Lecture 4
More on the LLVM Compiler

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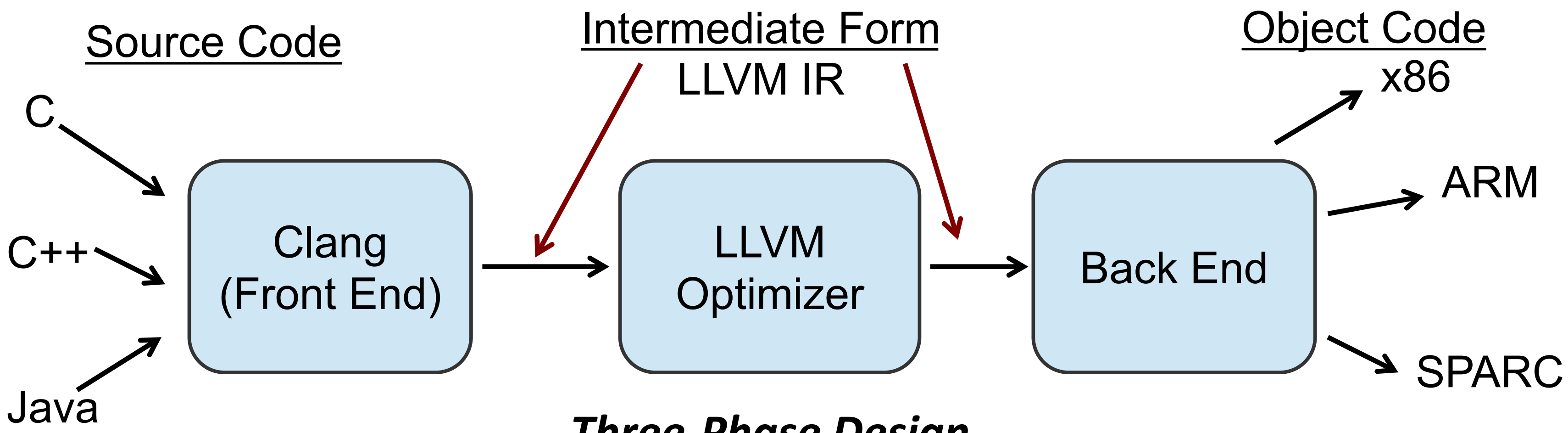
Luke Zarko, and Dominic Chen for their slides

Visualizing the LLVM Compiler System



Three-Phase Design

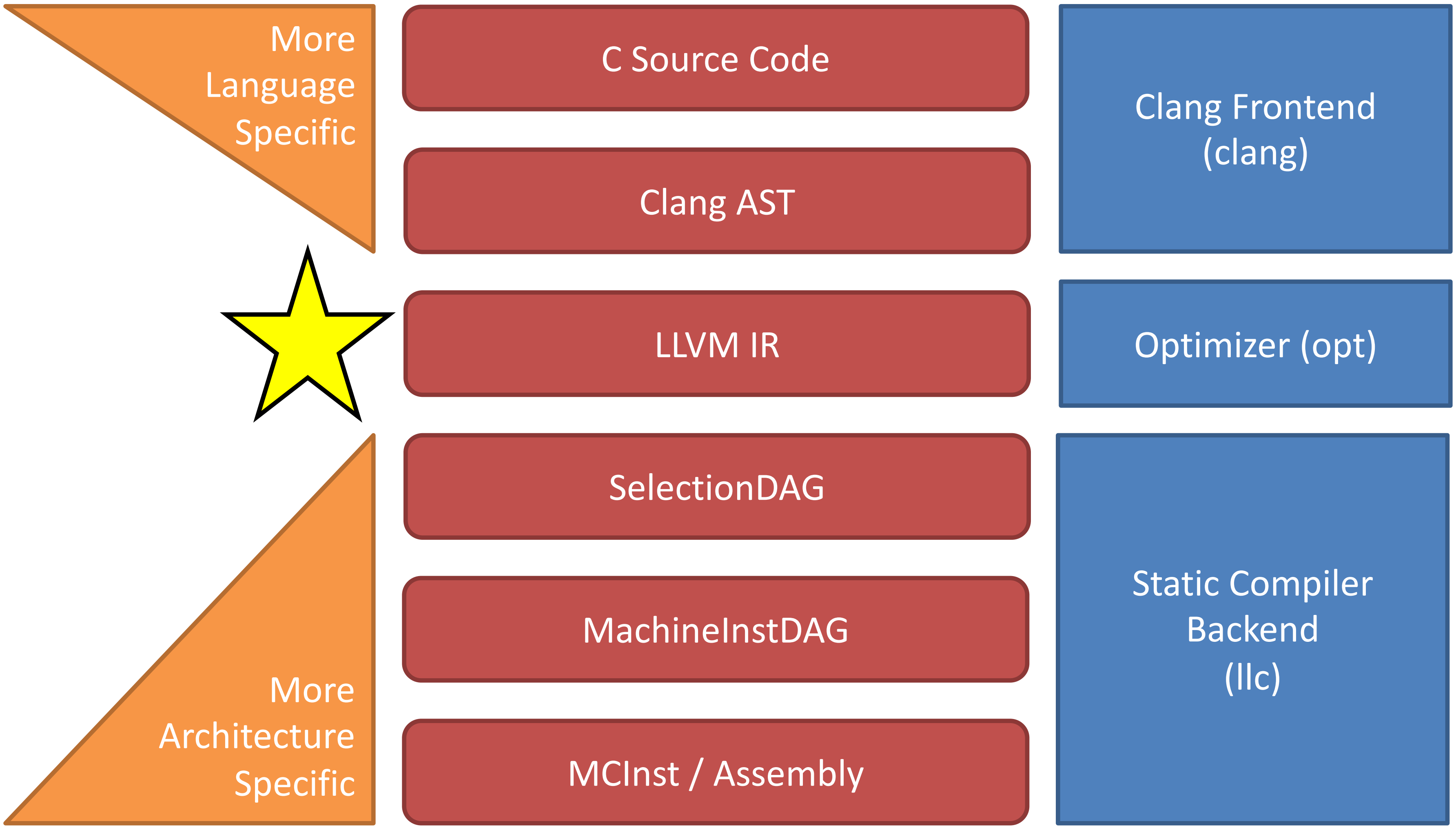
The LLVM Optimizer is a series of "passes"

