Analysing Native Code

Applied Static Analysis 2016

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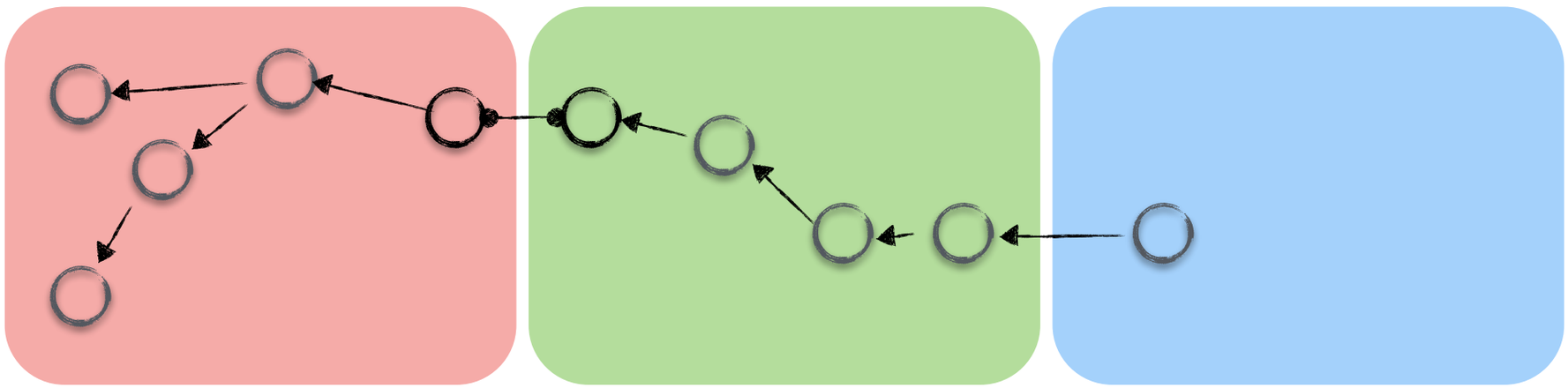
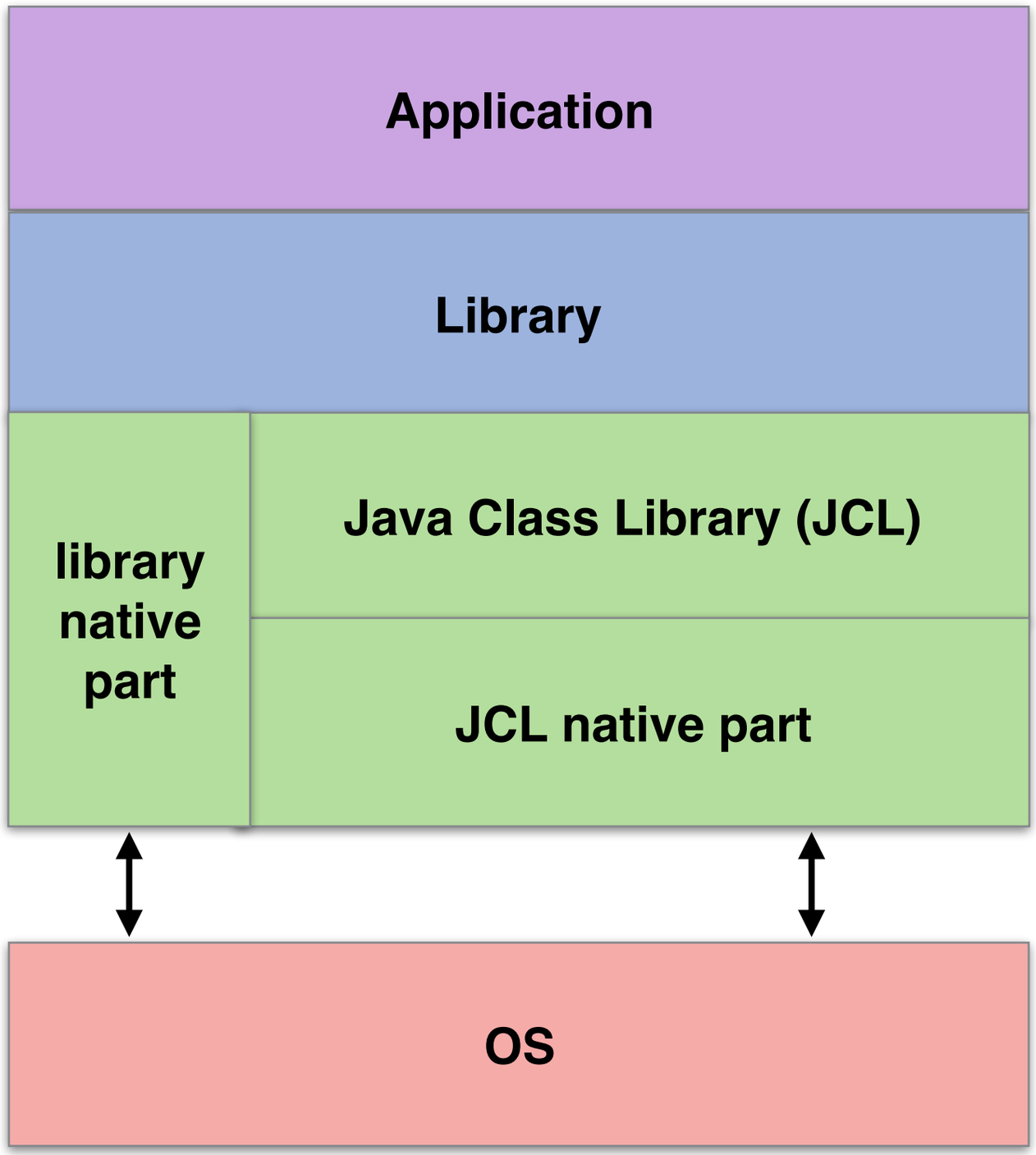
— printable version —



