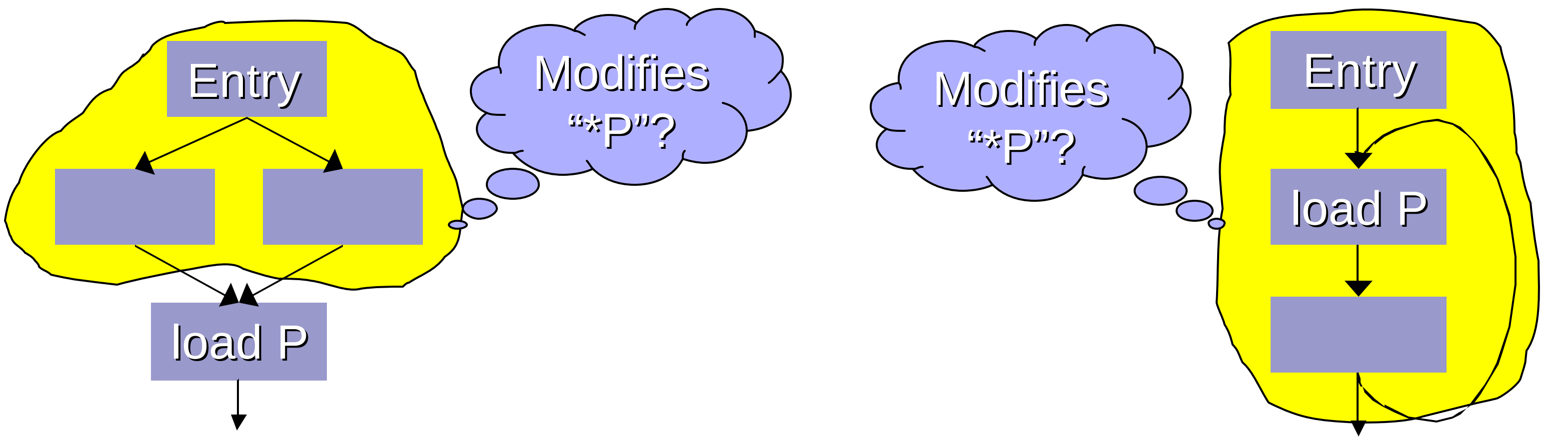

```
     // Get AliasAnalysis implementation from the pass manager.
156: AliasAnalysis &AA = getAnalysis<AliasAnalysis>();

     // Ensure *P is not modified from start of block to load
169: if (AA.canInstructionRangeModify(BB->front(), *Load,
                                      Arg, LoadSize))
       return false;  // Pointer is invalidated!
```

See also: docs/AliasAnalysis.html

Chris Lattner – **lattner@cs.uiuc.edu**

Arg Promotion: safety check #4/4

#6: "*P" cannot change from Fn entry to BB




```
175: for (pred_iterator PI = pred_begin(BB), E = pred_end(BB);
          PI != E; ++PI)     // Loop over predecessors of BB.
       // Check each block from BB to entry (DF search on inverse graph).
       for (idf_iterator<BasicBlock*> I = idf_begin(*PI);
            I != idf_end(*PI); ++I)
        // Might *P be modified in this basic block?
        if (AA.canBasicBlockModify(**I, Arg, LoadSize))
          return false;
```


Chris Lattner – **lattner@cs.uiuc.edu**

Arg Promotion: xform outline #1/4

#1: Make prototype with new arg types: #197

- Basically just replaces 'int*' with 'int' in prototype

#2: Create function with new prototype:

```
214: Function *NF = new Function(NFTy, F->getLinkage(),
                                      F->getName());
     F->getParent()->getFunctionList().insert(F, NF);
```

#3: Change all callers of F to call NF:

```
     //  If there are uses of F, then calls to it remain.
221: while (!F->use_empty()) {
       // Get a caller of F.
       CallSite CS = CallSite::get(F->use_back());
```


Chris Lattner – **lattner@cs.uiuc.edu**

Arg Promotion: xform outline #2/4

#4: For each caller, add loads, determine args

- Loop over the args, inserting the loads in the caller

```
220: std::vector<Value*> Args;

226: CallSite::arg_iterator AI = CS.arg_begin();
     for (Function::aiterator I = F->abegin(); I != F->aend();
          ++I, ++AI)
       if (!ArgsToPromote.count(I))    // Unmodified argument.
         Args.push_back(*AI);
       else {                          // Insert the load before the call.
         LoadInst *LI = new LoadInst(*AI, (*AI)->getName()+".val",
                                     Call); // Insertion point
         Args.push_back(LI);
       }
```