- **Analysis and optimization passes, run one after another**
- ***Analysis* passes do not change code, *optimization* passes do**

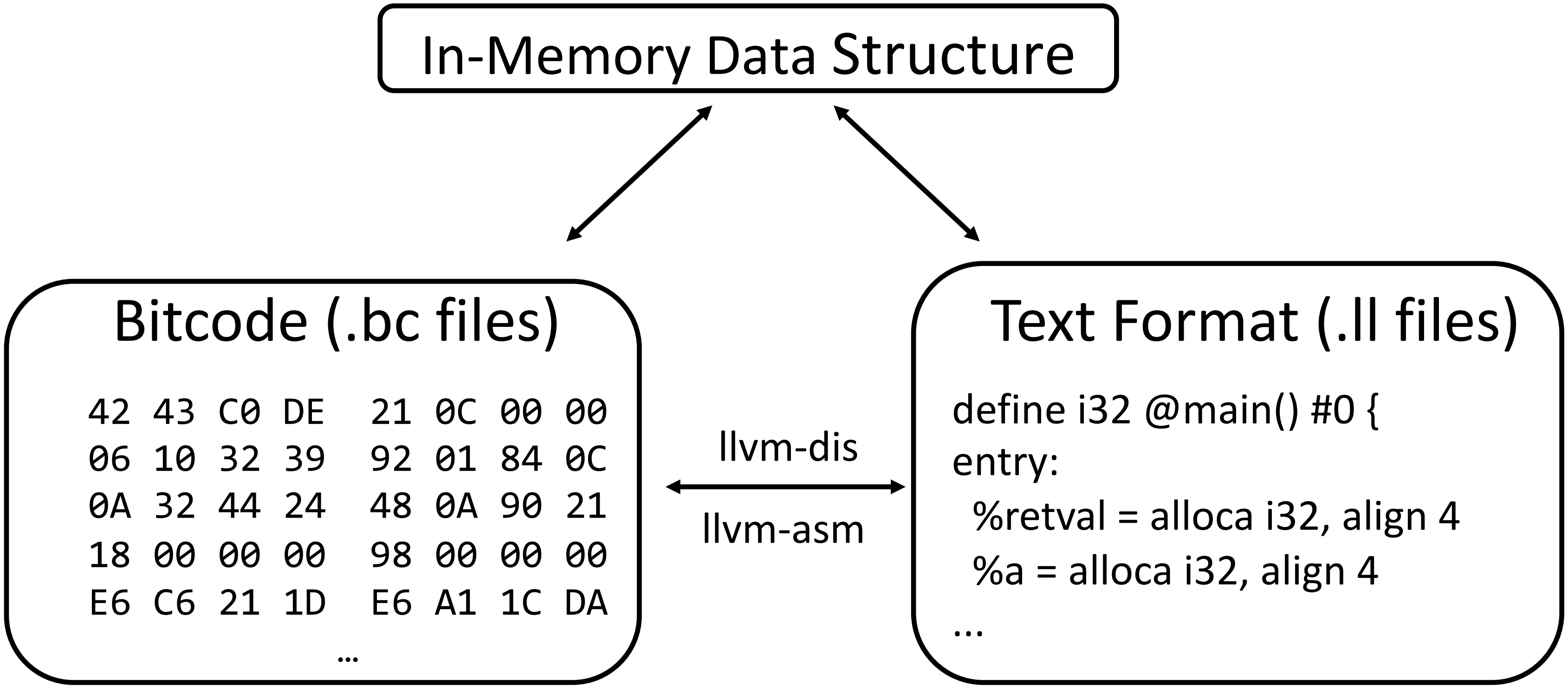
LLVM Intermediate Form is a *Virtual Instruction Set*

- Language- and target-independent form
  - Used to perform the same passes for all source and target languages
- Internal Representation (IR) and external (persistent) representation

LLVM: From Source to Binary



LLVM IR



Bitcode files and LLVM IR text files are **lossless serialization formats**!
We can pause optimization and come back later.