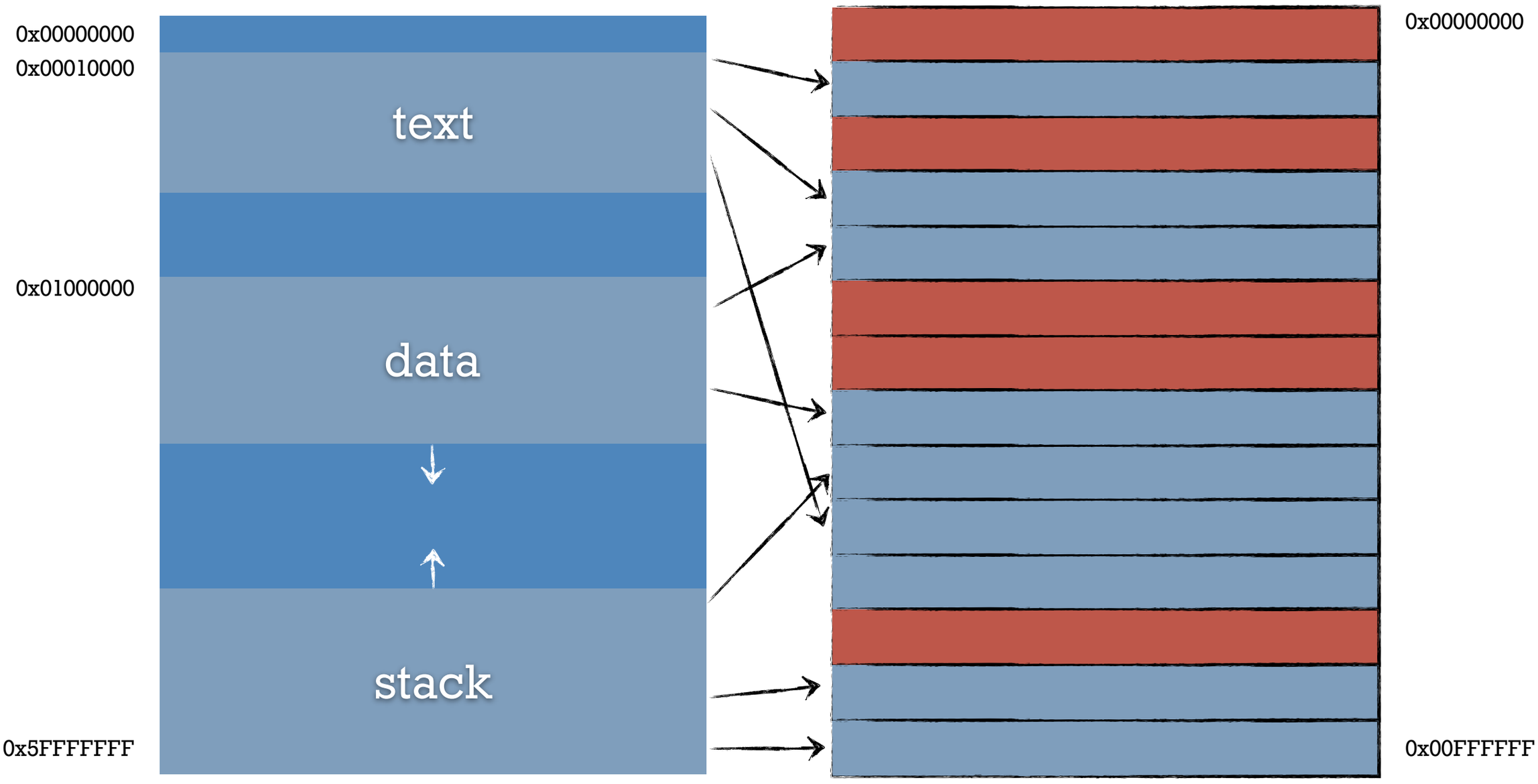
JCL
Native Code

JCL Code

User Code


Application
Library
library native part
Java Class Library (JCL)
JCL native part
OS

Process isolation & virtual memory

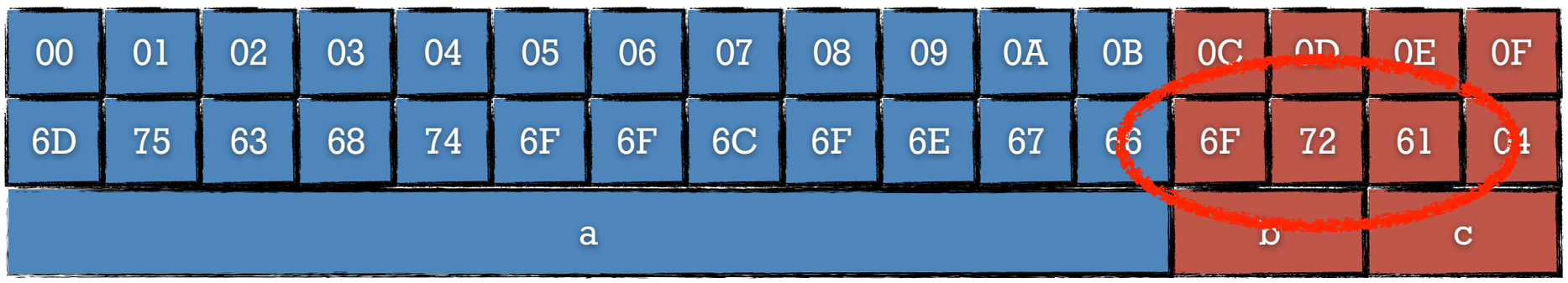


Buffer overflows

```
char a[12];
unsigned int b = 8;
unsigned int c = 4;


strcpy(a, “test”);
```

```
strcpy(a, “muchtoolongfora”);
```



Please all stand up for a moment

Sit down, when the following is true for you:

I've never used a console

I don't know what C and C++ are

I have never read any C or C++ code

I have never written any C or C++ code

I hate writing code in C or C++

Why is this different?

- Direct memory access
- Pointer arithmetic
- All kinds of unsafe programming
- C code might behave differently on different machines

Why should I care?

- Because your Java program calls into native.
- You use native code all the time … and you want to in order to have any effect on the outside world other than using energy and heating up the planet.
- Also other people do that for you
  - > 70% of the JCL methods do that
  - Many libraries use `sun.misc.Unsafe`

sun.misc.What?!

```
package sun.misc
public final class Unsafe


public native long allocateMemory(long bytes)

public void copyMemory(long srcAddress,
                       long destAddress,
                       long bytes)

public native int getInt(long address)
```

Is this used?

