IEEE SecDev 2021

IEEE COMPUTER SOCIETY

LLVM Tutorial

John Criswell, Ethan Johnson, and Colin Provonost

UNIVERSITY of ROCHESTER

#IEEESecDev https://secdev.ieee.org/2021

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Goals

Today's Goal

- Create LLVM pass that instruments store instructions
- Optimize checks on store instructions

Programming Background

- C++
  - Other language bindings exist, but C++ is “native”
- Know how to use classes, pointers, and references
- Know how to use C++ iterators
- Know how to use Standard Template Library (STL)

Virtual Machine Image

https://www.cs.rochester.edu/u/ejohns48/secdev21/

Start Your Virtual Machines!

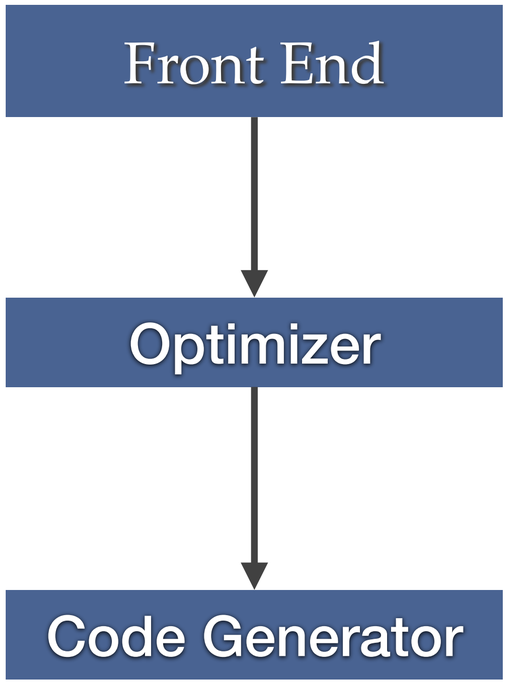
- Login name: user
- Login password: llvm is cool
- Source code is in /home/user/src/SecDev

LLVM Compiler Structure

LLVM is a Compiler Infrastructure

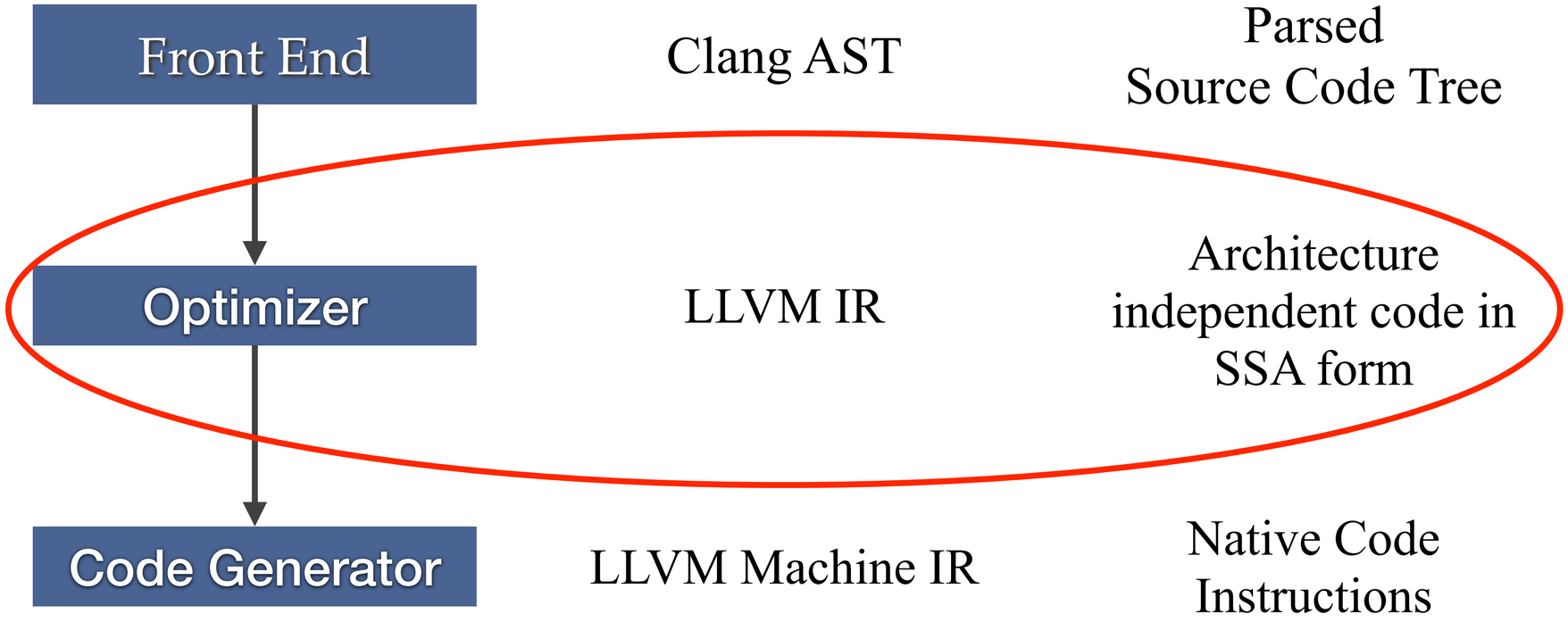
- Set of libraries for building compiler tools
- Write tools to analyze software behavior
- Write tools that control program behavior

