The LLVM Compiler Framework and Infrastructure

15-411: Compiler Design

Slides by David Koes

Substantial portions courtesy Chris Lattner and Vikram Adve

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++ gcc frontend
  - Backends for C, X86, Sparc, PowerPC, Alpha, Arm, Thumb, IA-64…

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, …

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 APIA's**
  - Basics, PassManager, dataflow, ArgPromotion
- **Important LLVM Tools**

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’

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!**

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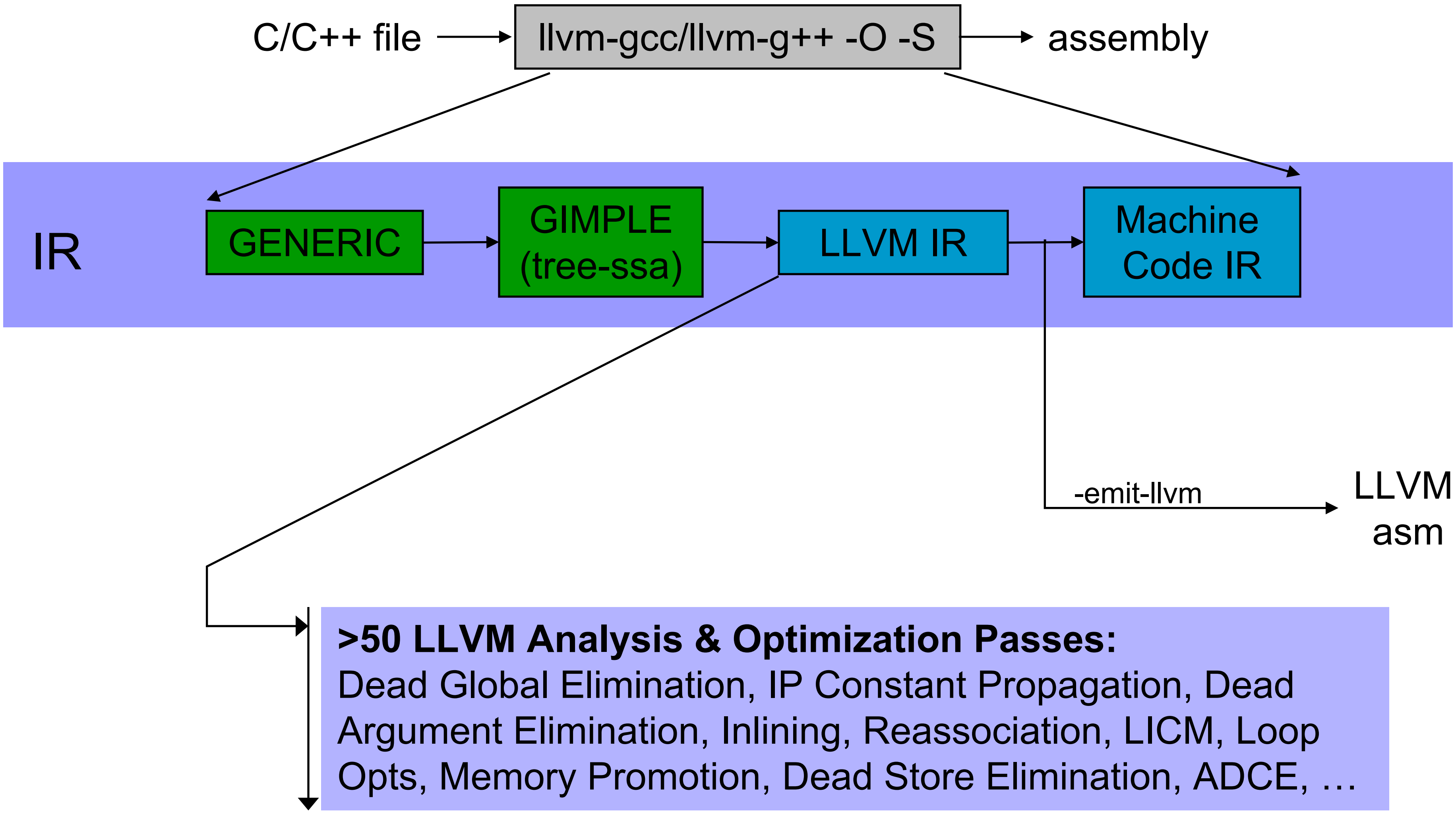
The LLVM C/C++ Compiler

- **From the high level, it is a standard compiler:**
  - Compatible with standard makefiles
  - Uses GCC 4.2 C and C++ parser
  - Generates native executables/object files/assembly