- Oh yes it is…
- 3% of the top 1,000 maven artifacts directly
- 47% of them use it transitively

```
// crashing your JVM in one line
unsafe.freeMemory(1);
```

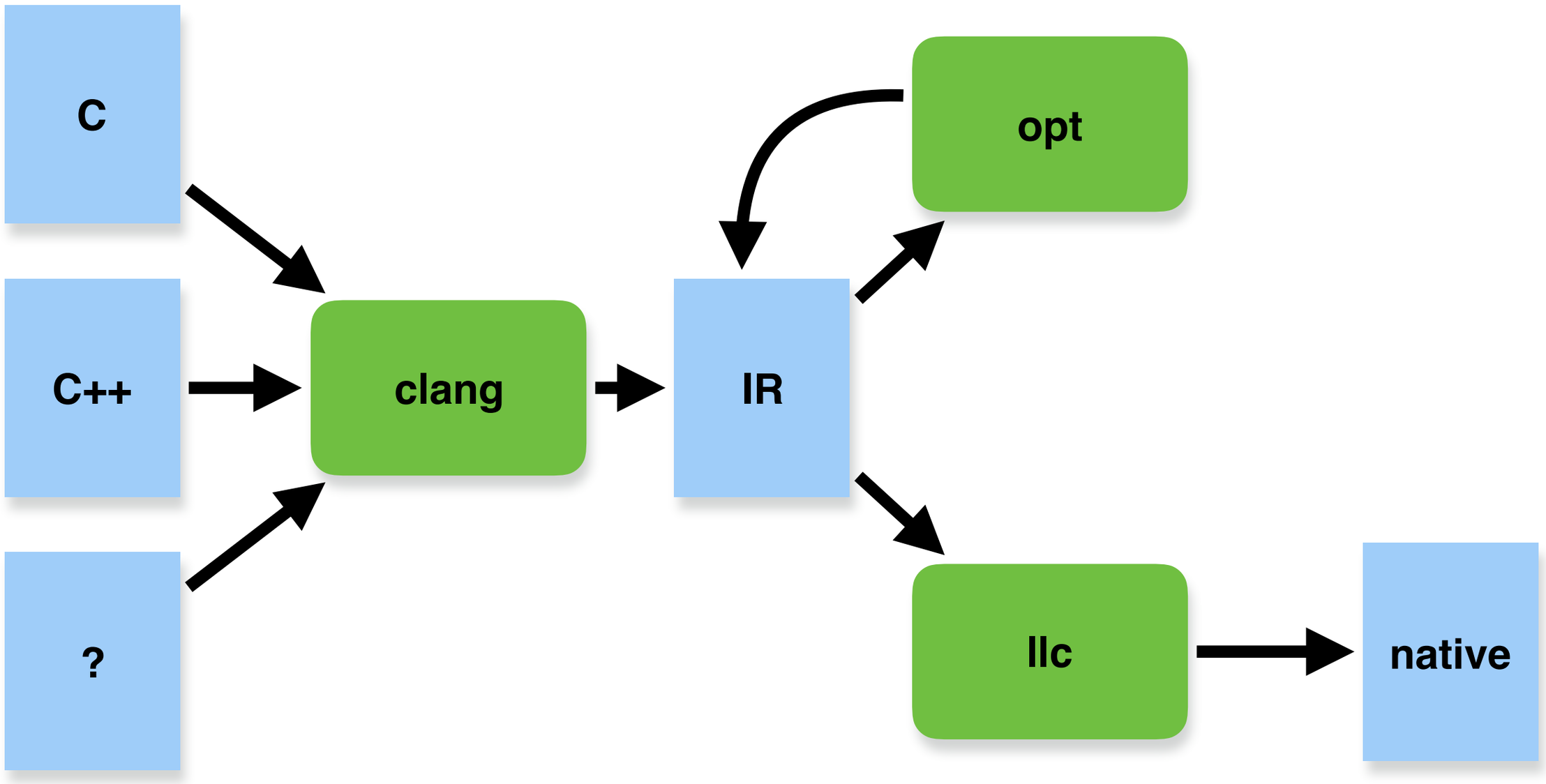
Luis Mastrangelo, Luca Ponzanelli, Andrea Mocci, Michele Lanza, Matthias Hauswirth, and Nathaniel Nystrom. 2015. **Use at your own risk: the Java unsafe API in the wild**. In Proceedings of the 2015 ACM SIGPLAN International Conference on Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA 2015)

So… yes you should care about the native layer when analyzing Java code

LLVM

- Compiler Infrastructure
- Lightweight
- Modular
- Reusable
- SSA-based

LLVM Components



Preparing for this Lecture

- Lose any fear towards a UNIX console NOW
- Install LLVM on your machine

```
wget http://llvm.org/releases/3.8.0/llvm-3.8.0.src.tar.xz
tar xvfz llvm-3.8.0.src.tar.xz
cd llvm-3.8.0.src
cp Makefile.config.in Makefile.config
mkdir build
cd build
cmake -g “Unix Makefiles” ../
make
```

It should also work with Ninja, Visual Studio, or XCode
— I use `make` here —

- Get a coffee…. Or maybe five.

exercise 6.1a

Preparing for this Lecture

- Now we've got LLVM, but we will also need **`clang`**

```
wget http://llvm.org/releases/3.8.0/cfe-3.8.0.src.tar.xz
tar xfz cfe-3.8.0.src.tar.xz
cd cfe-3.8.0.src
cmake -g "Unix Makefiles" ../llvm-3.8.0.src
make
```

- Get a coffee…. Or tea… there's always tea

exercise 6.1a

Or use our Docker Container

```
docker run --rm -ti bhermann/llvm
```

- Time for coffee depends on your download speed
- Doing this right now will probably not work given the classroom's bandwidth

exercise 6.1b

Working with the container

Stay updated

```
docker pull bhermann/llvm
```

Having something persistent

```
docker run -ti -v /your/path:/home/llvm/workspace bhermann/llvm
```

Factorial Example

```
int factorial (int n) {
   int r = 1;
   while (n > 0) {
      r *= n;
      n--;
   }
   return r;
}
```