Ahead of Time (AOT) Compiler

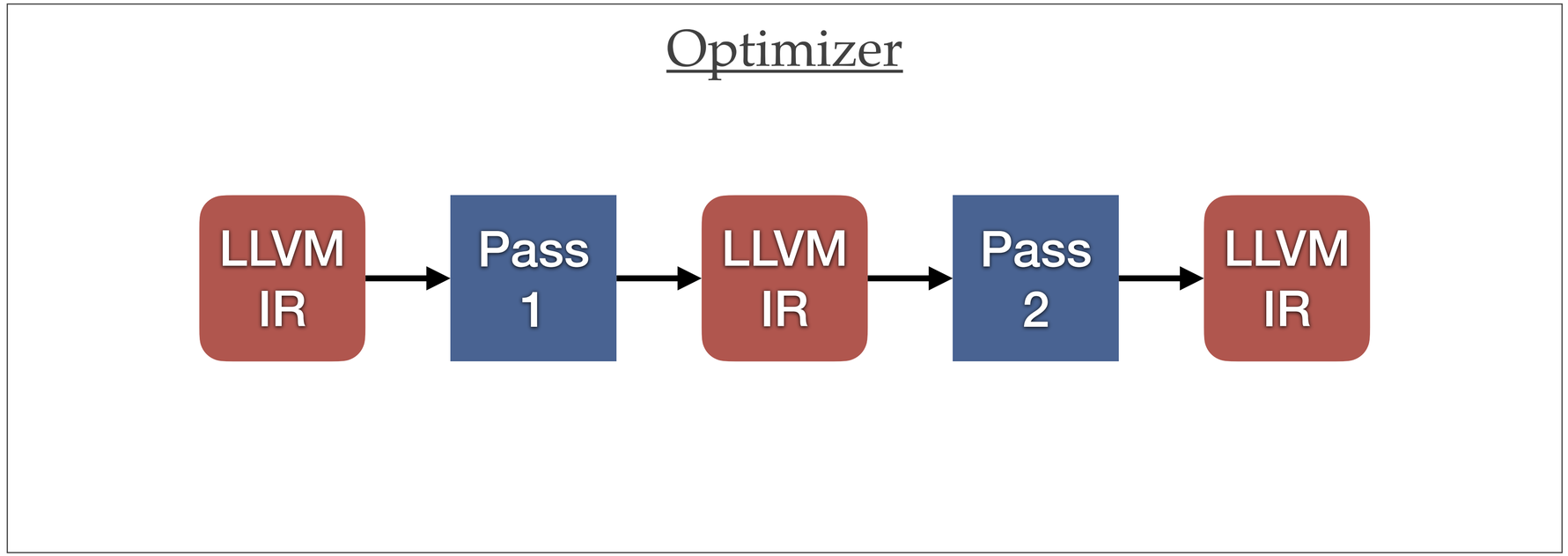


Front End	Clang AST	Parsed Source Code Tree
Optimizer	LLVM IR	Architecture independent code in SSA form
Code Generator	LLVM Machine IR	Native Code Instructions

Ahead of Time (AOT) Compiler



Optimizer Structure



LLVM
Intermediate Representation

LLVM IR is a *language* into which programs are translated for analysis and transformation

LLVM IR Forms

- LLVM Assembly Language
  - Text form saved on disk for humans to read
- LLVM Bitcode
  - Binary form saved on disk for programs to read
- LLVM In-Memory IR
  - Data structures used for analysis and optimization

LLVM IR Example

```
$ make
$ sh compile-tests
$ cd run
$ llvm-dis global.bc
```

Compile SecDev Pass

Compile test programs with LLVM

Disassemble and put output in global.ll

LLVM Assembly Language

```
define dso_local void @set_foo(i32 %new_foo) #0 {
entry:
  %new_foo.addr = alloca i32, align 4
  store i32 %new_foo, i32* new_foo.addr, align 4, !tbaa !2
  %0 = load i32, i32* %new_foo.addr, align 4, !tbaa !2
  store i32 %0, i32* @foo, align 4, !tbaa !4
  ret void
}
```