Chris Lattner – **lattner@cs.uiuc.edu**

Arg Promotion: xform outline #3/4

#5: Replace the call site of F with call of NF

```
     // Create the call to NF with the adjusted arguments.
242: Instruction *New = new CallInst(NF, Args, "", Call);

     // If the return value of the old call was used, use the retval of the new call.
     if (!Call->use_empty())
       Call->replaceAllUsesWith(New);

     // Finally, remove the old call from the program, reducing the use-count of F.
     Call->getParent()->getInstList().erase(Call);
```

#6: Move code from old function to new Fn

```
259: NF->getBasicBlockList().splice(NF->begin(),
                                    F->getBasicBlockList());
```

Arg Promotion: xform outline #4/4

#7: Change users of F's arguments to use NF's

```
264: for (Function::aiterator I = F->abegin(), I2 = NF->abegin();
          I != F->aend(); ++I, ++I2)
       if (!ArgsToPromote.count(I)) { // Not promoting this arg?
         I->replaceAllUsesWith(I2);   // Use new arg, not old arg.
       } else {
         while (!I->use_empty()) {    // Only users can be loads.
           LoadInst *LI = cast<LoadInst>(I->use_back());
           LI->replaceAllUsesWith(I2);
           LI->getParent()->getInstList().erase(LI);
         }
       }
```

#8: Delete old function:

```
286: F->getParent()->getFunctionList().erase(F);
```

Tutorial Overview

- **Introduction to the running example**
- **LLVM C/C++ Compiler Overview**
  - High-level view of an example LLVM compiler
- **The LLVM Virtual Instruction Set**
  - IR overview and type-system
- **LLVM C++ IR and important API's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**
  - opt, code generator, JIT, test suite, bugpoint
- **Example applications of LLVM**

LLVM tools: two flavors

- **"Primitive" tools: do a single job**
  - llvm-as: Convert from .ll (text) to .bc (binary)
  - llvm-dis: Convert from .bc (binary) to .ll (text)
  - llvm-link: Link multiple .bc files together
  - llvm-prof: Print profile output to human readers
  - llvmc: Configurable compiler driver
- **Aggregate tools: pull in multiple features**
  - gccas/gccld: Compile/link-time optimizers for C/C++ FE
  - bugpoint: automatic compiler debugger
  - llvm-gcc/llvm-g++: C/C++ compilers

See also: `docs/CommandGuide/`

opt tool: 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:**

```
61: RegisterOpt<SimpleArgPromotion> X("simpleargpromotion",
              "Promote 'by reference' arguments to 'by value'");
```

- **From this, they are exposed through opt:**

```
> opt -load libsimpleargpromote.so –help
  ...
 -sccp               - Sparse Conditional Constant Propagation
 -simpleargpromotion - Promote 'by reference' arguments to 'by
 -simplifycfg        - Simplify the CFG
  ...
```

Running Arg Promotion with opt

- **Basic execution with ‘opt’:**
  - **`opt -simpleargpromotion in.bc -o out.bc`**
  - Load .bc file, run pass, write out results
  - Use “-load filename.so” if compiled into a library
  - PassManager resolves all dependencies
- **Optionally choose an alias analysis to use:**
  - **`opt –basicaa –simpleargpromotion` (default)**
  - Alternatively, **`–steens-aa`, `–anders-aa`, `–ds-aa`, …**
- **Other useful options available:**
  - **`-stats`: Print statistics collected from the passes**
  - **`-time-passes`: Time each pass being run, print output**

Chris Lattner – **lattner@cs.uiuc.edu**

Example -stats output (gccas 176.gcc)

```
===-------------------------------------------------------------------------===
                          ... Statistics Collected ...
===-------------------------------------------------------------------------===
  23426 adce            - Number of instructions removed
   1663 adce            - Number of basic blocks removed
5052592 bytecodewriter  - Number of bytecode bytes written
  57489 cfgsimplify     - Number of blocks simplified
   4186 constmerge      - Number of global constants merged
    211 dse             - Number of stores deleted
  15943 gcse            - Number of loads removed
  54245 gcse            - Number of instructions removed
    253 inline          - Number of functions deleted because all callers found
   3952 inline          - Number of functions inlined
   9425 instcombine     - Number of constant folds
 160469 instcombine     - Number of insts combined
    208 licm            - Number of load insts hoisted or sunk
   4982 licm            - Number of instructions hoisted out of loop
    350 loop-unroll     - Number of loops completely unrolled
  30156 mem2reg         - Number of alloca's promoted
   2934 reassociate     - Number of insts with operands swapped
    650 reassociate     - Number of insts reassociated
     67 scalarrepl      - Number of allocas broken up
    279 tailcallelim    - Number of tail calls removed
  25395 tailduplicate   - Number of unconditional branches eliminated
    ..........................
```