- **Distinguishing features:**
  - Uses LLVM optimizers, not GCC optimizers
  - Pass -emit-llvm to output LLVM IR
    - -S: human readable “assembly”
    - -c: efficient “bitcode” binary

Looking into events at compile-time



C/C++ file → llvm-gcc/llvm-g++ -O -S → assembly

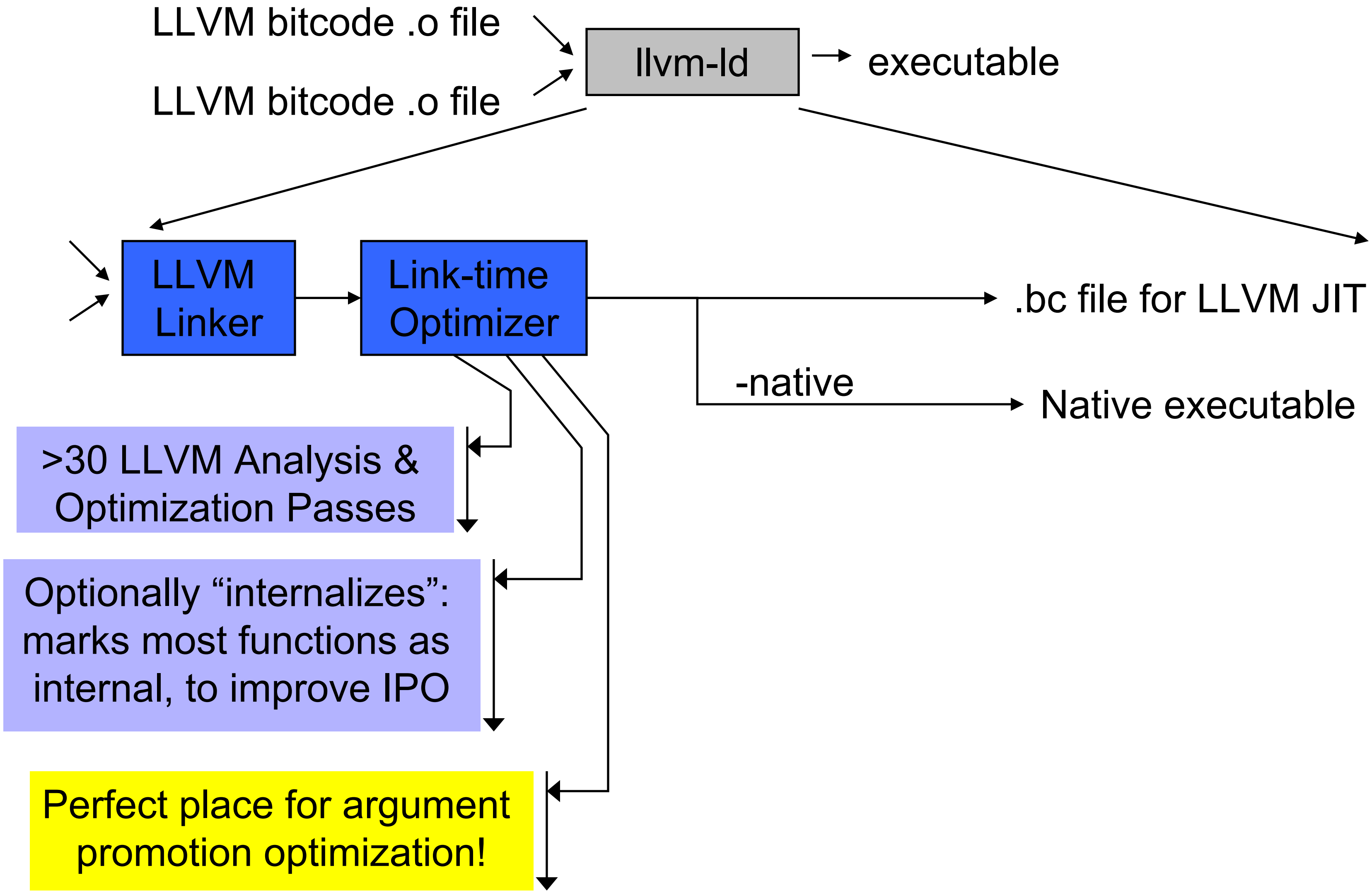
IR

GENERIC → GIMPLE (tree-ssa) → LLVM IR → Machine Code IR

-emit-llvm → LLVM asm

>50 LLVM Analysis & Optimization Passes:
Dead Global Elimination, IP Constant Propagation, Dead Argument Elimination, Inlining, Reassociation, LICM, Loop Opts, Memory Promotion, Dead Store Elimination, ADCE, …

Looking into events at link-time



LLVM bitcode .o file

LLVM bitcode .o file

llvm-ld

executable

LLVM Linker

Link-time Optimizer

.bc file for LLVM JIT

-native

Native executable

>30 LLVM Analysis & Optimization Passes

Optionally “internalizes”: marks most functions as internal, to improve IPO

Perfect place for argument promotion optimization!