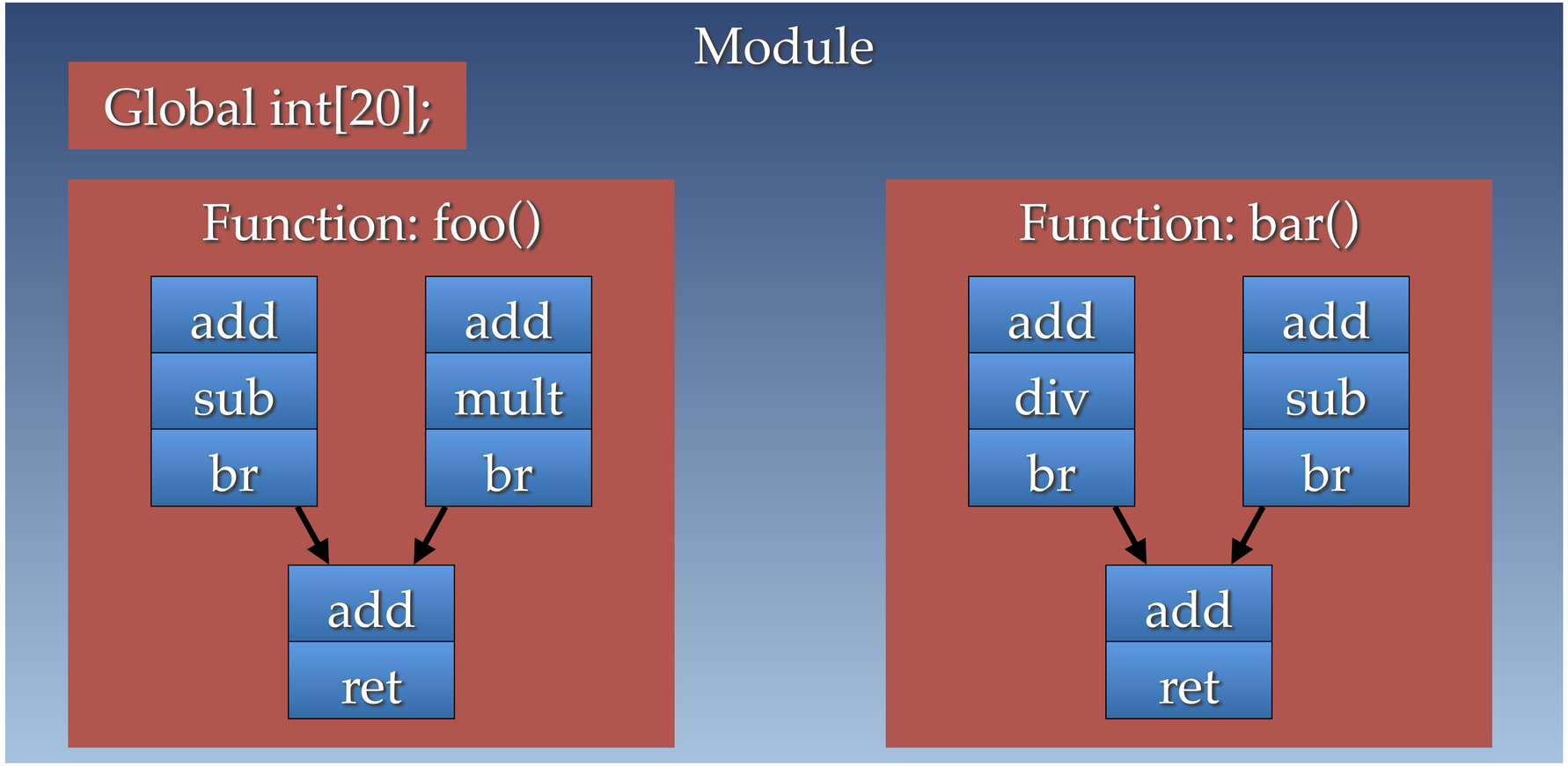
Code organized as functions

Simple load / store instructions

Overview of LLVM IR

- Each assembly/bitcode file is a Module
- Each Module is comprised of
  - Global variables
  - A set of Functions which are comprised of
    - A set of basic blocks which are comprised of
      - A set of instructions

LLVM Bitcode File



LLVM Instruction Set

- RISC-like architecture
  - Virtual registers in SSA form
  - Load instructions read from memory objects
  - Store instructions write to memory objects
  - All other instructions read or write virtual registers

Instructions for Computation

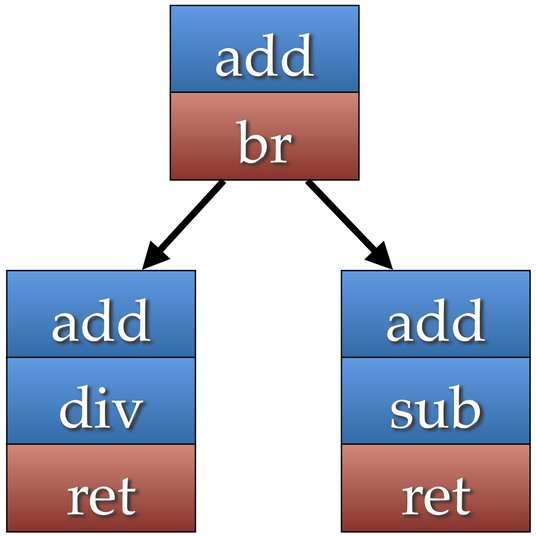
- Arithmetic and binary operators
  - Two's complement arithmetic (add, sub, multiply, etc)
  - Bit-shifting and bit-masking
- Pointer arithmetic (getelementptr or "GEP")
- Comparison instructions (icmp, fcmp)
  - Generates a boolean result

Memory Access Instructions

- Load instruction reads memory
- Store instruction writes to memory
- Atomic compare and exchange
- Atomic read / modify / write

Control Flow Instructions

- Terminator instructions
  - Indicate which basic block(s) to jump to next
  - Conditional branch, unconditional branch, switch
  - Return instruction to return to caller
- Call instruction calls a function
  - It can occur in the middle of a basic block



Memory Allocation Instructions

- Stack allocation (alloca)
  - Allocates memory on the stack
- Calls to heap-allocation functions (e.g., malloc())
  - Not a special instruction; just uses a call instruction
- Global variable declarations
  - Not really instructions, but allocate memory
  - All globals are *pointers* to memory objects