Doing Things The LLVM Way - Strings

- LLVM does not use either **char *** or **std::string** to represent strings internally.
  - **char *s** use null terminators to represent strings -> bad for byte strings
  - **std::strings** are ok, but not recommended for performance reasons

- If it takes a **StringRef**, it can take a **std::string** or string literal as well:

```
getFunction("myfunc")                getFunction(std::string("myfunc"))

getFunction(StringRef("myfunc",6))
```

All Equivalent!

- Use **.str()** on a **StringRef** to get a **std::string**.
- Should avoid using C-style strings altogether

Doing Things The LLVM Way - Strings

- Forget **std::cout** and **std::cerr**! You want **outs()**, **errs()**, and **null()**.
  - Oddly, there's not equivalent of std::endl in LLVM

- Printing the Name of a Function:

```
~~std::cout  << F->getName().str() << std::endl;~~
outs() << F->getName() << “\n”;
```

- Printing an Instruction:

```
Instruction *I;
I->dump();       or       outs() << *I << “\n”;
```

- Printing an Entire Basic Block:

```
BB->dump()       or       outs() << *BB << “\n”;
```

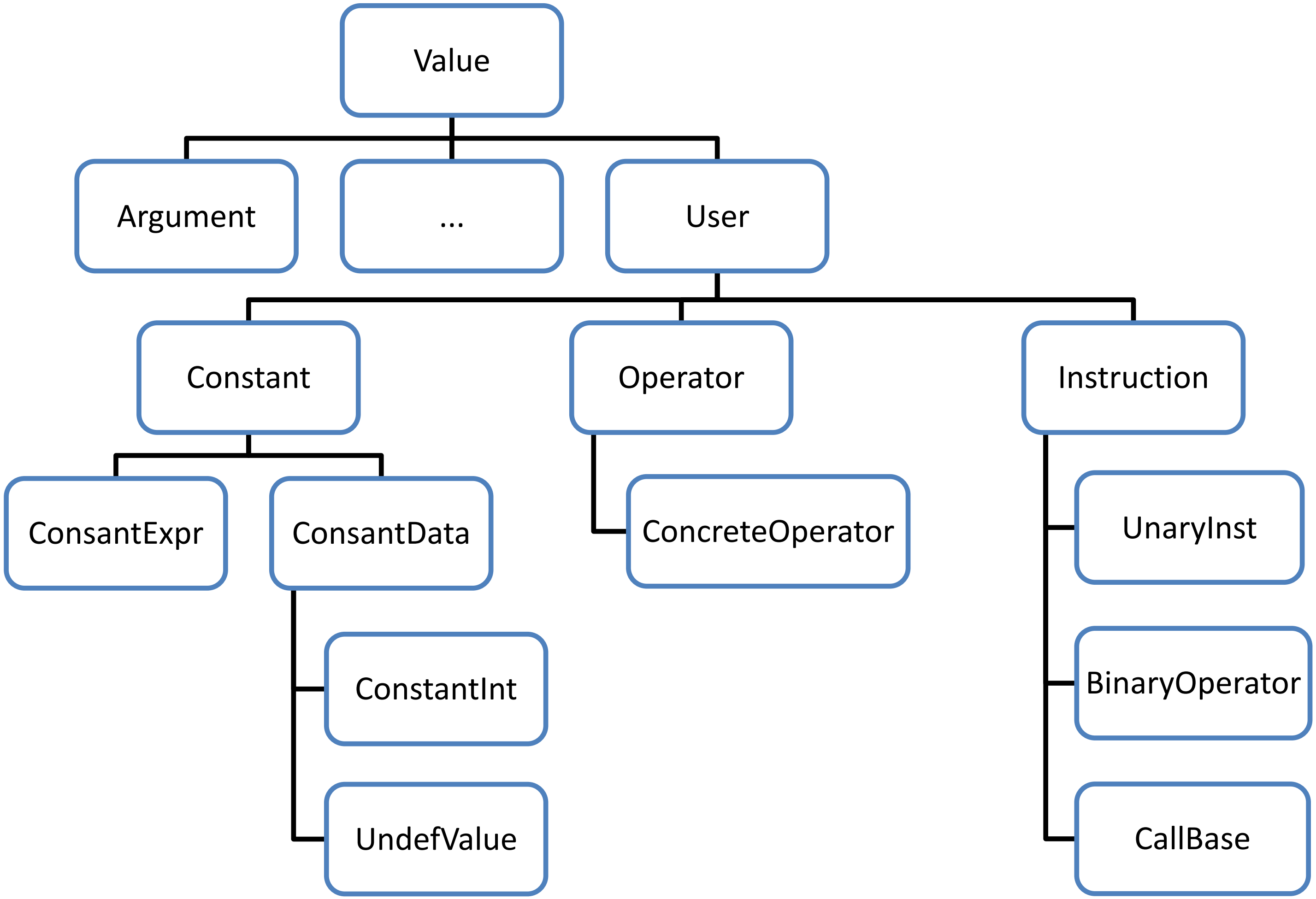
<u>Doing Things the LLVM Way – Data Structures</u>