PC	Instruction
0	
1	
2	goto →12
5	
6	
7	
8	
9	
12	iload_0
13	ifgt →5
16	
17	

LLVM Representation

```
; ModuleID = 'factorial.c'
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_

; Function Attrs: nou
define i32 @factorial
  %1 = alloca i32, al
  %r = alloca i32, al
  store i32 %n, i32*
  store i32 1, i32* %
  br label %2

; <label>:2                                         ; preds = %5, %0
  %3 = load i32* %1, align 4
  %4 = icmp sgt i32 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                                         ; preds = %2
  %6 = load i32* %1, align 4
  %7 = load i32* %r, align 4
  %8 = mul nsw i32 %7, %6
  store i32 %8, i32* %r, align 4
```

Data Layout (dash separated)
little-endian
ELF mangling
64-bit integers
80 to 128-bit floats
native CPU integers are 8, 16, 32, and 64 -bit
Stack alignment is 128-bits

LLVM Representation

```
; ModuleID = 'factorial.c'
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"

; Function Attrs
define i32 @fact
  %1 = alloca i3
  %r = alloca i3
  store i32 %n,
  store i32 1, i
  br label %2

; <label>:2                                         ; preds = %5, %0
  %3 = load i32* %1, align 4
  %4 = icmp sgt i32 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                                         ; preds = %2
  %6 = load i32* %1, align 4
  %7 = load i32* %r, align 4
  %8 = mul nsw i32 %7, %6
```

Target Triple (dash separated)
Architecture (e.g., x86_64, ARM, PowerPC)
Vendor (e.g., pc, apple)
Operating System (e.g., linux, macosx10.7.0)
Environment (e.g., gnu)

LLVM Representation

```
; ModuleID = 'factorial.c'
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"

; Function Attrs: nounwind uwtable
define i32 @factorial(i32 %n) #0 {
  %1 = alloca i32, align 4
  %r = alloca i32, align 4
  store i32 %n, i32* %1, align 4
  store i32 1, i32* %r, align 4
  br label %2

; <label>:2                                       ; preds = %5, %0
  %3 = load i32* %1, align 4
  %4 = icmp sgt i32 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                                       ; preds = %2
  %6 = load i32* %1, align 4
  %7 = load i32* %r, align 4
  %8 = mul nsw i32 %7, %6
```

Function Definition
Return type (here: i32 —> 32-bit Integer)
Function name (@-prefixed —> global identifier)
Argument list (%-prefixed —> local identifier)
Attribute reference

Down to Machine Code

```
    .text
    .file  "factorial.c"
    .globl factorial
    .align 16, 0x90
    .type  factorial,@function
factorial:                              # @factorial
    .cfi_startproc
# BB#0:
    pushq  %rbp
.Ltmp0:
    .cfi_def_cfa_offset 16
.Ltmp1:
    .cfi_offset %rbp, -16
    movq   %rsp, %rbp
.Ltmp2:
    .cfi_def_cfa_register %rbp
    movl   %edi, -4(%rbp)
    movl   $1, -8(%rbp)
.LBB0_1:                                # =>This Inner Loop Header: Depth=1
    cmpl   $0, -4(%rbp)
    jle .LBB0_3
# BB#2:                                 #   in Loop: Header=BB0_1 Depth=1
```

Exercises & Examples

- In our course Git repository, `llvm` directory
- `examples` contains all examples discussed here
- `exercises` contains all exercises
- `workspace` can be used as your personal area
- And if you have the Docker container you already have them in your home directory
- Please perform all commands following and inspect the output closely

Basic Tooling

- Familiarize yourself with the tooling

```
clang -S -emit-llvm factorial.c -o -
```

Output to stdout

Only run preprocess and compilation steps (outputs human readable format)

Use LLVM IR

Input file

```
clang -cc1 -ast-dump factorial.c
```

Use only compiler front-end

Dump the complete AST on the console

exercise 6.2

Abstract Syntax Tree

```
TranslationUnitDecl 0x2f3d6f0 <<invalid sloc>> <invalid sloc>
|-TypedefDecl 0x2f3dbf0 <<invalid sloc>> <invalid sloc> implicit __int128_t '__int128'
|-TypedefDecl 0x2f3dc50 <<invalid sloc>> <invalid sloc> implicit __uint128_t 'unsigned __int128'
|-TypedefDecl 0x2f3dfa0 <<invalid sloc>> <invalid sloc> implicit __builtin_va_list '__va_list_tag [1]'
`-FunctionDecl 0x2f3e0c0 <factorial.c:1:1, line:8:1> line:1:5 factorial 'int (int)'
  |-ParmVarDecl 0x2f3e000 <col:16, col:20> col:20 used n 'int'
  `-CompoundStmt 0x2f7dfa0 <col:23, line:8:1>
    |-DeclStmt 0x2f3e1f8 <line:2:2, col:11>
    | `-VarDecl 0x2f3e180 <col:2, col:10> col:6 used r 'int' cinit
    |   `-IntegerLiteral 0x2f3e1d8 <col:10> 'int' 1
    |-WhileStmt 0x2f3e3a8 <line:3:2, line:6:2>
    | |-<<<NULL>>>
    | |-BinaryOperator 0x2f3e270 <line:3:9, col:13> 'int' '>'
    | | |-ImplicitCastExpr 0x2f3e258 <col:9> 'int' <LValueToRValue>
    | | | `-DeclRefExpr 0x2f3e210 <col:9> 'int' lvalue ParmVar 0x2f3e000 'n' 'int'
    | | `-IntegerLiteral 0x2f3e238 <col:13> 'int' 0
    | `-CompoundStmt 0x2f3e380 <col:16, line:6:2>
    |   |-CompoundAssignOperator 0x2f3e300 <line:4:3, col:8> 'int' '*=' ComputeLHSTy='int'
ComputeResultTy='int'
    |   | |-DeclRefExpr 0x2f3e298 <col:3> 'int' lvalue Var 0x2f3e180 'r' 'int'
    |   | `-ImplicitCastExpr 0x2f3e2e8 <col:8> 'int' <LValueToRValue>
    |   |   `-DeclRefExpr 0x2f3e2c0 <col:8> 'int' lvalue ParmVar 0x2f3e000 'n' 'int'
    |   `-UnaryOperator 0x2f3e360 <line:5:3, col:4> 'int' postfix '--'
    |     `-DeclRefExpr 0x2f3e338 <col:3> 'int' lvalue ParmVar 0x2f3e000 'n' 'int'
    `-ReturnStmt 0x2f3e410 <line:7:2, col:9>
      `-ImplicitCastExpr 0x2f3e3f8 <col:9> 'int' <LValueToRValue>
        `-DeclRefExpr 0x2f3e3d0 <col:9> 'int' lvalue Var 0x2f3e180 'r' 'int'
```