Single Static Assignment (SSA)

- Each function has infinite set of ***virtual registers***
- Only ***one*** instruction assigns a value to a virtual register (called the ***definition*** of the register)
- An instruction and the register it defines are ***synonymous***

%z = add %x, %y

Single Static Assignment (SSA)

- Instruction and the register it defines are ***synonymous***

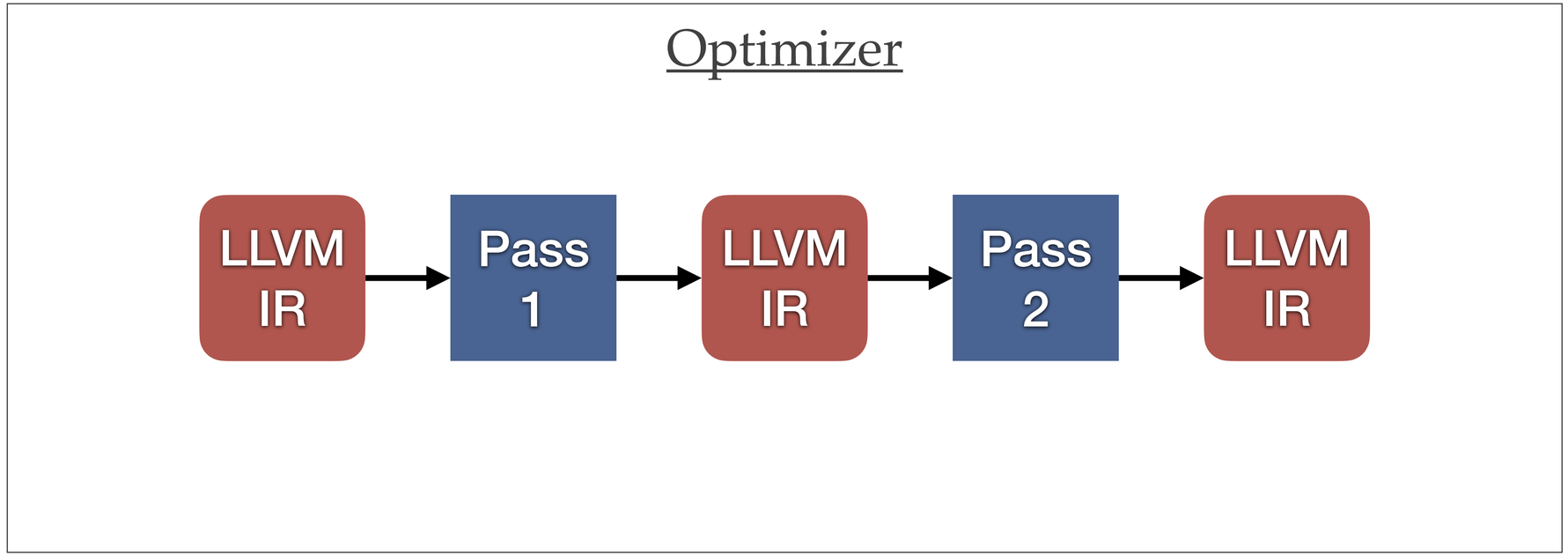
%z = add %x, %y

BinaryOperator

Name: %z
Operator: add
Operands: %x, %y

Writing an LLVM Pass

Optimizer Structure



Two Types of Passes

Pass Type	Description
Analysis Pass	❖ Does not modify program ❖ Provides information "out of band" to other passes
Transform (Optimization) Pass	❖ Modifies the program ❖ May call analysis pass methods to get "out of band" information

LLVM IR Pass Types

- ModulePass
- FunctionPass
- BasicBlockPass
- I recommend ignoring “funny” passes
  - LoopPass
  - RegionPass

Rules for LLVM Passes

- Only modify values and instructions at scope of pass
  - ModulePass can modify anything
  - FunctionPass should not modify anything outside of the function
  - BasicBlockPass should not modify anything outside of the basic block

Let's Write a Simple Pass

SecDev.h Example

```
struct SecDev : public ModulePass {
 public:
  // Pass Identifier variable
   static char ID;

   // ModulePass public methods
   SecDev() : ModulePass(ID) {}
   StringRef getPassName() const { return “LLVM Tutorial Pass"; }
   bool runOnModule (Module & M);

 private:
   // Methods for transforming different instructions
   void visitLoadInst  (LoadInst & LI);
   void visitStoreInst (StoreInst & SI);
};
```

runOnModule()

- Entry point for ModulePass
- Receives a reference to the Module as input
- Can locate functions, basic blocks, globals from Module
- Return true if the pass modifies the program
  - An analysis pass ***always*** returns ***false***.
  - A transform pass can return either ***true*** or ***false***.