Chris Lattner – **lattner@cs.uiuc.edu**

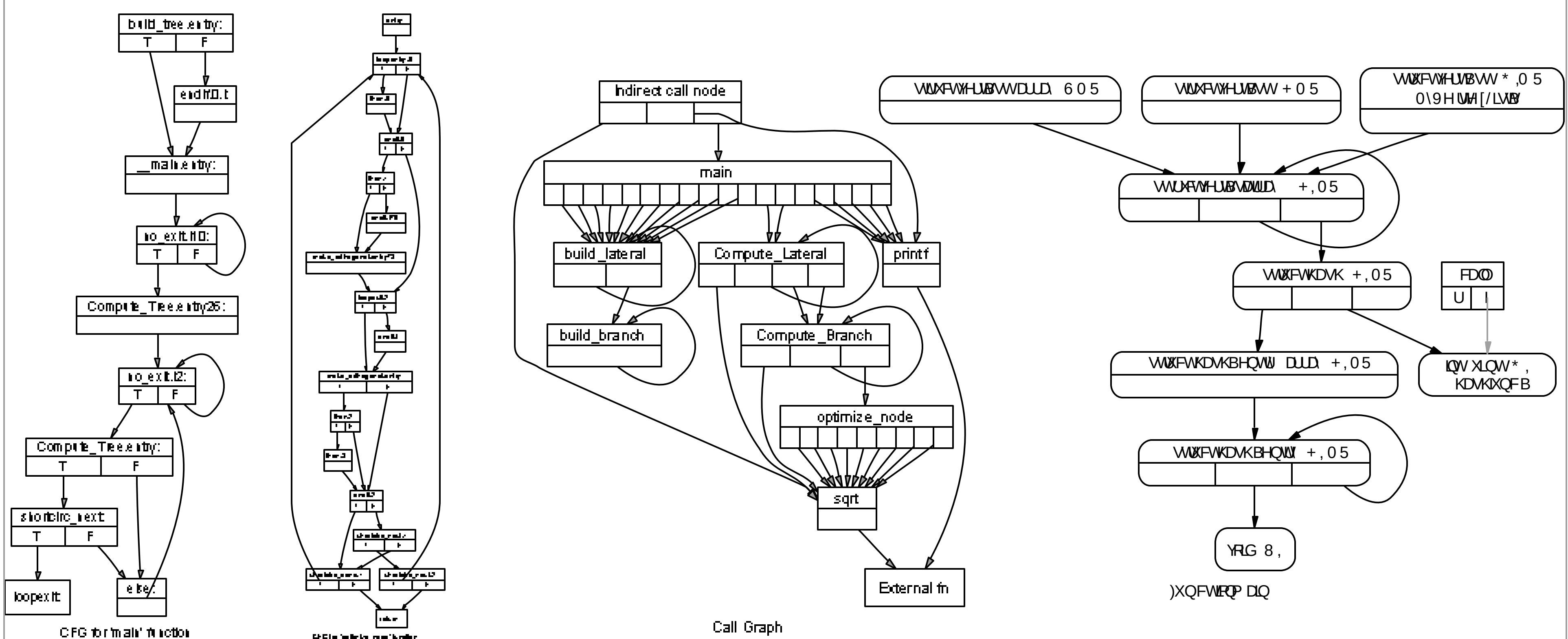
Example -time-passes (gccas 176.gcc)

```
===-------------------------------------------------------------------------===
                  ... Pass execution timing report ...
===-------------------------------------------------------------------------===
  ---User Time---   --System Time--   --User+System--   ---Wall Time---  --- Name ---
 16.2400 ( 23.0%)   0.0000 (  0.0%)  16.2400 ( 22.9%)  16.2192 ( 22.9%)  Global Common Subexpression Elimination
 11.1200 ( 15.8%)   0.0499 ( 13.8%)  11.1700 ( 15.8%)  11.1028 ( 15.7%)  Reassociate expressions
  6.5499 (  9.3%)   0.0300 (  8.3%)   6.5799 (  9.3%)   6.5824 (  9.3%)  Bytecode Writer
  3.2499 (  4.6%)   0.0100 (  2.7%)   3.2599 (  4.6%)   3.2140 (  4.5%)  Scalar Replacement of Aggregates
  3.0300 (  4.3%)   0.0499 ( 13.8%)   3.0800 (  4.3%)   3.0382 (  4.2%)  Combine redundant instructions
  2.6599 (  3.7%)   0.0100 (  2.7%)   2.6699 (  3.7%)   2.7339 (  3.8%)  Dead Store Elimination
  2.1600 (  3.0%)   0.0300 (  8.3%)   2.1900 (  3.0%)   2.1924 (  3.1%)  Function Integration/Inlining
