15-411: LLVM

Jan Hoffmann

Substantial portions courtesy of Deby Katz

and Gennady Pekhimenko, Olatunji Ruwase,Chris Lattner, Vikram Adve, and David Koes Carnegie

Advertisements

15-316: Software Foundations of Security and Privacy

Testimonials:

"It's going to be the best course. Ever." -Matt and Jean
"It was so easy." -no one, because the course is new

Website:

http://www.cs.cmu.edu/~15316/

Topics:

- Verification and proof
- Testing
- Privilege separation
- Authentication, identity, and trust
- Confidentiality
- Integrity
- Policy models
- Information flow and audit
- Statistical release

Prerequisites: 15-122, 15-213

New course!

17-355/17-665: Program Analysis

Why take program analysis?

- **Explore the meaning of programs.** Program analysis is about automated tools for understanding programs
- **Study the theory of abstraction.** *Abstract interpretation* is a fundamental—and beautiful—theory about abstraction: how to precisely relate the concrete execution of a program to an abstraction of that execution.
- **Build awesome tools** that help you automatically:
  - Find **bugs**
  - Prove **security/correctness properties**
  - Generate **tests**

For more information:
http://www.cs.cmu.edu/~aldrich/courses/17-355/

15-312: Principles of Programming Languages

From Quora:
“Principles of Programming Languages with Bob Harper shaped the way I think about programming more than anything else at Carnegie Mellon.”

Topics: programming language design, type theory, semantics, and implementation

Instructors: Bob Harper and Jan Hoffmann

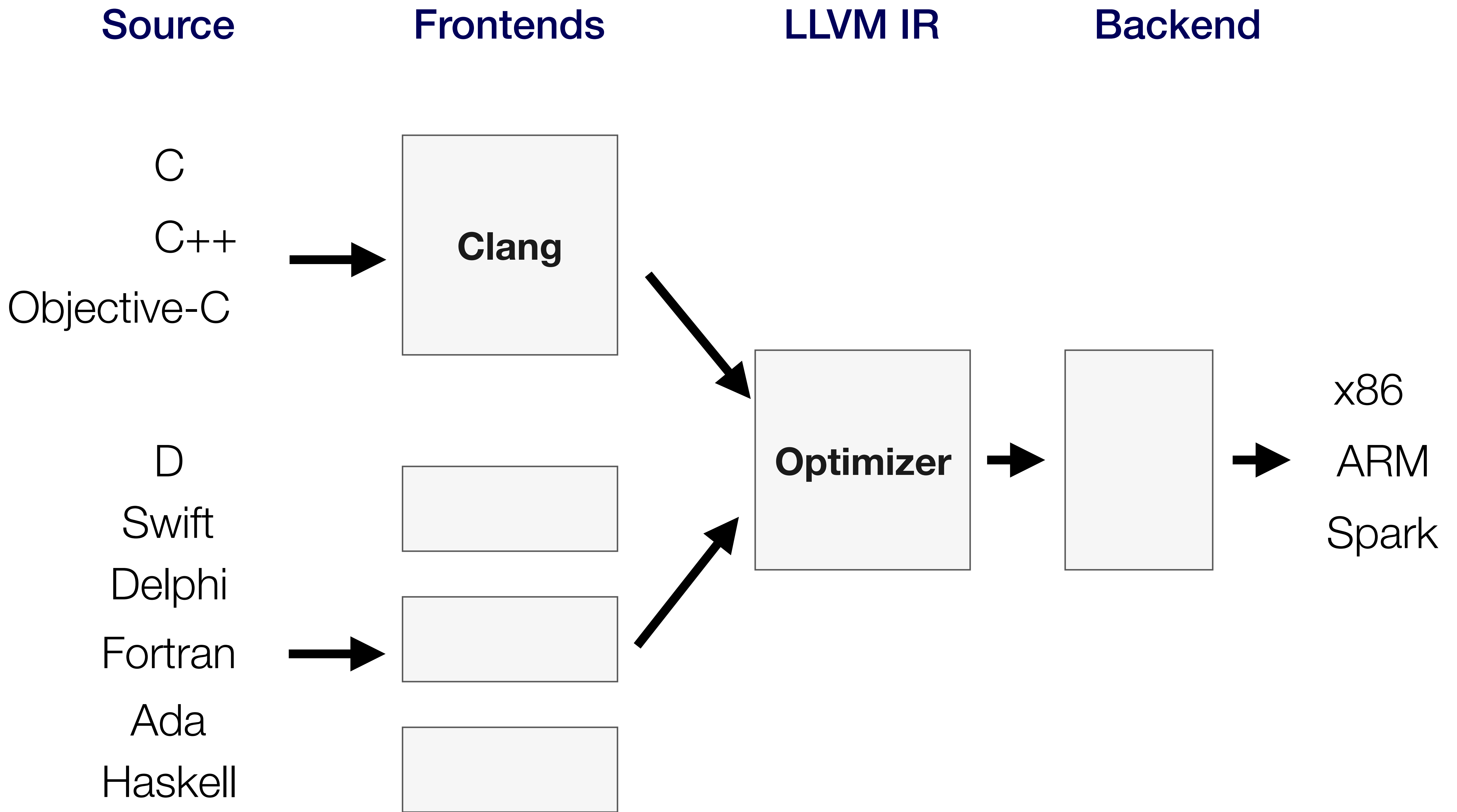
What is LLVM?