SecDev.cpp Example

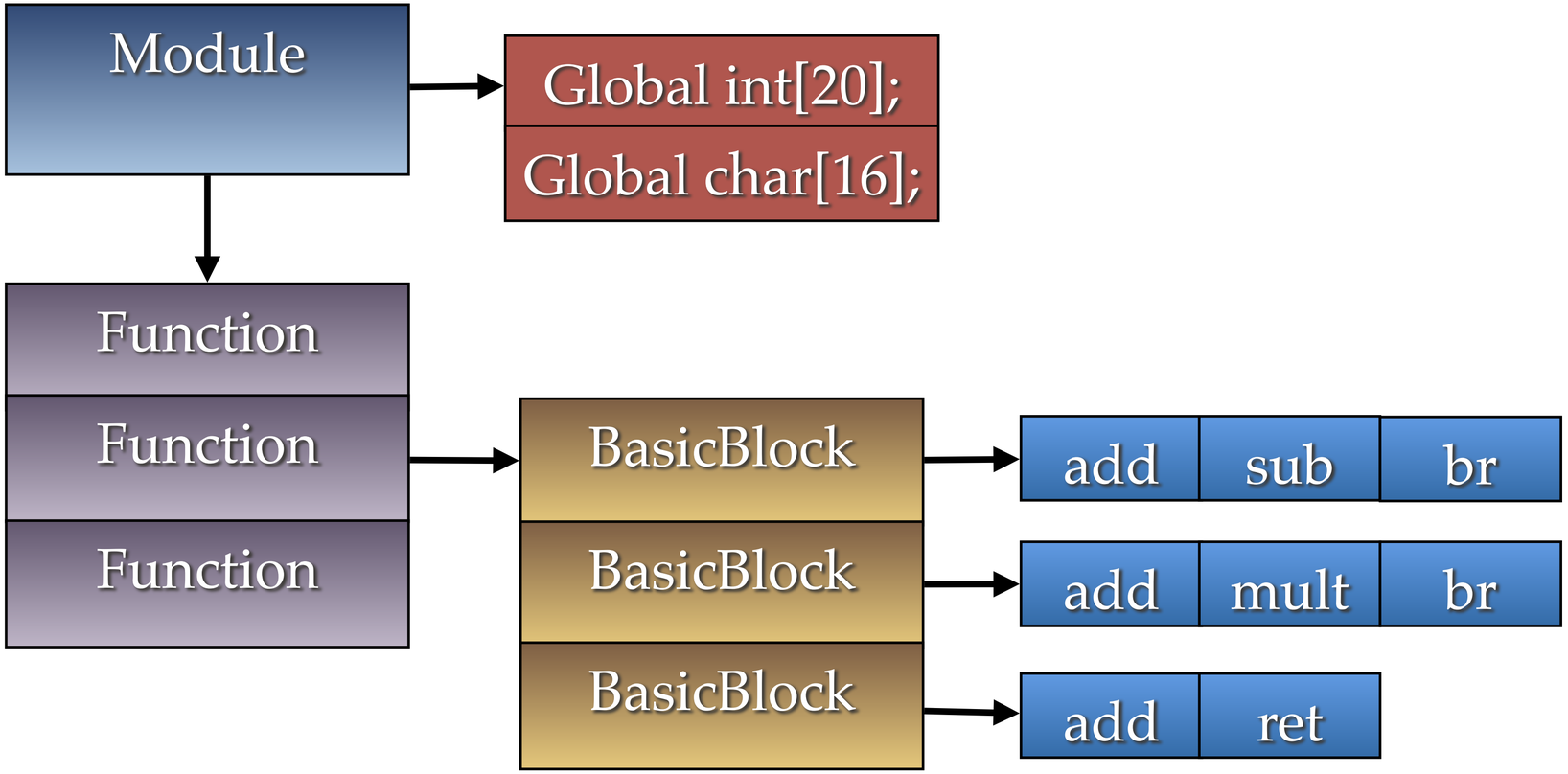
```
static RegisterPass<SecDev> P (“secdev”, “LLVM Tutorial Pass”);

bool
SecDev::runOnModule (Module & M) {
 return true;
}
```

In-Memory LLVM IR

LLVM Classes

- There is a class for each type of IR object
  - Module class
  - Function class
  - BasicBlock class
  - Instruction class
- Classes provide iterators for objects within them

LLVM In-Memory IR



Class Iterators

- Each class provides iterators for items it contains
  - Module::iterator iterates over functions
  - Function::iterator iterates over basic blocks
  - BasicBlock::iterator iterates over instructions

Iterator Example

```
//
// Iterate over all instructions within a BasicBlock
//
BasicBlock * BB = …;
BasicBlock::iterator it;
BasicBlock::iterator ie;

for (it = BB->begin(), ie = BB->end(); it != ie; ++it) {
 Instruction * I = &*it;
};
```