  2.1600 (  3.0%)   0.0100 (  2.7%)   2.1700 (  3.0%)   2.1125 (  2.9%)  Sparse Conditional Constant Propagation
  1.6600 (  2.3%)   0.0000 (  0.0%)   1.6600 (  2.3%)   1.6389 (  2.3%)  Aggressive Dead Code Elimination
  1.4999 (  2.1%)   0.0100 (  2.7%)   1.5099 (  2.1%)   1.4462 (  2.0%)  Tail Duplication
  1.5000 (  2.1%)   0.0000 (  0.0%)   1.5000 (  2.1%)   1.4410 (  2.0%)  Post-Dominator Set Construction
  1.3200 (  1.8%)   0.0000 (  0.0%)   1.3200 (  1.8%)   1.3722 (  1.9%)  Canonicalize natural loops
  1.2700 (  1.8%)   0.0000 (  0.0%)   1.2700 (  1.7%)   1.2717 (  1.7%)  Merge Duplicate Global Constants
  1.0300 (  1.4%)   0.0000 (  0.0%)   1.0300 (  1.4%)   1.1418 (  1.6%)  Combine redundant instructions
  0.9499 (  1.3%)   0.0400 ( 11.1%)   0.9899 (  1.4%)   0.9979 (  1.4%)  Raise Pointer References
  0.9399 (  1.3%)   0.0100 (  2.7%)   0.9499 (  1.3%)   0.9688 (  1.3%)  Simplify the CFG
  0.9199 (  1.3%)   0.0300 (  8.3%)   0.9499 (  1.3%)   0.8993 (  1.2%)  Promote Memory to Register
  0.9600 (  1.3%)   0.0000 (  0.0%)   0.9600 (  1.3%)   0.8742 (  1.2%)  Loop Invariant Code Motion
  0.5600 (  0.7%)   0.0000 (  0.0%)   0.5600 (  0.7%)   0.6022 (  0.8%)  Module Verifier
  …
```