- LLVM provides lots of data structures:

  BitVector, DenseMap, DenseSet, ImmutableList, ImmutableMap, ImmutableSet, IntervalMap, IndexedMap, MapVector, PriorityQueue, SetVector, ScopedHashTable, SmallBitVector, SmallPtrSet, SmallSet, SmallString, SmallVector, SparseBitVector, SparseSet, StringMap, StringRef, StringSet, Triple, TinyPtrVector, PackedVector, FoldingSet, UniqueVector, ValueMap

- Provide better performance through *specialization*
- STL data structures work fine as well
- Only use these data structures in HW if you really want to

Doing Things The LLVM Way – Class Hierarchy



LLVM Instructions <--> Values

```c
int main() {
    int x = 1;
    int y = 2;
    int z = 3;
    x = y+z;
    y = x+z;
    z = x+y;
}
```

clang + mem2reg

```llvm
; Function Attrs: nounwind
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 3
  %add1 = add nsw i32 %add, 3
  %add2 = add nsw i32 %add,
%add1
  ret i32 0
}
```

Instruction I: “`%add1 = add nsw i32 %add, 3`”

Operand 1

Operand 2

You can’t “get” %add1 from Instruction I.
Instruction serves as the Value %add1.

LLVM Instructions <--> Values

```
int main() {
    int x = 1;
    int y = 2;
    int z = 3;
    x = y+z;
    y = x+z;
    z = x+y;
}
```

clang + mem2reg

```
; Function Attrs: nounwind
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 3
  %add1 = add nsw i32 %add, 3
  %add2 = add nsw i32 %add,
%add1
  ret i32 0
}
```

Instruction I: “%add1 = add nsw i32 %add, 3”

`outs() << *(I.getOperand(0));` ⟶ “%add = add nsw i32 2, 3”

`outs() << *(I.getOperand(0)->getOperand(0));` ⟶ “2”

Only makes sense for an SSA Compiler

Doing Things The LLVM Way – Casting and Type Introspection

Given a **Value *v**, what kind of **Value** is it?

```
isa<Argument>(v)
```

Is v an instance of the **Argument** class?

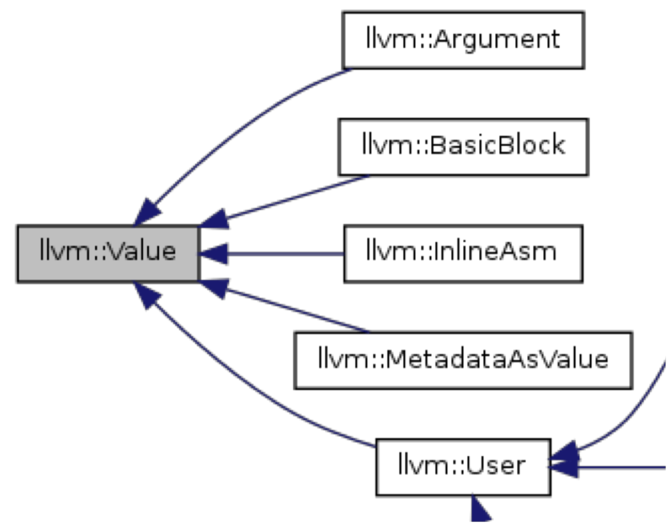
```
Argument *v = cast<Argument>(v)
```

I **know** v is an **Argument**, perform the cast. Causes assertion failure if you are wrong.

```
Argument *v = dyn_cast<Argument>(v)
```

Cast v to an **Argument** if it is an argument, otherwise return **NULL**. Combines both **isa** and **cast** in one command.

dyn_cast is not to be confused with the C++ **dynamic_cast** operator!