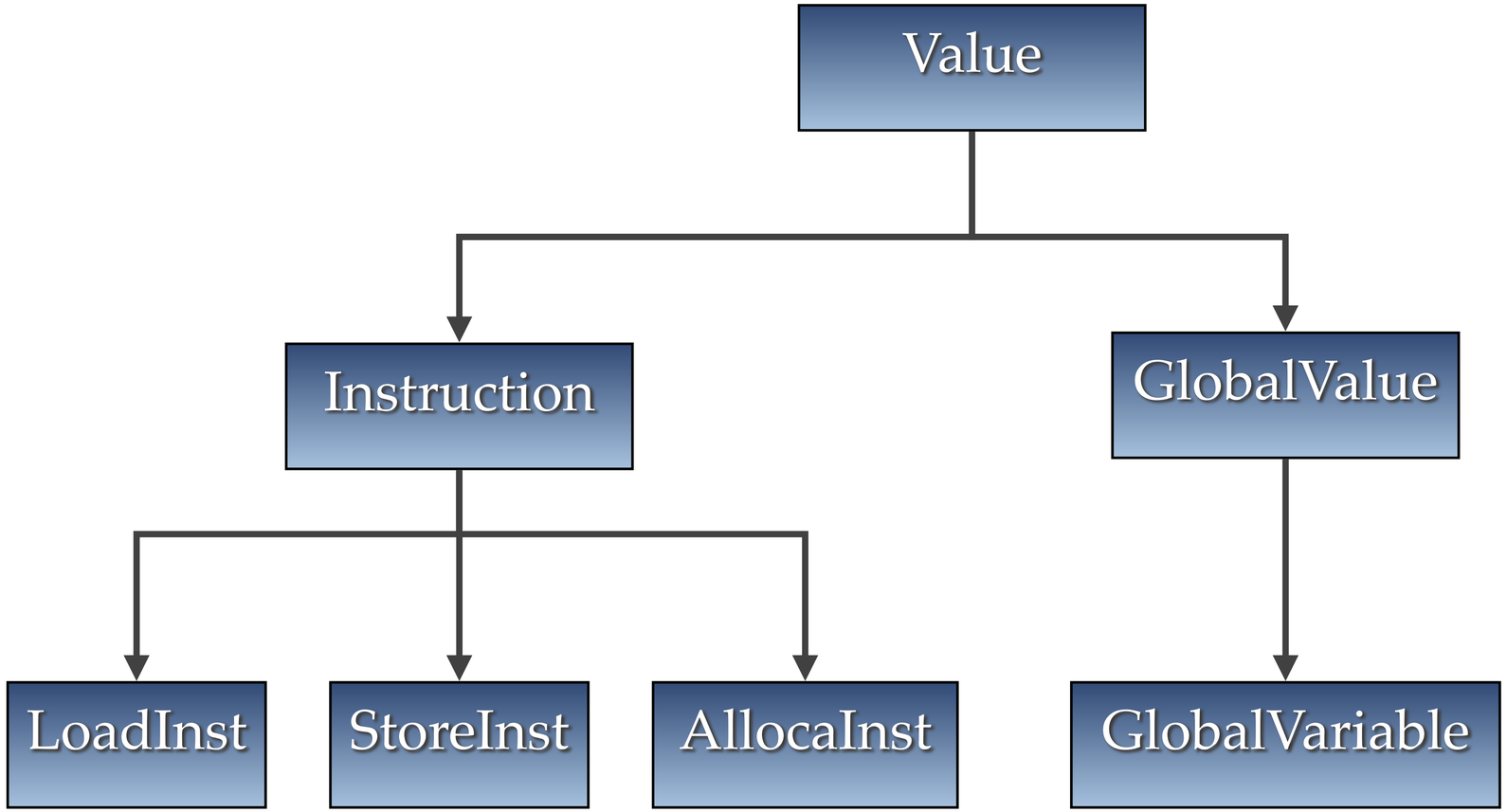
SecDev.cpp Example

```
static RegisterPass<SecDev> P (“secdev”, “LLVM Tutorial Pass”);

bool
SecDev::runOnModule (Module & M) {
 //
 // Iterate over all instructions within a Module
 //
 for (Module::iterator fi = M.begin(); fi != M.end(); ++fi) {
  for (Function::iterator bi = fi->begin(); bi != fi->end(); ++bi) {
   for (BasicBlock::iterator it = bi->begin(); it != bi->end; ++it) {
    Instruction * I = &*it;
   }
  }
 }

 return true;
}
```