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!

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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!

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);
```

```
bb:                    ; preds = %bb, %entry
   %i.1 = phi i32 [ 0, %entry ], [ %i.2, %bb ]
  %AiAddr = getelementptr float* %A, i32 %i.1
  call void @Sum( float* %AiAddr, %pair* %P )
  %i.2 = add i32 %i.1, 1
  %exitcond = icmp eq i32 %i.2, %N
  br i1 %exitcond, label %return, label %bb
```

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);
```

```
bb:                      ; preds = %bb, %entry
    %i.1 = phi i32 [ 0, %entry ], [ %i.2, %bb ]
   %AiAddr = getelementptr float* %A, i32 %i.1
   call void @Sum( float* %AiAddr, %pair* %P )
   %i.2 = add i32 %i.1, 1
   %exitcond = icmp eq i32 %i.2, %N
   br i1 %exitcond, label %return, label %bb
```

LLVM Type System Details

- **The entire type system consists of:**
  - Primitives: integer, floating point, label, void
    - no “signed” integer types
    - arbitrary bitwidth integers (i32, i64, i1)
  - Derived: pointer, array, structure, function, vector,…
  - 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; }` → `{ i32 }`
  - Inheritance: `class T : S { int X; }` → `{ S, i32 }`
  - Methods: `class T { void foo(); }` → `void foo(T*)`
- **Same idea as lowering to machine code**

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

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);
}
```

```
define internal i32 @callee(i32* %X) {
entry:
  %tmp2 = load i32* %X
  %tmp3 = add i32 %tmp2, 1
  ret i32 %tmp3
}

define internal i32 @caller() {
entry:
  %T = alloca i32
  store i32 4, i32* %T
  %tmp1 = call i32 @callee( i32* %T )
  ret i32 %tmp1
}
```

All loads/stores are explicit in the LLVM representation

Our example, desired transformation

```
define i32 @callee(i32* %X) {
  %tmp2 = load i32* %X
  %tmp3 = add i32 %tmp2, 1
  ret i32 %tmp3
}

define i32 @caller() {
  %T = alloca i32
  store i32 4, i32* %T
  %tmp1 = call i32 @callee( i32* %T )
  ret i32 %tmp1
}
```

```
define internal i32 @callee1(i32 %X.val)
{
  %tmp3 = add i32 %X.val, 1
  ret i32 %tmp3
}

define internal i32 @caller() {
  %T = alloca i32
  store i32 4, i32* %T
  %Tval = load i32* %T
  %tmp1 = call i32 @callee1( i32 %Tval )
  ret i32 %tmp1
}
```

Other transformation (-mem2reg) cleans up the rest

```
define internal i32 @caller() {
  %tmp1 = call i32 @callee1( i32 4 )
  ret i32 %tmp1
}
```

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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

LLVM Coding Basics cont.

- **BasicBlock doesnA̦t provide a reverse iterator**
  - Highly obnoxious when doing the assignment

```
for(BasicBlock::iterator I = bb->end(); I != bb->begin(); ) {
   --I;
   Instruction *insn = I;
   …
```

- **Traversing successors of a BasicBlock:**