Abstract Syntax Tree

```
TranslationUnitDecl 0x2f3d6f0 <<invalid sloc>> <invalid sloc>
|-TypedefDecl 0x2f3dbf0 <<invalid sloc>> <invalid sloc> implicit __int128_t '__int128'
|-TypedefDecl 0x2f3dc50 <<invalid sloc>> <invalid sloc> implicit __uint128_t 'unsigned __int128'
|-TypedefDecl 0x2f3dfa0 <<invalid sloc>> <invalid sloc> implicit __builtin_va_list '__va_list_tag [1]'
`-FunctionDecl 0x2f3e0c0 <factorial.c:1:1, line:8:1> line:1:5 factorial 'int (int)'
  |-ParmVarDecl 0x2f3e000 <col:16, col:20> col:20 used n 'int'
  `-CompoundStmt 0x2f7dfa0 <col:23, line:8:1>
    |-DeclStmt 0x2f3e1f8 <line:2:2, col:11>
    | `-
    |
    |-Wh
    | |-
    | |-
    | |
    | |
    | |
    | `-
    |
ComputeR
    |
    |    | `-ImplicitCastExpr 0x2f3e2e8 <col:8> 'int' <LValueToRValue>
    |    |   `-DeclRefExpr 0x2f3e2c0 <col:8> 'int' lvalue ParmVar 0x2f3e000 'n' 'int'
    |    `-UnaryOperator 0x2f3e360 <line:5:3, col:4> 'int' postfix '--'
    |      `-DeclRefExpr 0x2f3e338 <col:3> 'int' lvalue ParmVar 0x2f3e000 'n' 'int'
    `-ReturnStmt 0x2f3e410 <line:7:2, col:9>
      `-ImplicitCastExpr 0x2f3e3f8 <col:9> 'int' <LValueToRValue>
        `-DeclRefExpr 0x2f3e3d0 <col:9> 'int' lvalue Var 0x2f3e180 'r' 'int'
```

We could also analyze code on this level, but we won't be doing this in this lecture

Basic Tooling

- Optimizing

```
clang -c -emit-llvm factorial.c
opt -O1 -o factorial-o1.bc factorial.bc
llvm-dis factorial.bc
llvm-dis factorial-o1.bc
```

Compile to LLVM IR

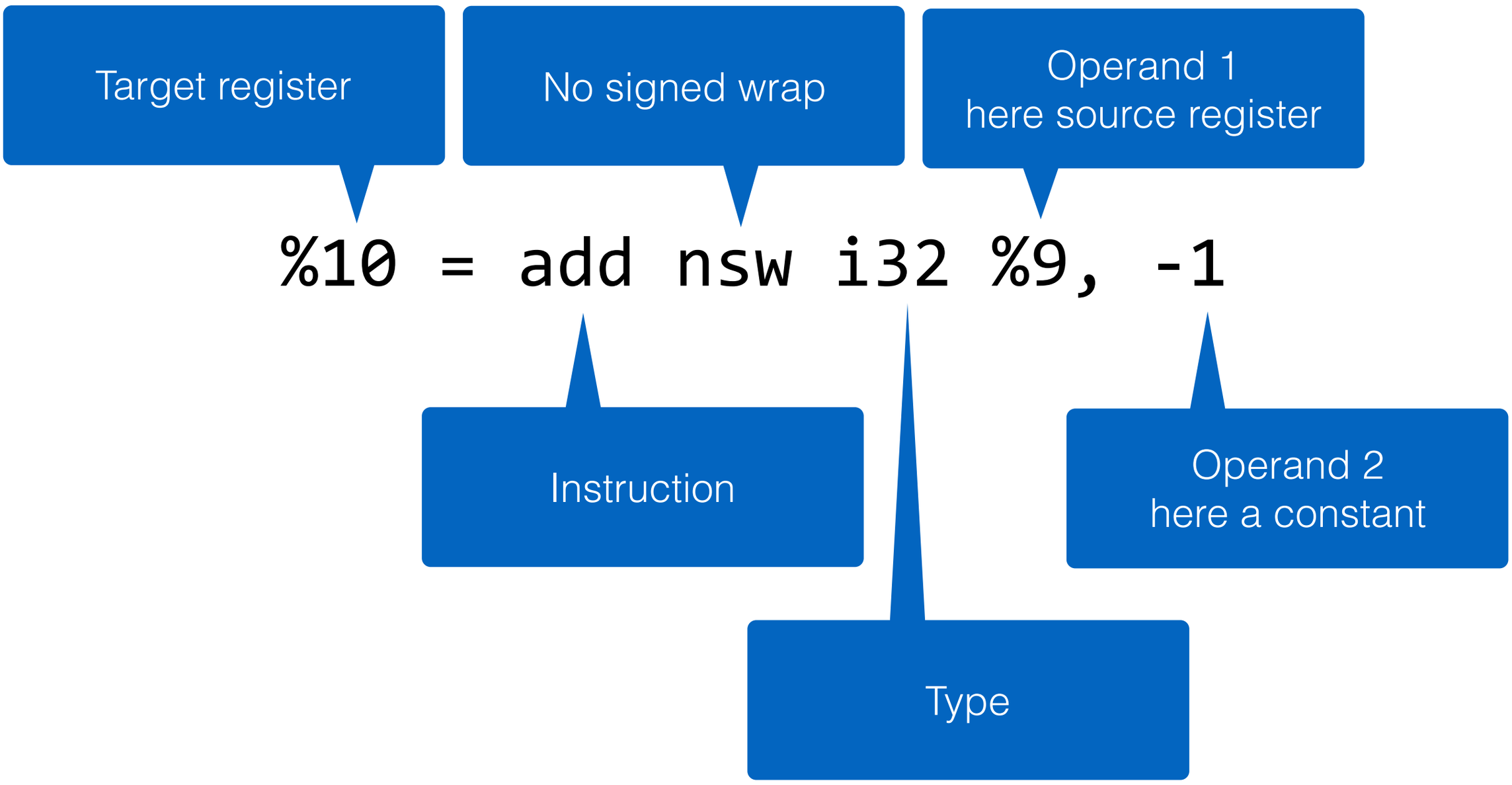
Optimize Bitcode

Disassemble to human readable form

- Compare `factorial.ll` and `factorial-o1.ll`
- Optimized version is shorter and contains `phi` instructions
- Continue for `-O2` and `-O3`

exercise 6.3

Instructions in LLVM IR



LLVM IR

- RISC-like instruction set, but
- Strongly typed — every instruction has typed arguments
- Explicit control flow
- Explicit data flow (Static Single Assignment form)

Why should we include type information in assembly languages?

