Introduction to LLVM
Part 2: Further Details

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LLVM Overview

- C++ based compiler framework
- (Fairly) well documented API
- Structures to help you process programs
  - Iterators for modules, functions, blocks, uses
  - Functions to inspect data types and contstants
  - Almost every class has a dump() method that prints the object to standard error
  - Tip: in gdb, use p obj->dump() to see the object

LLVM IR

- Machine independent assembly
  - Not completely – integer sizes have sizes, ir files tagged with architecture
- Arbitrary # of registers
  - Target machine specific pass does actual allocation
- Locals start with %, globals with @
- All instructions that produce values can have a name
  - Not assignments – store, branch

Iterators

- Module::iterator – module == source file, iterates through functions in the module
- Function::iterator – iterates through basic blocks in the module
- BasicBlock::iterator – iterates through instructions in a block
- Value::use_iterator – iterates through uses
  - Instructions are subclasses of values, which also include constants

More on iterators

- User::op_iterator – iterates through operands (Instruction is a user)
  - Tip: Many instruction classes have members for particular operands – ie LoadInst::getPointerOperand()
- inst_iterator – goes through instructions in a function
  - for(inst_iterator i=inst_begin(f);i!=inst_end(f);i++)
  - Declared in <Transforms/Utils/FunctionUtils.h>
- Most iterators automatically cast to a pointer to the object type (except inst_iterator)
- Be careful if modifying the list while iterating
  - Problem if using ++ after removing an item

Instructions

- Instruction types have specific subclasses
  - LoadInst, StoreInst, CmpInst, BranchInst, etc
  - Subclasses may have subclasses
- Exception: Most math operations have BinaryOperator class with a code for operation
- Alloca – allocates memory on the stack – don't use in a loop

Moving Instructions

- EraseFromParent() – remove from basic block, drop all references, deallocates
- RemoveFromParent() – just remove from basic block.
  - Use this if you will re-attach this instruction
  - Does not drop references (clear the use list), so if you don't reattach you'll get a crash in the module verifier
  - dropAllReferences will clean up
- MoveBefore / InsertBefore / InsertAfter are available

Types

- Not exactly what PL people think of as types
- Integer (size as a property), Float (different class for float, double, half), Arrays (can often get # elements), Structures (can get members), Pointers
  - Tip: type->getPointerTo() gets a pointer to a particular type
  - Booleans are i1 (1 bit integer)
- Vector types are included, and can be added, subtracted, etc. Can turn into SIMD instructions when compiled if the target supports them.
- GEP instruction: finds a field within a complex pointer type (or array)

LLVM Passes

- For assignments, don't use LLVM passes unless instructed to
  - Want you to implement them to really understand how they work
- For projects, use whatever you want
- Analysis passes – provide information
- Transform passes – modify the program
- Module Verifier – opt automatically runs this (unless you turn it off) to make sure that you haven't broken the module

Module Verifier

- Opt automatically runs this unless you turn it off
- Sanity checks
- You may need to break the module temporarily while working on it
- Types of binary operator parameters are the same
- Terminators (branches) only at the end of basic blocks
- Void instructions are not named (store, branch)
- Function parameters are not void type

Module Verifier (more)

- Function call arguments match function prototype
- All instructions in a basic block (refer back to erasefromparent vs removefromparent)
- Constants in a switch are the right type
- Entry node of a function has no predecessors
- PHI nodes are valid (more later)

Loop Information (-loops)

- Analysis/LoopInfo.h
- Basic blocks in a loop
- Headers, pre-headers
- Exit and exiting blocks
- Back edges
- Canonical induction variable (more later but either:
  - Starts at 0 and counts up by 1 OR
  - Starts at some number and counts down to 0
- Loop count (in many cases)

Scalar Evolution (-scalar-evolution)

- Tracks changes to variables through multiple loop nests
- Start value, step size (pseudo machine independent way with sizeof, indexof – can use with TargetData)
- Constants, add a value each iteration, multiply a value each iteration, more complicated affine progression across loops
  - Can be used to aggregate accesses into larger blocks
  - Can be used to find out if accesses go the wrong way for caches (accessing row major arrays columnwise)

Target Data (-targetdata)

- Endian-ness
- Pointer sizes
- Alignment
- Actual size in bits of variables
- Actual structure layout

Alias Analyses

```
%1 = load i32* %A
store i32 5, i32* %B
%3 = add i32 %1,i32 9
store i32 %3, i32* %C
```

What happens if A==B==C?

- LLVM includes a number of passes that perform different types of alias information
- Can get information about both global and local variables
- Included passes take into account the fact that many standard C library functions don't access memory

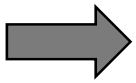
Notes on writing passes

- You must declare which analysis passes you use (and possibly what you change) in getAnalysisUsage
- The CommandLine library allows you to implement command line parameters very easily
  - Will tell you if there are conflicts for parameter names at run time. Can't tell at compile time because passes are loaded dynamically.

Memory To Register (-mem2reg)

- Removes memory operations where possible, puts code in SSA form
- EG: C=A+B
  D=C+2

```
%1 = load i32* %A
%2 = load i32* %B
%3 = add i32 %1,%2
store i32 %3, i32* %C
%4 = load i32* %C
%5 = add i32 %4, 2
store i32 %5, i32* %D
```



```
%1 = load i32* %A
%2 = load i32* %B
%3 = add i32 %1,%2
store i32 %3, i32* %C
%5 = add i32 %4, 2
store i32 %5, i32* %D
```


SSA Basics

- SSA = Single Static Assignment = each variable (abstract register) assigned exactly 1 time
- Phi nodes – construct to handle cases where a variable may have more than one value
  - May be self referential (in loops)
  - Inside a block – select statement sometimes used
- In LLVM:
  - Must be at the beginning of the block
  - Must have exactly 1 entry for every predecessor
  - Must have at least one entry
  - May include undef values

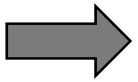
Simplify CFG

- Removes unnecessary basic blocks by merging unconditional branches if the second block only has one predecessor
- Removes unreachable blocks
- Removes phi nodes with only a single predecessor
- Many of the conditions that this pass cleans up are created by other optimization passes

Aggressive Dead Code Elimination

- Liveness based dead code elimination – assumes code is dead unless proven otherwise
- EG: C=A+B
  D=C+2
  Assume this is the only code (other than initializing A,B somewhere) and that Mem2Reg has been run

```
%1 = load i32* %A
%2 = load i32* %B
%3 = add i32 %1,%2
store i32 %3, i32* %C
%5 = add i32 %4, 2
store i32 %5, i32* %D
```



```
%1 = load i32* %A
%2 = load i32* %B
%3 = add i32 %1,%2
%5 = add i32 %4, 2
store i32 %5, i32* %D
```

Other useful passes

- Sparse conditional constant propagation – aggressively searches for constants
- Correlated propagation – replaces select statements that depend on constants
- Loop invariant code motion – moves code out of loops
- Dead global elimination
- Canonicalize Induction Variables – all loops count up from 0
- Canonicalize Loops – puts loop structure in standard form

Links

- Pass Howto: http://llvm.org/docs/WritingAnLLVMPass.html
- LLVM Development reference http://llvm.org/docs/ProgrammersManual.html
- LLVM IR: http://llvm.org/docs/LangRef.html
- GEP: http://llvm.org/docs/GetElementPtr.html
- CommandLine library: http://llvm.org/docs/CommandLine.html
- Built in passes: http://llvm.org/docs/Passes.html
- Everything else: http://llvm.org/docs