Doing Things The LLVM Way – Casting and Type Introspection

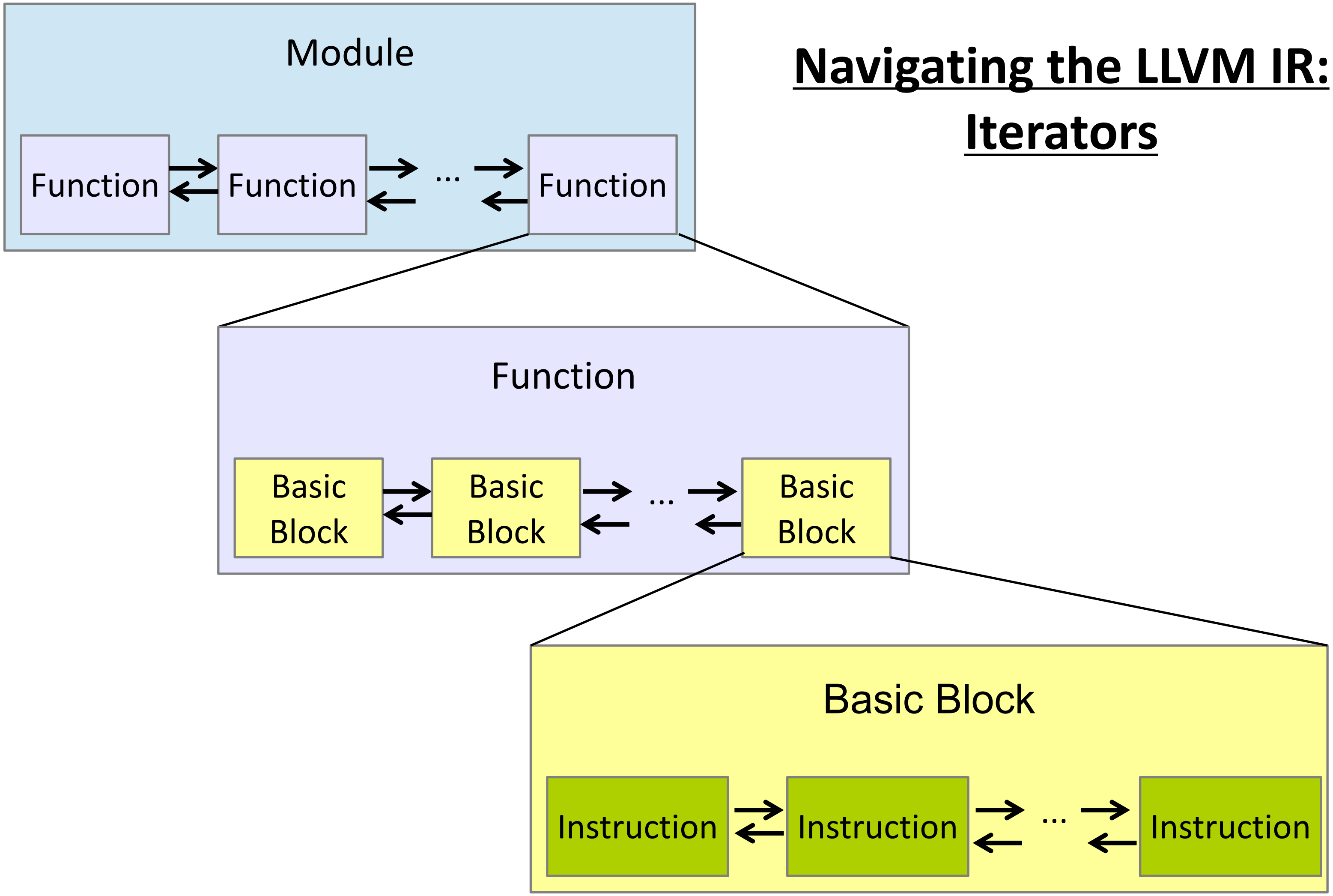
```
Static bool isLoopInvariant(const Value *V, const Loop *L) {
    if (isa<Constant>(V) || isa<Argument>(V) || isa<GlobalValue<(V)) {
        return true;
    }

    //otherwise it must be an instruction…
    return !L->contains(cast<Instruction>(V)->getParent());
    …
}
```

Doing Things The LLVM Way – Casting and Type Introspection

```
void analyzeInstruction(Instruction * I) {
    if (CallInst * CI = dyn_cast<CallInst>(I)) {
        outs() << “I’m a Call Instruction!\n”;
    }
    if (UnaryInstruction * UI = dyn_cast<UnaryInstruction>(I)) {
        outs() << “I’m a Unary Instruction!\n”;
    }
    if (CastInstruction * CI = dyn_cast<CastInstruction>(I)) {
        outs() << “I’m a Cast Instruction!\n”;
        }
    …
}
```

Navigating the LLVM IR: Iterators



Navigating the LLVM IR - Iterators

- **Module::iterator**
  - Modules are the large units of analysis
  - Iterates through the functions in the module
- **Function::iterator**
  - Iterates through a function's basic blocks
- **BasicBlock::iterator**
  - Iterates through the instructions in a basic block
- **Value::use_iterator**
  - Iterates through **uses** of a value
  - Recall that instructions are treated as values
- **User::op_iterator**
  - Iterates over the operands of an instruction (the "user" is the instruction)
  - Prefer to use convenient accessors defined by many instruction classes

Navigating the LLVM IR - Iterators

- Iterate through every instruction in a function:

```
for (Function::iterator FI = func->begin(); FI != func->end(); ++FI) {
     for (BasicBlock::iterator BBI = FI->begin(); BBI != FI->end(); ++BBI) {
          outs() << “Instruction: ” << *BBI << “\n”;
     }
}
```

- Using **InstIterator** (provided by "llvm/IR/InstIterator.h“):

```
#include “llvm/IR/InstIterator.h”

for (inst_iterator I = inst_begin(F), E = inst_end(F); I != E; ++I) {
     outs() << *I << “\n”;
}
```

Navigating the LLVM IR - Iterators

```
Function &Func = ...
for (BasicBlock &BB : Func)
    errs() << "Basic block (name=" << BB.getName() << ") has
           " << BB.size() << " instructions.\n";
```

Navigating the LLVM IR - Hints on Using Iterators

- Be careful when modifying an object while iterating over it (iterator invalidation)
  - Can cause unexpected behavior; use a separate removal list
- Use preincrement (++i) rather than postincrement (i++)
  - Avoids problems with iterators doing unexpected things
  - Likely more performant, especially for complex iterators
- Iterators can overlap with each other
  - e.g., **InstIterator** walks over all instructions in a function, which overlaps with **BasicBlock::iterator**

Navigating the LLVM IR – More Iterators

- Finding a Basic Block's predecessors/successors:

```
#include "llvm/Support/CFG.h"
BasicBlock *BB = ...;

for (pred_iterator PI = pred_begin(BB); PI != pred_end(BB); ++PI) {
    BasicBlock *pred = *PI;
    // ...
}
```

Many useful iterators are defined outside of Function, BasicBlock, etc.