Let’s compare

- IA-64 xor

```
xor r1 = r2, r3
```

- What guarantees do we have for this operation?

- LLVM IR xor

```
%r = xor i32 %v1, %v2
```

Operands are 32-bit integers

Result in a 32-bit integer

- What guarantees do we have for this operation?

Typed Assembly Languages

- Do you know more typed assembly languages?

e.g., Java Bytecode

Greg Morrisett, David Walker, Karl Crary, and Neal Glew. **From system f to typed assembly language**. ACM Trans. Program. Lang. Syst., 21(3):527– 568, May 1999

Greg Morrisett, Karl Crary, Neal Glew, Dan Grossman, Richard Samuels, Frederick Smith, David Walker, Stephanie Weirich, and Steve Zdancewic. **TALx86: A realistic typed assembly language**. In In Second Workshop on Compiler Support for System Software, pages 25–35, 1999

Writing Analysis Passes

LLVM is its own ecosystem

- LLVM comes with many classes that are useful when writing analyses and transforms

- Error handling

- Data structures

- Analysis/Transform API

- Always a good read: http://llvm.org/docs/ProgrammersManual.html

Passes in LLVM

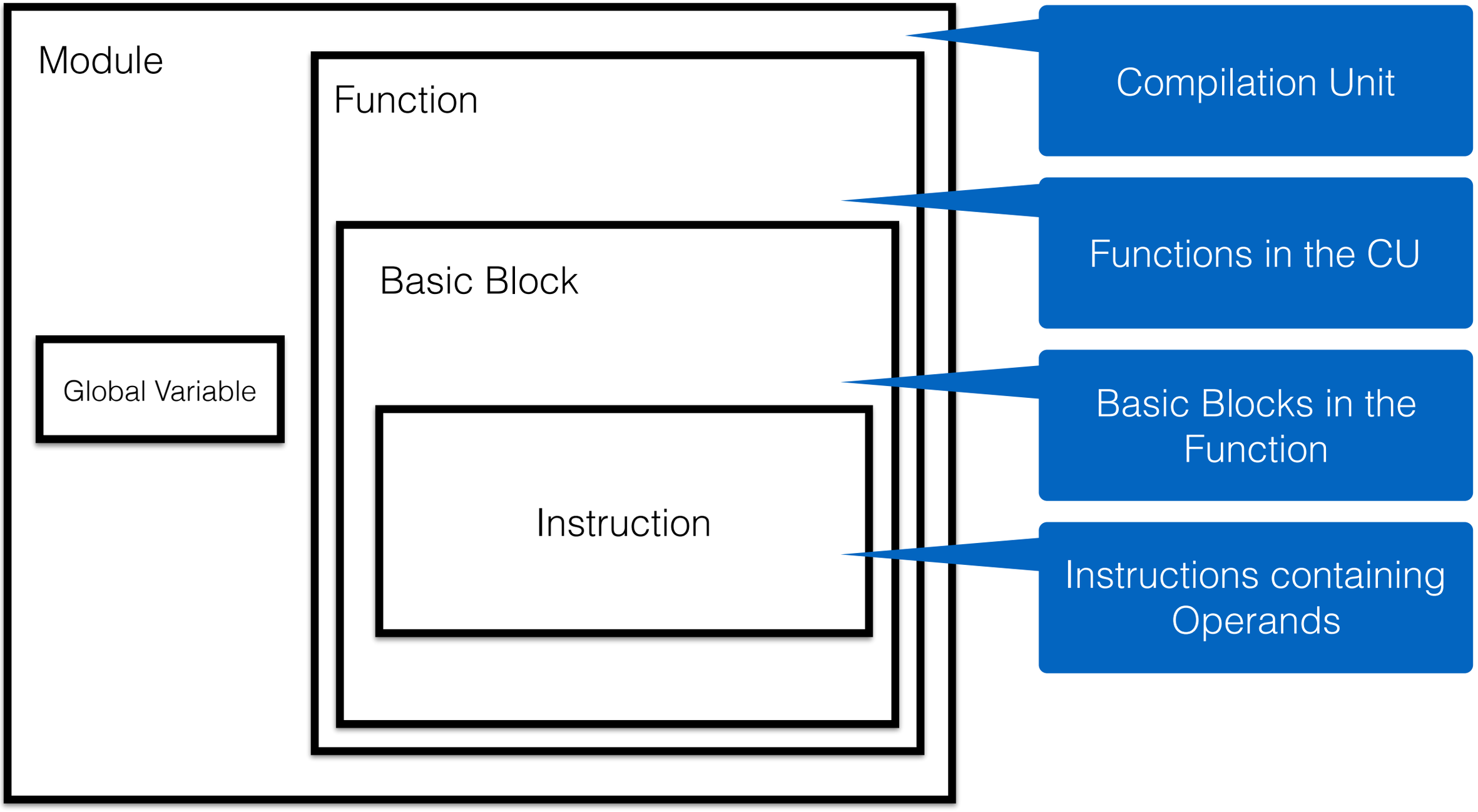
- During runtime LLVM applies a sequence of analyses and transformations on the target program to achieve a desired result