A collection of modular and reusable compiler and toolchain technologies

- Implemented in C++
- LLVM has been started by Vikram Adve and Chris Lattner at UIUC in 2000
- Originally ‘Low Level Virtual Machine’ for research on dynamic compilation
- Evolved into an umbrella project for a lot different things

LLVM Components

- **LLVM Core:** optimizer for source- and target independent LLVM IR code generator for many architectures
- **Clang:** C/C++/Objective C compiler that uses LLVM Core Includes the Clang Static Analyzer for bug finding
- **libcc+:** implementation of C++ standard library
- **LLDB:** debugger for C, C++, and Objective C
- **dragonegg:** GCC parser front end for compiling Fortran, Ada, …
- …



LLVM Compiler Framework

LLVM Analysis Passes

Dead Code Elimination
Inlining
Basic-Block Vectorization
Profile Guided Block Placement
Break critical edges in CFG
Merge Duplicate Global
Simple constant propagation
Dead Code Elimination
Dead Argument Elimination
Dead Type Elimination
Dead Instruction Elimination
Dead Store Elimination
Deduce function attributes

Dead Global Elimination
Global Variable Optimizer
Global Value Numbering
Canonicalize Induction Variables
Function Integration/Inlining
Combine redundant instructions
Internalize Global Symbols
Interprocedural constant propa.
Jump Threading
Loop-Closed SSA Form Pass
Loop Strength Reduction
Rotate Loops
Loop Invariant Code Motion

LLVM Analysis Passes

Canonicalize natural loops
Unroll loops
Unswitch loops
-mem2reg: Promote Memory to Register
MemCpy Optimization
Merge Functions
Unify function exit nodes
Remove unused exception handling
Reassociate expressions
Demote all values to stack slots
Sparse Conditional Cons. Propaga.
Simplify the CFG

Code sinking
Strip all symbols from a module
Strip debug info for unused symbols
Strip Unused Function Prototypes
Strip all llvm.dbg.declare intrinsics
Tail Call Elimination
Delete dead loops
Extract loops into new

LLVM IR

Example 1

```
int add (int x) {
  int y = 8128;
  return x+y;    }
```

```
; Function Attrs: nounwind ssp uwtable
define i32 @add(i32 %x) #0 {
  %1 = alloca i32, align 4
  %y = alloca i32, align 4
  store i32 %x, i32* %1, align 4
  store i32 8128, i32* %y, align 4
  %2 = load i32* %1, align 4
  %3 = load i32* %y, align 4
  %4 = add nsw i32 %2, %3
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}
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Example 1

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Functions are parametrized with arguments.

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```

Functions are parametrized with arguments.

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Instructions have types: i32 is for 32bit integers.

No signed wrap: result of overflow undefined.

Example2

```
int loop  (int n) {
  int i = n;
  while(i<1000){i++;}
  return i;
}
```

```
; Function Attrs: nounwind ssp uwtable
define i32 @loop(i32 %n) #0 {
  %1 = alloca i32, align 4
  %i = alloca i32, align 4
  store i32 %n, i32* %1, align 4
  %2 = load i32* %1, align 4
  store i32 %2, i32* %i, align 4
  br label %3

; <label>:3                                 ; preds = %6, %0
  %4 = load i32* %i, align 4
  %5 = icmp slt i32 %4, 1000
  br i1 %5, label %6, label %9

; <label>:6                                 ; preds = %3
  %7 = load i32* %i, align 4
  %8 = add nsw i32 %7, 1
  store i32 %8, i32* %i, align 4
  br label %3

; <label>:9                                 ; preds = %3
  %10 = load i32* %i, align 4
  ret i32 %10
}
```

Example2

```c
int loop  (int n) {
  int i = n;
  while(i<1000){i++;}
  return i;
}
```

```llvm
; Function Attrs: nounwind ssp uwtable
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LLVM IR

- Three address pseudo assembly
- Reduced instruction set computing (RISC)
- Static single assignment (SSA) form
- Infinite register set
- Explicit type info and typed pointer arithmetic
- Basic blocks

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```
for (i = 0; i < N; i++)
   Sum(&A[i], &P);
```