Navigating the LLVM IR – Casting and Iterators

```
for (Function::iterator FI = func->begin(); FI != func->end(); ++FI) {
    for (BasicBlock::iterator BBI = FI->begin(); BBI != FI->end(); ++BBI) {
        Instruction * I = BBI;
        if (CallInst * CI = dyn_cast<CallInst>(I)) {
            outs() << “I’m a Call Instruction!\n”;
        }
        if (UnaryInstruction * UI = dyn_cast<UnaryInstruction>(I)) {
            outs() << “I’m a Unary Instruction!\n”;
        }
        if (CastInstruction * CI = dyn_cast<CastInstruction>(I)) {
            outs() << “I’m a Cast Instruction!\n”;
        }
        …
    }
}
```

Very Common Code Pattern!

Navigating the LLVM IR – Visitor Pattern

```
class MyVisitor : public InstVisitor<MyVisitor> {
    void visitCallInst(CallInst &CI) {
        outs() << "I'm a Call Instruction!\n";
    }
    void visitUnaryInstruction(UnaryInstruction &UI) {
        outs() << "I'm a Unary Instruction!\n";
    }
    void visitCastInst(CastInst &CI) {
        outs() << "I'm a Cast Instruction!\n";
    }
    void visitBinaryOperator(BinaryOperator &I) {
        switch (I.getOpcode()) {
        case Instruction::Mul:
            outs() << "I'm a multiplication Instruction!\n";
        }
    }
}
```

No need for iterators or casting!

A given instruction only triggers one method: a **CastInst** will not call **visitUnaryInstruction** if **visitCastInst** is defined.

You can case out on operators too, even if there isn't a specific class for them!

Writing Passes - Changing the LLVM IR

- Getting rid of Instructions:
  - **eraseFromParent()**
    - Remove from basic block, drop all references, delete
  - **removeFromParent()**
    - Remove from basic block
    - Use if you will re-attach the instruction
    - Does not drop references (or clear the use list), so if you don't re-attach it Bad Things will happen
- **moveBefore/insertBefore/insertAfter** are also available
- **replaceInstWithValue** and **replaceInstWithInst** are also useful to have

Writing Passes – Adding New Instructions

```
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 2
  %add1 = add nsw i32 %add, 2
  %mul = mul nsw i32 %add, %add1
  %sub = sub nsw i32 %add1, %mul
  %add2 = add nsw i32 %mul, 5
  ret i32 %sub
}
```

```
define i32 @main() #0 {
entry:
  %add = add nsw i32 2, 2
  %add1 = add nsw i32 %add, 2
  %0 = add i32 %add, 0
  %mul = mul nsw i32 %add, %add1
  %sub = sub nsw i32 %add1, %mul
  %add2 = add nsw i32 %mul, 5
  ret i32 %sub
}
```

```
Instruction *I = "%mul = mul nsw i32 %add, %add1";

Instruction *newInst = BinaryOperator::Create(Instruction::Add, I.getOperand(0),
                            ConstantInt::get(I.getOperand(0)->getType(), 0));

I->getParent()->getInstList().insert(I, newInst)
```

Writing Passes - Correctness

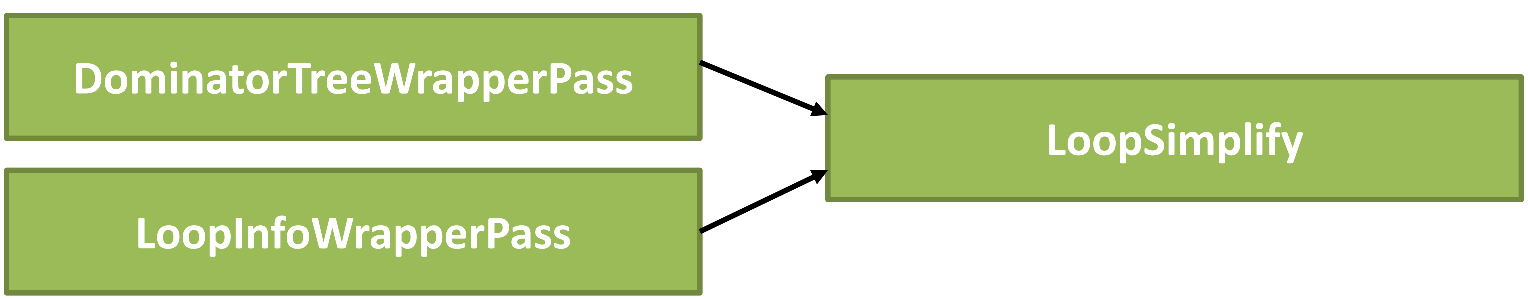
- When you modify code, be careful not to change the meaning!
- You can break module invariants while in your pass, but you should repair them before you finish
  - Some module invariant examples:
    - Types of binary operator parameters are the same
    - Terminator instructions only at the end of BasicBlocks
    - Functions are called with correct argument types
    - Instructions belong to Basic blocks
    - Entry node has no predecessor
- opt automatically runs a pass (-verify) to check module invariants
  - **But it doesn't check correctness in general!**
- Think about multi-threaded correctness