- These analyses and transformations are called passes

- Machine independent passes are invoked using `opt`

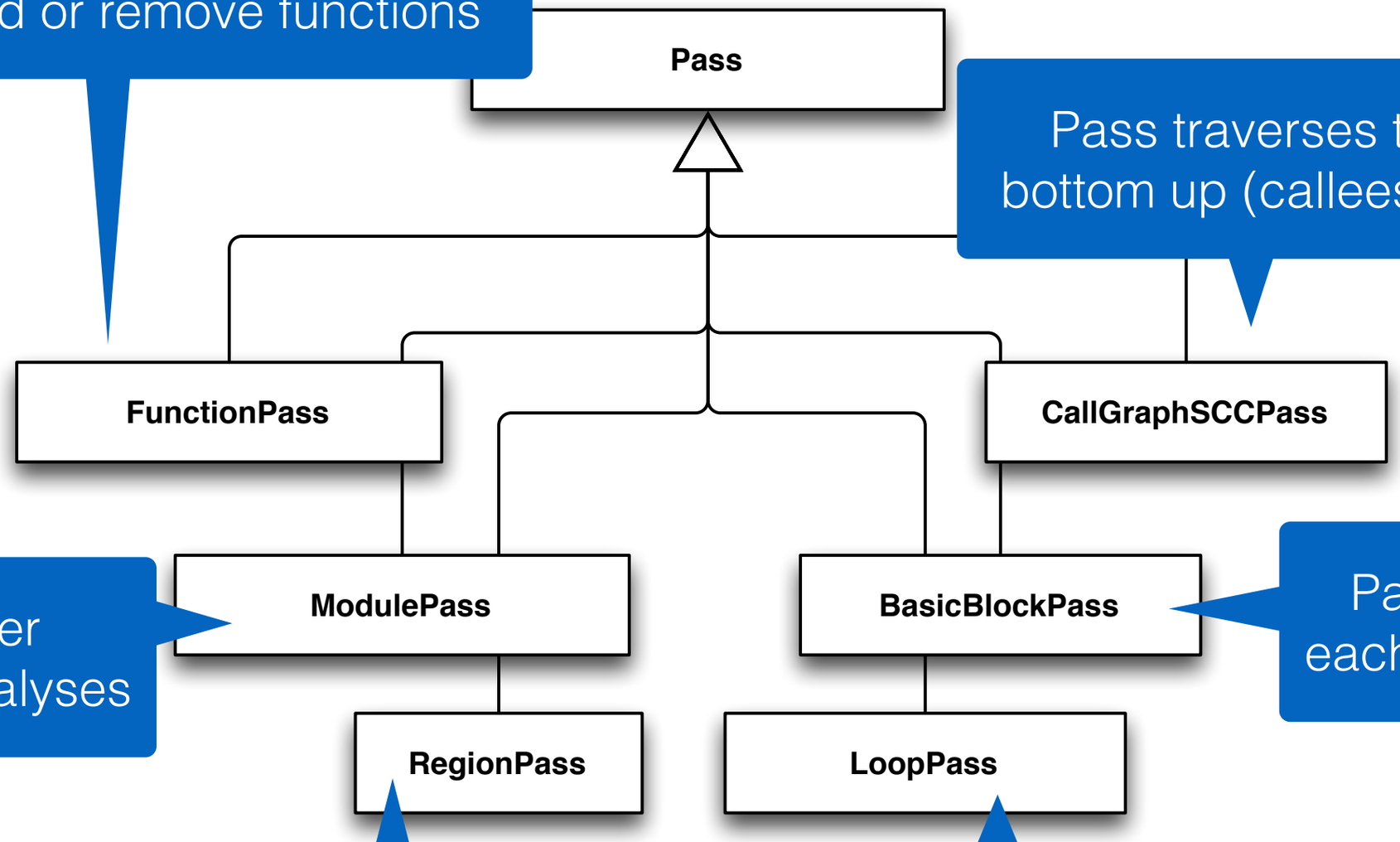
- Machine dependent passes are invoked using `llc`

Scopes in the Language



Scopes for Analyses

Function scope
May not add or remove functions



Pass traverses the call graph bottom up (callees before callers)

Use for inter procedural analyses

Pass runs on each basic block

Pass runs on each region in a function

Pass runs on each loop

Setting up your environment

- Compiling the exercises

```
cd exercises
mkdir build
cd build
cmake -g "Unix Makefiles" -DLLVM_DIR=${LLVMSRC_DIR} ..
make
```

Change this if not using our docker container

- Running the first custom analysis pass

```
cd ~/examples
clang -c -emit-llvm test.c
opt-3.8 -load ../exercises/build/FirstPass/libFirstPass.so -help

opt-3.8 -load ../exercises/build/FirstPass/libFirstPass.so
        -FirstPass < test.bc > /dev/null
```

That's an alias in the docker container — use the `opt` you build against —

exercise 6.4

What makes an analysis pass?

```
#include "llvm/Pass.h"
#include "llvm/IR/Function.h"
#include "llvm/Support/raw_ostream.h"

using namespace llvm;

namespace {
    struct FirstPass : public FunctionPass {
    static char ID;
    FirstPass() : FunctionPass(ID) {}

    bool runOnFunction(Function &F) override {
            errs() << "Function recognized: ";
            errs().write_escaped(F.getName());
            errs() << '\n';
            return false;
    }
    };
}

char FirstPass::ID = 0;
static RegisterPass<FirstPass> X("FirstPass", "Function printer pass", false,
false);
```

Include what you need

Use the LLVM namespace

We implement a FunctionPass

The implementation

The registration block

How does that compile?

```
~/exercises/
            CMakeLists.txt
            FirstPass/
                        CMakeLists.txt
                        FirstPass.cpp
```

Binding to LLVM and list of subdirectories to consider

```
cmake_minimum_required(VERSION 2.8)
find_package(LLVM REQUIRED CONFIG)

message(STATUS "Found LLVM ${LLVM_PACKAGE_VERSION}")
message(STATUS "Using LLVMConfig.cmake in: ${LLVM_DIR}")

include_directories(${LLVM_INCLUDE_DIRS})
message(STATUS "Using includes in: ${LLVM_INCLUDE_DIRS}")
add_definitions(${LLVM_DEFINITIONS})
message(STATUS "Using definitions in in: ${LLVM_DEFINITIONS}")
add_definitions("-std=c++11")
set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -fno-rtti -std=c++11")

add_subdirectory(FirstPass)
```

Add your analyses here

How does that compile?

```
~/exercises/
            CMakeLists.txt
            FirstPass/
                        CMakeLists.txt
                        FirstPass.cpp
```

Compilation information for the specific analysis

Analysis implementation

```
cmake_minimum_required(VERSION 2.8)
add_library(FirstPass MODULE FirstPass.cpp)
```