Chris Lattner – **lattner@cs.uiuc.edu**

Analyze tool: Visualize analysis results

- **Print most LLVM data structures**
  - Dominators, loops, alias sets, CFG, call graph, …
  - Converts most LLVM data structures to ‘dot’ graphs



LLC Tool: Static code generator

- **Compiles LLVM → native assembly language**
  - Currently for X86, Sparc, PowerPC (others in alpha)
  - **`llc file.bc -o file.s -march=x86`**
  - **`as file.s –o file.o`**
- **Compiles LLVM → portable C code**
  - **`llc file.bc -o file.c -march=c`**
  - **`gcc –c file.c –o file.o`**
- **Targets are modular & dynamically loadable:**
  - **`llc –load libarm.so file.bc -march=arm`**

The LLVM Code Generator

- **Target independent:**
  - Driven by an algorithm independent target description
    - Data layout, Register, Instruction, Scheduling, …
- **Basic code generator layout:**

Target Specific (by hand for now)

Target Independent

Target Specific (generated)

- **All passes are replaceable**
  - e.g. Trivial to change and add … ators
- **Targets c… pa…**
  - … special support for FP stack

4 algorithms available today
llc -regalloc=foo

Scheduling, Peephole, ?

Exposes all target-specific details about a function (calling conventions, etc)

See also: docs/CodeGenerator.html

Chris Lattner – **lattner@cs.uiuc.edu**

Porting LLVM to a new target

- **LLVM targets are very easy to write:**
  - Anecdotal evidence suggests 1 week for a basic port
    - … for someone familiar with the target machine and compilers in general, but not with LLVM
- **LLVM targets are written with “tablegen” tool**
  - Simple declarative syntax
  - Designed to factor out redundancy in target desc
- **Some C++ code is still required**
  - Primarily in the instruction selector
  - Continuing work to improve this

See also: docs/TableGenFundamentals.html and WritingAnLLVMBackend.html

LLI Tool: LLVM Execution Engine

- **LLI allows direct execution of .bc files**
  - **E.g.: `lli grep.bc -i foo *.c`**
- **LLI uses a Just-In-Time compiler if available:**
  - Uses same code generator as LLC
    - Optionally uses faster components than LLC
  - Emits machine code to memory instead of ".s" file
  - JIT is a library that can be embedded in other tools
- **Otherwise, it uses the LLVM interpreter:**
  - Interpreter is extremely simple and very slow
  - Interpreter is portable though!

C and C++ Program Test Suite

- **Large collection of programs and benchmarks:**
  - Standard suites (e.g. SPEC 95/2000, Olden, Ptrdist, McCat, Stanford, Freebench, Shootout…)
  - Individual programs: sgefa, siod, sim, pi, povray, …
  - Proprietary suites (e.g. SPEC) require suite source
- **Consistent build environment:**
  - Easy add hooks to build for profiling/instrumentation
  - Easy to get performance numbers from entire test suite
- **Entire test suite is checked every night:**
  - Hosted on Linux,Solaris,FreeBSD on X86,Sparc & PPC

See also: `docs/TestingGuide.html`

Chris Lattner – **lattner@cs.uiuc.edu**

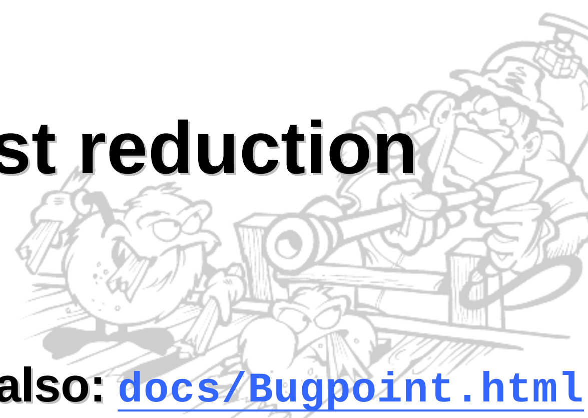
Integrated Debugging Tools

- **Extensive assertions throughout code**
  - Find problems as early as possible (close to source)
- **LLVM IR Verifier: Checks modules for validity**
  - Checks type properties, dominance properties, etc.
  - Automatically run by opt
  - Problem found?: print an error message and abort
- **LLVM IR Leak Detector**
  - Efficient and simple “garbage collector” for IR objects
  - Ensure IR objects are deallocated appropriately

Chris Lattner – **lattner@cs.uiuc.edu**

The Bugpoint automated bug finder

- **Simple idea: automate 'binary' search for bug**
  - Bug isolation: which passes interact to produce bug
  - *Test case reduction*: reduce input program
- **Optimizer/Codegen crashes:**
  - Throw portion of test case away, check for crash
    - If so, keep going
    - Otherwise, revert and try something else
  - Extremely effective in practice
- **Simple greedy algorithms for test reduction**
- **Completely black-box approach**



See also: docs/Bugpoint.html

Debugging Miscompilations

- **Optimizer miscompilation:**
  - Split testcase in two, optimize one. Still broken?
  - Keep shrinking the portion being optimized
- **Codegen miscompilation:**
  - Split testcase in two, compile one with CBE, broken?
  - Shrink portion being compiled with non CBE codegen
- **Code splitting granularities:**
  - Take out whole functions
  - Take out loop nests
  - Take out individual basic blocks

Chris Lattner – **lattner@cs.uiuc.edu**

How well does this thing work?

- **Extremely effective:**
  - Can often reduce a 100K LOC program and 60 passes to a few basic blocks and 1 pass in 5 minutes
  - Crashes are found much faster than miscompilations
    - no need to run the program to test a reduction
- **Interacts with integrated debugging tools**
  - Runtime errors are detected faster
- **Limitations:**
  - Program must be deterministic
    - … or modified to be so
  - Finds “a” bug, not “the” bug

Chris Lattner – **lattner@cs.uiuc.edu**

Tutorial Overview

- **Introduction to the running example**
- **LLVM C/C++ Compiler Overview**
  - High-level view of an example LLVM compiler
- **The LLVM Virtual Instruction Set**
  - IR overview and type-system
- **LLVM C++ IR and important API's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**
  - opt, code generator, JIT, test suite, bugpoint
- **Example applications of LLVM**