LLVM Pass Manager

- **Compiler is organized as a series of "passes":**
  - Each pass is an analysis or transformation
  - Each pass can depend on results from previous passes
- **Six useful types of passes:**
  - BasicBlockPass: iterate over basic blocks, in no particular order
  - CallGraphSCCPass: iterate over SCC's, in bottom-up call graph order
  - FunctionPass: iterate over functions, in no particular order
  - LoopPass: iterate over loops, in reverse nested order
  - ModulePass: general interprocedural pass over a program
  - RegionPass: iterate over single-entry/exit regions, in reverse nested order
- **Passes have different constraints (e.g. FunctionPass):**
  - FunctionPass can only look at the "current function"
  - Cannot maintain state across functions

LLVM Pass Manager

- Given a set of passes, the PassManager tries to ***optimize the execution time*** of the set of passes
  - Share information between passes
  - Pipeline execution of passes
- PassManager must understand how passes interact
  - Passes may require ***information*** from other passes
  - Passes may require ***transformations*** applied by other passes
  - Passes may ***invalidate information or transformations*** applied by other passes



LLVM Pass Manager

- The **getAnalysisUsage()** function defines how a pass interacts with other passes
- Given **getAnalysisUsage(AnalysisUsage &AU)** for PassX:
  - **AU.addRequired<PassY>()** → PassY must be executed first
  - **AU.addPreserved<PassY>()** → PassY is still preserved by running PassX
  - **AU.setPreservesAll()** → PassX preserves all previous passes
  - **AU.setPreservesCFG()** → PassX might make changes, but not to the CFG
  - If nothing is specified, it is assumed that all previous passes are invalidated

DeadStoreElimination Pass:

```
void getAnalysisUsage(AnalysisUsage &AU) const override {
    AU.setPreservesCFG();
    AU.addRequired<DominatorTreeWrapperPass>();
    AU.addRequired<AliasAnalysis>();
    AU.addRequired<MemoryDependenceAnalysis>();
    AU.addPreserved<AliasAnalysis>();
    AU.addPreserved<DominatorTreeWrapperPass>();
    AU.addPreserved<MemoryDependenceAnalysis>();
}
```

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:**
  - **When you write a pass, you must write the registration**

```
RegisterPass<FunctionInfo> X("function-info",
        "15745: Function Information");
```

Using Passes

- **For homework assignments, do not use passes provided by LLVM unless instructed to**
  - We want you to implement the passes yourself!

- **For projects, you can use whatever you want**
  - Your own passes or LLVM's passes

Useful LLVM Passes: Memory to Register (-mem2reg)

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %a = alloca i32, align 4
  %b = alloca i32, align 4
  store i32 0, i32* %retval
  store i32 5, i32* %a, align 4
  store i32 3, i32* %b, align 4
  %0 = load i32* %a, align 4
  %1 = load i32* %b, align 4
  %sub = sub nsw i32 %0, %1
  ret i32 %sub
}
```

mem2reg

```
define i32 @main() #0 {
entry:
  %sub = sub nsw i32 5, 3
  ret i32 %sub
}
```

Not always possible:
Sometimes stack operations are too complex

```c
int main(int argc,
          char * arv[]) {
  int x;
  if (argc > 5) {
    x = 2;
  }
  else {
    x = 3;
  }
  return x;
}
```

clang + mem2reg

```llvm
define i32 @main(i32 %argc,
                 i8** %arv) #0 {
entry:
  %cmp = icmp sgt i32 %argc, 5
  br i1 %cmp, label %if.then,
              label %if.else
if.then:
  br label %if.end

if.else:
  br label %if.end

if.end:
  %x.0 = phi i32
        [ 2, %if.then ],
        [ 3, %if.else ]
  ret i32 %x.0
}
```

`%x.0 = 2` from `%if.then`

`%x.0 = 3` from `%if.else`

```c
int main(int argc, char * argv[]) {
  int vals[4] = {2,4,8,16};
  int x = 0;
  vals[1] = 3;
  x += vals[0];
  x += vals[1];
  x += vals[2];
  return x;
}
```