Exercise: Count Instructions

- Goal: Count instructions as a histogram per instruction type
- Scope: Complete code file
- Example: 14 `store` instructions, 14 `load` instructions, 5 `imp` instructions, 4 `br` instructions

exercise 6.5

Instruction Histogram

`exercises/InstructionCount`

- We develop a `ModulePass`

```
struct InstructionCount : public ModulePass
```

- For the histogram we use a LLVM data structure

```
DenseMap<unsigned int, uint64_t> counts;
```

- We iterate over functions, basic blocks, and instructions

```
for(Function &fun : M) {
      for(BasicBlock &bb : fun) {
            for(Instruction &i : bb) {
```

exercise 6.5

Instruction Histogram

`exercises/InstructionCount`

- Let's look at the opcode of the instruction

```
unsigned int currentOpcode = i.getOpcode();
```

- We increment for each opcode

```
auto instCount = counts.find(currentOpcode);
if (counts.end() == instCount) {
  instCount = counts.insert(std::make_pair(currentOpcode,
0)).first;
}
++instCount->second;
```

- After the loops, we print out the histogram information

exercise 6.5

Data-flow Analysis

- Goal: Reconstruct how data flows through a program
- Application
  - Find programming mistakes
  - Find security flaws (confidentiality, integrity)
  - Optimization

Concepts

- For each basic block compute:

$$out_b = trans_b(in_b)$$

$$in_b = join_{p \in pred_b}(out_p)$$

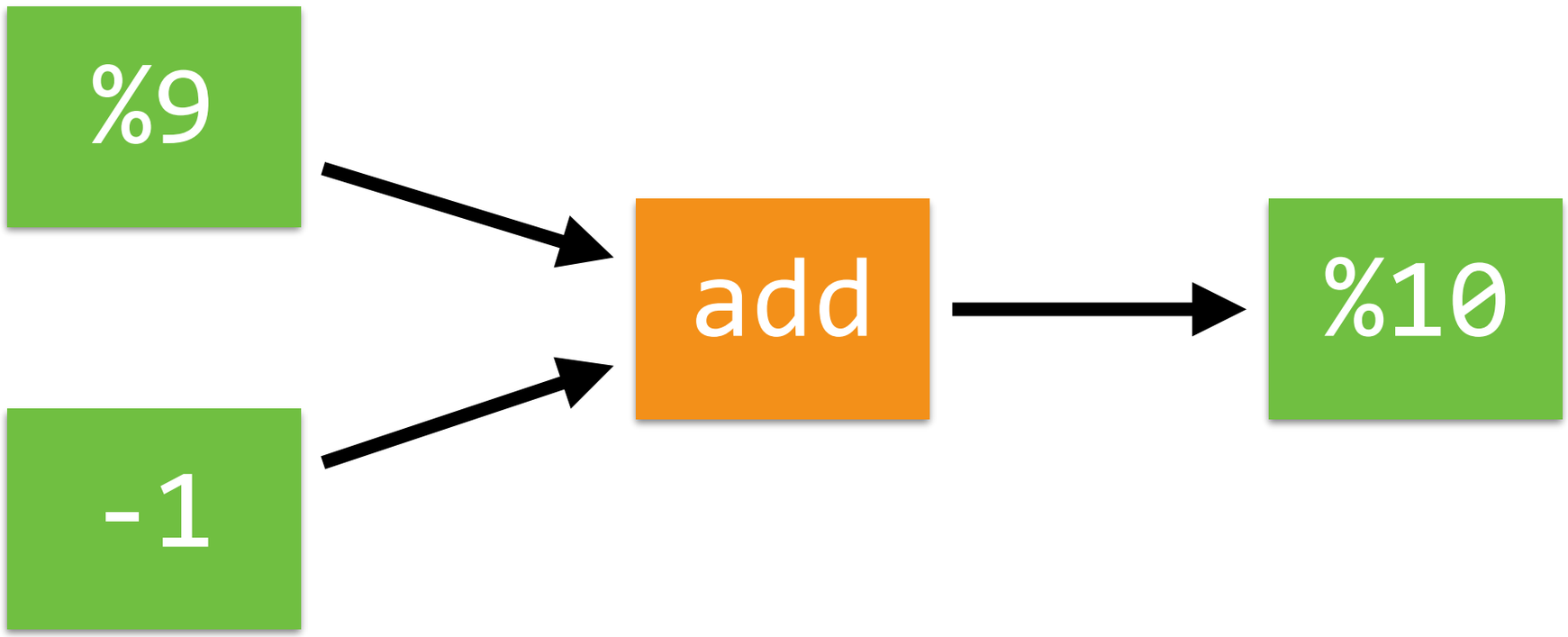
Transfer function

Join over all preceding blocks

- Beware of
  - entry points
  - cycles (i.e., loops)

Transfer functions

```
%10 = add nsw i32 %9, -1
```



Sensitivity

- A data-flow analysis is
  - **flow-sensitive**, if it honors the order of the statements
  - **path-sensitive**, if it honors the conditions applied on a path
  - **context-sensitive**, if an interprocedural analysis honors calling context when processing calls

Exercise: Parameter Flows

- Write an analysis that tracks the flow of parameter values of functions
- Report the flow of the values by printing out the instructions it flows over
- Also print out a string of identifiers that it influences
- Think easy and naive - we will refine that next time

exercise 6.6

Exercise: Parameter Flows

Example

```
$ opt-3.8 -instnamer < ~/examples/fib.bc > fib-named.bc

 define i32 @fib(i32 %n) #0 {
 bb:
   %tmp = alloca i32, align 4
   %tmp1 = alloca i32, align 4
   store i32 %n, i32* %tmp1, align 4
   %tmp2 = load i32, i32* %tmp1, align 4
...


Tracing argument n of function fib
Storing tracked value n in pointer tmp1
Loading tracked pointer tmp1 into value tmp2
...
```

Makes your life easier by naming all local variables

exercise 6.6

Exercises in this Block

exercise 6.1a **exercise 6.1b**	Getting your environment ready 
exercise 6.2	Understanding basic tooling 
exercise 6.3	Understanding optimization 
exercise 6.4	Setting up your build env. 
exercise 6.5	Instruction Histogram Analysis 
exercise 6.6	Parameter Data-flow Analysis