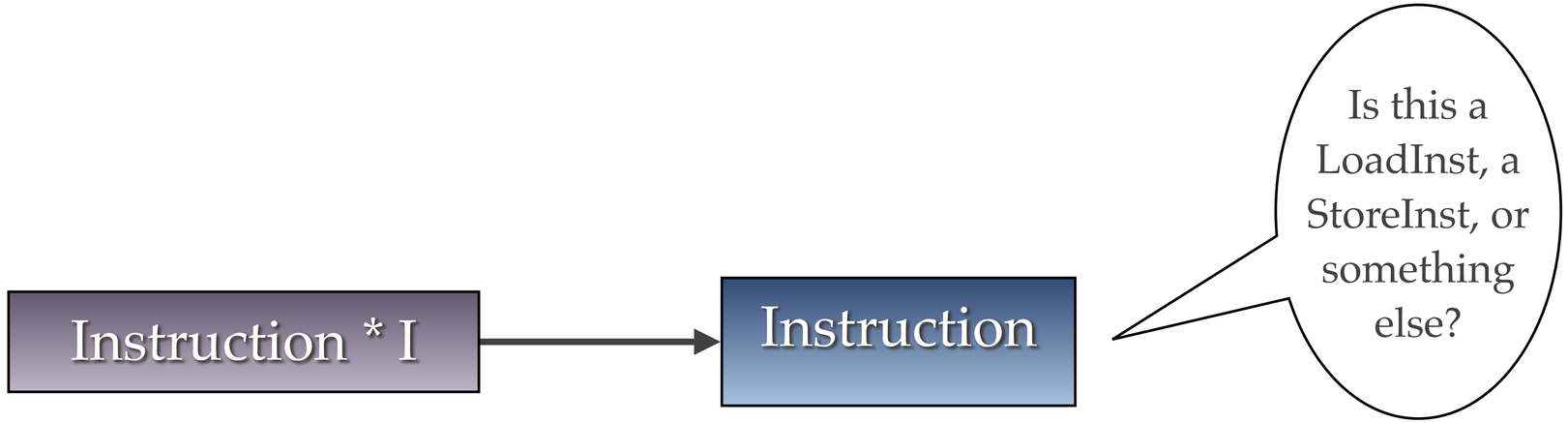
LLVM Class Hierarchy

- Anything that is an SSA value is a subclass of *Value*
- All Instruction classes are a subclass of *Instruction*
- Similar instructions share a common superclass

Simplified LLVM Class Hierarchy



Common Problem in Passes



Casting to Subclass in LLVM

Casting Function	Description	Example
isa<Class>()	Return true or false if value is of that class.	isa<BranchInst>(I)
dyn_cast<Class>()	Returns pointer to object of type Class or NULL	dyn_cast<BranchInst>(I)

Locating Store Instructions

```
//
// Iterate over all instructions within a BasicBlock
//
BasicBlock::iterator it;
BasicBlock::iterator ie;

for (it = BB->begin(), end = BB->end(); it != end; ++it) {
 Instruction * I = *it;

 if (StoreInst * SI = dyn_cast<StoreInst>(I)) {
  // Do something with store instruction SI
  visitStoreInst(SI);
 }
}
```

Let's Add a Run-time Check

Instrumenting Store Instructions

```
void SecDev::visitStoreInst (StoreInst * SI) {
 //
 // Retrieve the pointer operand from the store instruction.
 //
 Value * Pointer = SI->getPointerOperand();

 //
 // Cast the pointer argument of the store instruction to our void pointer
 // type.
 //
 LLVMContext & C = SI->getContext();
 Pointer = new BitCastInst(Pointer, getVoidPtrType(C), Pointer->getName(), SI);

 //
 // Insert a call instruction to the check memory function before the store
 // instruction.
 //

 CallInst::Create(checkMemory, ArrayRef<Value *>(Pointer), “”, SI);
}
```

Try Some Test Programs

```
$ cd run
$ ./global
$ ./int-sum
```

Watch calls to checkMemory() print out pointers used in loads and stores!

Can we optimize away unnecessary checks?

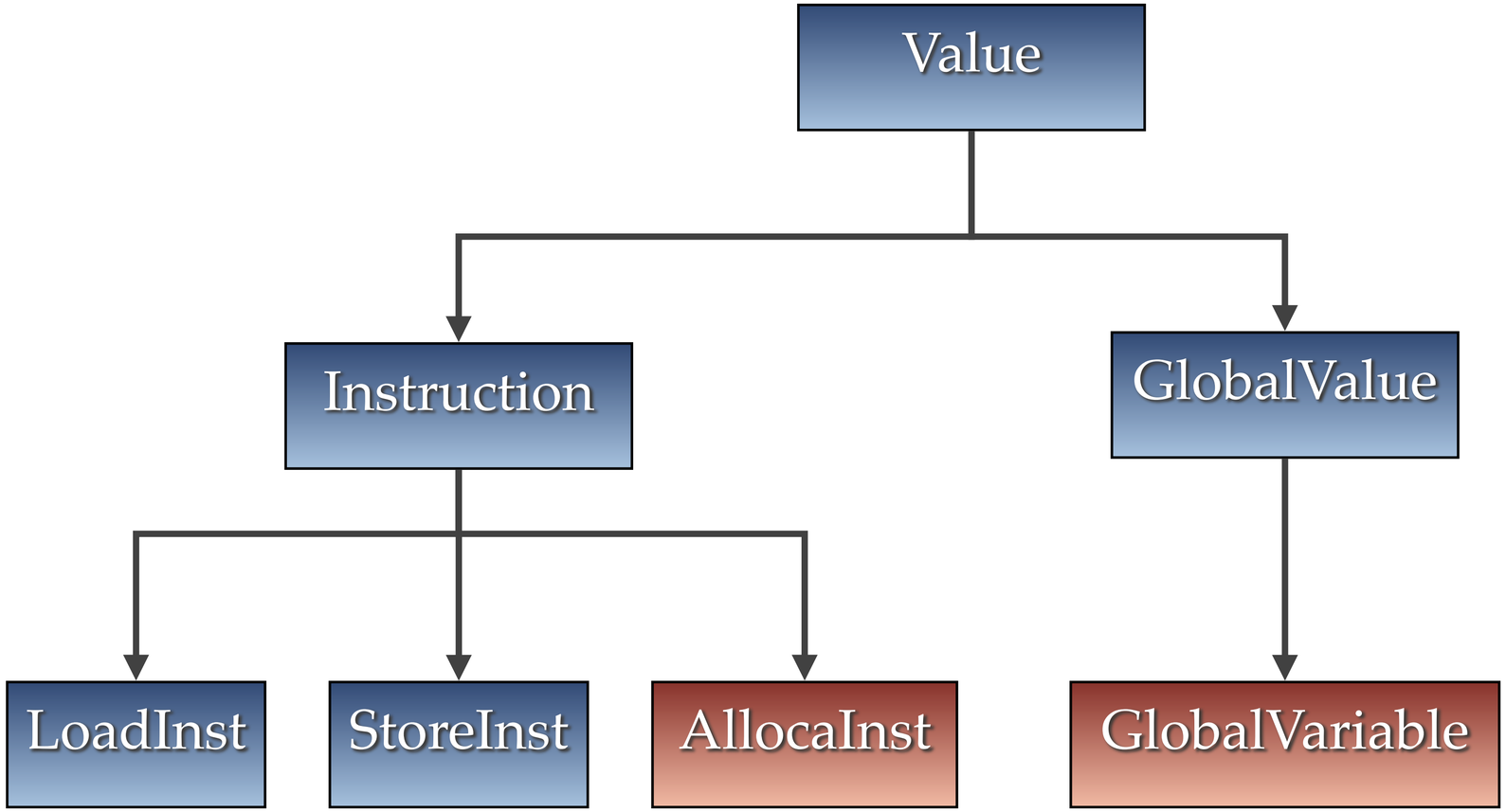
Conditions for Optimizing Store Instruction