```
@main.vals = private unnamed_addr constant [4 x i32]
                         [i32 2, i32 4, i32 8, i32 16], align 4
define i32 @main(i32 %argc, i8** %argv) #0 {
entry:
  %vals = alloca [4 x i32], align 4
  %0 = bitcast [4 x i32]* %vals to i8*
  call void @llvm.memcpy.p0i8.p0i8.i32(i8* %0, i8* bitcast ([4 x i32]*
@main.vals to i8*), i32 16, i32 4, i1 false)
  %arrayidx = getelementptr inbounds [4 x i32]* %vals, i32 0, i32 1
  store i32 3, i32* %arrayidx, align 4
  %arrayidx1 = getelementptr inbounds [4 x i32]* %vals, i32 0, i32 0
  %1 = load i32* %arrayidx1, align 4
  %add = add nsw i32 0, %1
  %arrayidx2 = getelementptr inbounds [4 x i32]* %vals, i32 0, i32 1
  %2 = load i32* %arrayidx2, align 4
  %add3 = add nsw i32 %add, %2
  %arrayidx4 = getelementptr inbounds [4 x i32]* %vals, i32 0, i32 2
  %3 = load i32* %arrayidx4, align 4
  %add5 = add nsw i32 %add3, %3
  ret i32 %add5
}
```

mem2reg does not solve all of our pointer problems ☹

```
int main(int argc, char * arv[]) {
  int x = 0;
  for (int i=0; i<argc; i++) {
    x += i;
  }
  return x;
}
```

```
define i32 @main(i32 %argc, i8** %arv) #0 {
entry:
  br label %for.cond

for.cond:
  %x.0 = phi i32 [ 0, %entry ], [ %add, %for.inc ]
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %cmp = icmp slt i32 %i.0, %argc
  br i1 %cmp, label %for.body, label %for.end

for.body:
  %add = add nsw i32 %x.0, %i.0
  br label %for.inc

for.inc:
  %inc = add nsw i32 %i.0, 1
  br label %for.cond

for.end:
  ret i32 %x.0
}
```

Names are just strings, they should not be used to identify loops

There are no "Loop" instructions!

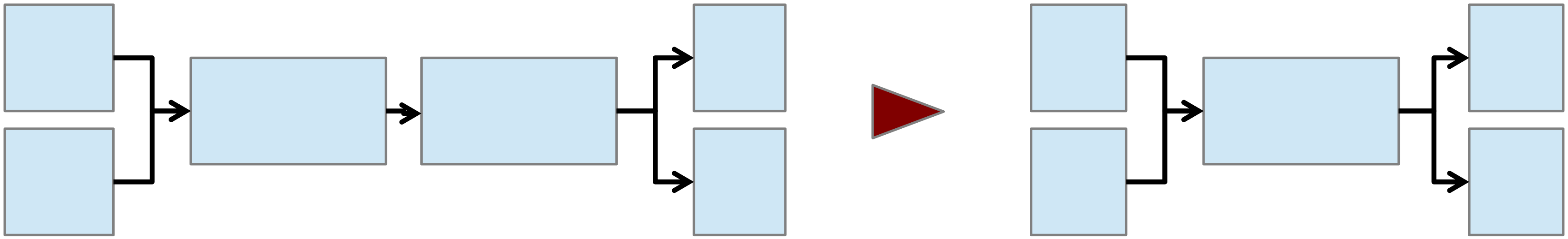
Loops are implemented with conditions and jumps

Useful LLVM Passes: Loop Information (-loops)

- llvm/Analysis/LoopInfo.h
- Reveals:
  - The basic blocks in a loop
  - Headers and pre-headers
  - Exit and exiting blocks
  - Back edges
  - “Canonical induction variable”
  - Loop Count

Useful LLVM Passes: Simplify CFG (-simplifycfg)

- Performs basic cleanup
  - Removes unnecessary basic blocks by merging unconditional branches if the second block has only one predecessor
  - Removes basic blocks with no predecessors
  - Eliminates phi nodes for basic blocks with a single predecessor
  - Removes unreachable blocks



Useful LLVM Passes: Others

- Scalar Evolution (-scalar-evolution)
  - Tracks changes to variables through nested loops
- Target Data (-targetdata)
  - Gives information about data layout on the target machine
  - Useful for generalizing target-specific optimizations
- Alias Analyses (-basicaa, -aa-eval, -scev-aa)
  - Several different passes give information about aliases
  - If you know that different names refer to different locations, you have more freedom to reorder code, etc.

Useful LLVM Passes: Others

- Liveness-based dead code elimination (-dce, adce)
  - Assumes code is dead unless proven otherwise
- Dead global elimination (-globaldce)
  - Deletes all globals that are not live
- Sparse conditional constant propagation (-sccp)
  - Aggressively search for constants
- Loop invariant code motion (-licm)
  - Move code out of loops where possible
- Canonicalize induction variables (-indvars)
  - All loops start from zero and step by one
- Canonicalize loops (-loop-simplify)
  - Put loop structures in standard form

Some Useful LLVM Documentation

- **LLVM Coding Standards**
  - http://llvm.org/docs/CodingStandards.html
- **LLVM Programmer's Manual**
  - http://llvm.org/docs/ProgrammersManual.html
- **LLVM Language Reference Manual**
  - http://llvm.org/docs/LangRef.html
- **Writing an LLVM Pass**
  - http://llvm.org/docs/WritingAnLLVMPass.html
- **LLVM's Analysis and Transform Passes**
  - http://llvm.org/docs/Passes.html
- **LLVM Internal Documentation**
  - http://llvm.org/docs/doxygen/html/

Remember: We're using LLVM 5.0.1, but the documentation is always for the most up to date code (i.e. for the upcoming LLVM 9.0.0)