```
for (succ_iterator SI = succ_begin(bb), E = succ_end(bb);
                                          SI != E; ++SI) {
  BasicBlock *Succ = *SI;
```

- **C++ is not Java**
  - primitive class variable not
  - you must manage memory
  - virtual vs. non-virtual functions
  - and much much more…

valgrind to the rescue!
http://valgrind.org

LLVM Pass Manager

- **Compiler is organized as a series of “passes”:**
  - Each pass is one analysis or transformation
- **Types of Pass:**
  - ModulePass: general interprocedural pass
  - CallGraphSCCPass: bottom-up on the call graph
  - FunctionPass: process a function at a time
  - LoopPass: process a natural loop 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`

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`

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

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

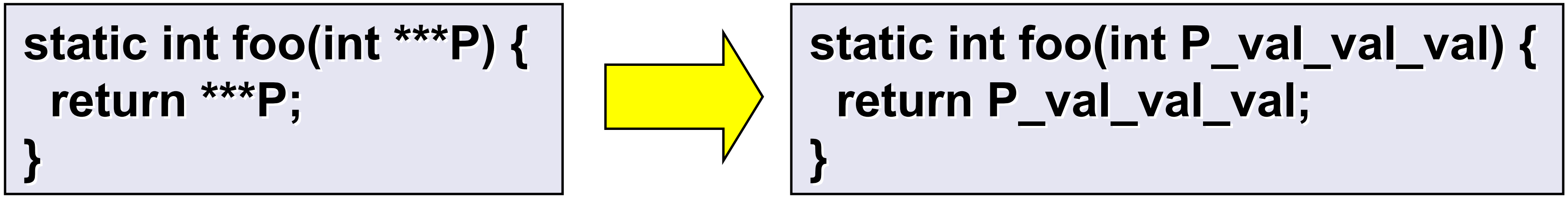
- **Arg Promotion requires AliasAnalysis info**
  - To prove safety of transformation
    - Works with any alias analysis algorithm though

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

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`

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:

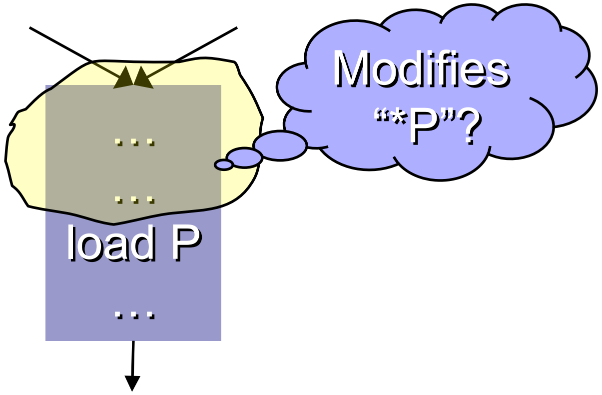
- No stores through argument pointer allowed!

```
// 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!



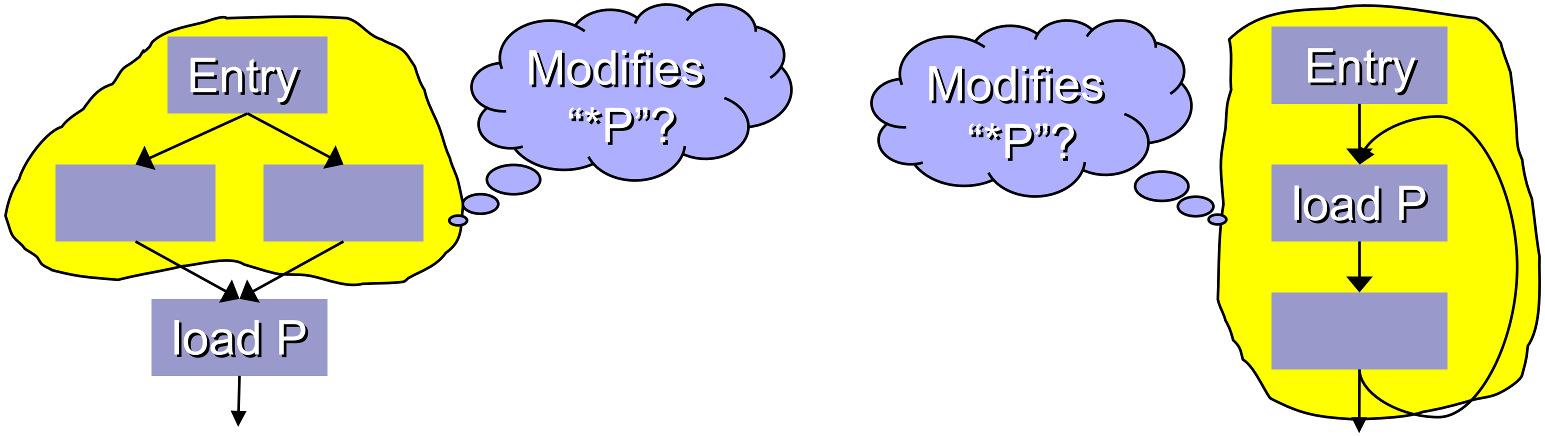
```
     // Get AliasAnalysis implementation from the pass manager.
156: AliasAnalysis &AA = getAnalysis<AliasAnalysis>();

     // 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

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;
```

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());
```

Arg Promotion: xform outline #2/4

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

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

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

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);
  }
```

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);
```

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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**
  - 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:**

```
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 ΆoptĄ**
  - `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**

Example -stats output (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
    ..........................
```

Example -time-passes (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
   `H
```

LLC Tool: Static code generator

- Compiles LLVM → native assembly language
  - `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`

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!