- Pointer points to global variable
- Pointer points to result of an alloca
  - In other words, pointer points to stack-allocated memory

Instrumenting Store Instructions

```
void SecDev::visitStoreInst (StoreInst * SI) {
  //
  // Retrieve the pointer operand from the store instruction.
  //
  Value * Pointer = SI->getPointerOperand();

  //
  // If the pointer points to a global variable or to stack-allocated
  // memory, forego adding the run-time check.
  //
  if (…) {
    return;
  }

  //
  // Cast the pointer argument of the store instruction to our void pointer
  // type.
  //
  LLVMContext & C = SI->getContext();
  Pointer = new BitCastInst(Pointer, getVoidPtrType(C), Pointer->getName(), SI);

  //
  // Insert a call instruction to the check memory function before the store
  // instruction.
  //
  CallInst::Create(checkMemory, ArrayRef<Value *>(Pointer), “”, SI);
}
```

Let's Look at Class Hierarchy



Instrumenting Store Instructions

```
void SecDev::visitStoreInst (StoreInst * SI) {
  //
  // Retrieve the pointer operand from the store instruction.
  //
  Value * Pointer = SI->getPointerOperand();

  //
  // If the pointer points to a global variable or to stack-allocated
  // memory, forego adding the run-time check.
  //
  if (isa<GlobalVariable>(Pointer) || isa<AllocaInst>(Pointer)) {
    return;
  }

  //
  // Cast the pointer argument of the store instruction to our void pointer
  // type.
  //
  LLVMContext & C = SI->getContext();
  Pointer = new BitCastInst(Pointer, getVoidPtrType(C), Pointer->getName(), SI);

  //
  // Insert a call instruction to the check memory function before the store
  // instruction.
  //
  CallInst::Create(checkMemory, ArrayRef<Value *>(Pointer), “”, SI);
}
```

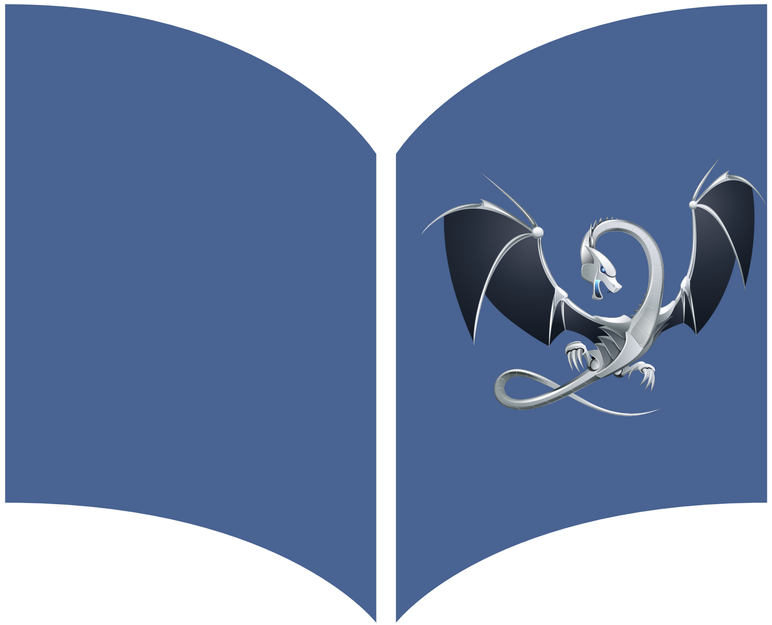
Beyond the Tutorial

Data Flow Analysis

- Books
  - *Compilers: Principles, Techniques, and Tools*
    - Aka "The Dragon Book"
  - *Principles of Program Analysis*
- Papers
  - Papers on SSA-based algorithms
  - Kam-Ullman paper on iterative data-flow analysis

Helpful Documents

- LLVM Language Reference Manual
- LLVM Programmer's Manual
- How to Write an LLVM Pass
- Online LLVM Doxygen pages



We'd love to hear your feedback!

https://forms.gle/u8i6rRQgP1dR1rwe7