Use Case 1: Edge or Path Profiling

Goal: *Profiling Research or PGO*

- **Implementation:**
  - *FunctionPass*: LLVM-to-LLVM transformation
  - Instrumentation: Use CFG, intervals, dominators
  - Code generation: Use C or any native back end
  - Profile feedback: Use profile query interface
- **Core extensions needed:** *none*
- **Major LLVM Benefits**
  - Language-independence, CFG, very simple IR

Use Case 2: Alias Analysis

Goal: *Research on new alias analysis algorithms*

- **Implementation:**
  - *ModulePass*: Whole-program analysis pass on LLVM
  - Use type information; SSA; heap/stack/globals
  - Compare *SimpleAA*, *Steensgard's*, *Andersen's*, *DSA*
  - Evaluate many clients via *AliasAnalysis* interface
- **Core extensions needed:** *none*
- **Major LLVM Benefits**
  - Language-independence, type info, SSA, DSA, IPO
  - *AliasAnalysis* interface with many pre-existing clients

Chris Lattner – **lattner@cs.uiuc.edu**

Use Case 3: LDS Prefetching

Goal: *Prefetching linked data structures*

- **Implementation:**
  - *ModulePass*: Link-time LLVM-to-LLVM transformation
  - *Code transformations*: use type info, loop analysis, unrolling, prefetch insertion
  - *Data transformations* (e.g,. adding history pointers): use *strong* type info from DSA, IPO
- **Core extensions needed:**
  - Prefetch operation: add as intrinsic (in progress)
- **Major LLVM Benefits**
  - Language-independence, type info, DSA, IPO

Chris Lattner – **lattner@cs.uiuc.edu**

Use Case 4: Language Front end

Goal: *Use LLVM to implement a new language*

- **Implementation:**
  - Parser (say to AST), Semantic checking
  - AST-to-LLVM translator
- **Core extensions needed:** *depends*
  - High-level type system is *omitted by design*
- **Major LLVM Benefits**
  - Low-level, but powerful type system
  - Very simple IR to generate (e.g., compare GCC RTL)
  - Extensive global and IP optimization framework
  - JIT engine, native back-ends, C back-end

Chris Lattner – **lattner@cs.uiuc.edu**

Use Case 5: JIT Compiler

Goal: *Write JIT compiler for a bytecode language*

- **Implementation:**
  - Extend the LLVM JIT framework
  - *Simple JIT*: Fast translation from bytecode to LLVM (then use LLVM JIT + GC)
  - *Optimizing JIT*: Language-specific optimizations + fast translation (then use LLVM optimizations, JIT, GC)
- **Core extensions needed:** *none in general*
- **Major LLVM Benefits**
  - Compact, typed, language-independent IR
  - Existing JIT framework and GC

Use Case 6: Architecture Research

Goal: *Compiler support for new architectures*

- **Implementation:**
  - Add new machine description (or modify one)
  - Add any new LLVM-to-LLVM transformations
- **Core extensions needed:** *depends on goals*
  - Imminent features: ***modulo sched; vector ops***
- **Major LLVM Benefits**
  - Low-level, typed, machine-independent IR
  - Explicit register/memory architecture
  - Aggressive mid-level and back-end compiler framework
  - *Full-system evaluation:* applications, libraries, even OS

Chris Lattner – **lattner@cs.uiuc.edu**

Five point LLVM Review

- **Extremely simple IR to learn and use**
  - 1-to-1 correspondence between .ll, .bc, and C++ IR
  - Very positive user reactions
- **Powerful and modular optimizer**
  - Easy to extend, or just use what is already there
- **Clean and modular code generator**
  - Easy to retarget, easy to replace/tweak components
- **Many “productivity tools” (bugpoint, verifier)**
  - Get more done, quicker!
- **Active dev community, good documentation**
  - Mailing lists, IRC, doxygen, extensive docs

Chris Lattner – **lattner@cs.uiuc.edu**

Get started with LLVM!

- **Download latest release or CVS:**

  http://llvm.cs.uiuc.edu/releases/

- **Follow the "Getting Started Guide":**

  http://llvm.cs.uiuc.edu/docs/GettingStarted.html
  - Walks you through install and setup
  - Lots of other docs available in "docs" directory
  - Join us on mailing lists and IRC

- **Happy hacking!**

Chris Lattner – **lattner@cs.uiuc.edu**