```
loop:                     ; preds = %bb0, %loop
  %i.1 = phi i32 [ 0, %bb0 ], [ %i.2, %loop ]
  %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.1, %N
  br i1 %exitcond, label %outloop, label %loop
```

LLVM IR Structure

- **Module contains Functions and GlobalVariables**
  - Module is unit of compilation, analysis, and optimization
- **Function contains BasicBlocks and 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**

Type System

- llvm.org:

  “The LLVM type system is one of the most important features of the intermediate representation.

  Being typed enables a number of optimizations to be performed on the intermediate representation directly, without having to do extra analyses on the side before the transformation.

  A strong type system makes it easier to read the generated code and enables novel analyses and transformations that are not feasible to perform on normal three address code representations”

Single Value Types

Integer Types

```
iN
```

Single Value Types

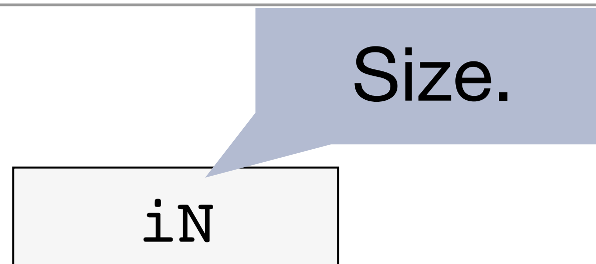
Integer Types

```
iN
```

Size.

Single Value Types

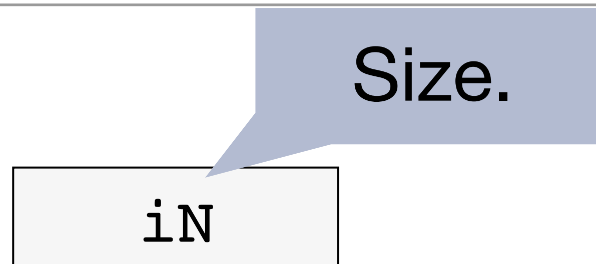
Integer Types



i1	a single-bit integer.
i32	a 32-bit integer.
i1942652	a really big integer of over 1 million bits.

Single Value Types

Integer Types



i1	a single-bit integer.
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Float Types

half	16-bit floating point value
float	32-bit floating point value
double	64-bit floating point value

Functions and Void

Void

```
void
```

Function Types

```
<returntype> (<parameter list>)
```

i32 (i32)	function taking an i32, returning an i32
float (i16, i32 *) *	Pointer to a function that takes an i16 and a pointer to i32, returning float.
i32 (i8*, ...)	A vararg function that takes at least one pointer to i8 (char in C), which returns an integer

Functions and Void

Void

No representation and no size.

```
void
```

Function Types

```
<returntype> (<parameter list>)
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Pointers and Vectors

Pointer Types

```
<type>*
```

[4 x i32]*	A pointer to array of four i32 values.
i32 (i32*) *	A pointer to a function that takes an i32*, returning an i32.

Vectors

```
< <# elements> x <elementtype> >
```

<4 x i32>	Vector of 4 32-bit integer values.
<8 x float>	Vector of 8 32-bit floating-point values.
<2 x i64>	Vector of 2 64-bit integer values.

Arrays and Structs

Arrays Types

```
[<# elements> x <elementtype>]
```

[40 x i32]	Array of 40 32-bit integer values.
[12 x [10 x float]]	12x10 array of single precision floating point values.
[2 x [3 x [4 x i16]]]	2x3x4 array of 16-bit integer values.

Struct Types

```
%T1 = type { <type list> }      ; Normal struct type
%T2 = type <{ <type list> }>    ; Packed struct type
```

{ i32, i32, i32 }	A triple of three i32 values
{ float, i32 (i32) *}	A pair, where the first elem. is a float and the second element is a pointer to a function that takes an i32, returning an i32.
<{ i8, i32 }>	A packed struct known to be 5 bytes in size.

Generating LLVM Code

High-Level Approach

It is not necessary to directly produce SSA form:

- Allocate all variables on the stack
- Store instructions are not limited by SSA form

```
store i32 %x, i32* %p, align 4
```

- Use LLVM's **mem2reg** optimization to turn stack locations into variables
  - promotes memory references to be register references
  - changes alloca instructions which only have loads and stores as uses
  - introduces phi functions

Options

- Using the LLVM C++ interface & OCaml or Haskell bindings

- Generating an LLVM assembly (.ll file)

```
define i32 @main() #0 {
entry:
  %retval = alloca i32, align 4
  %a = alloca i32, align 4
...
```

- Generating LLVM bitcode (.bc file)

```
42 43 C0 DE  21 0C 00 00
06 10 32 39  92 01 84 0C
0A 32 44 24  48 0A 90 21
18 00 00 00  98 00 00 00
E6 C6 21 1D  E6 A1 1C DA
```

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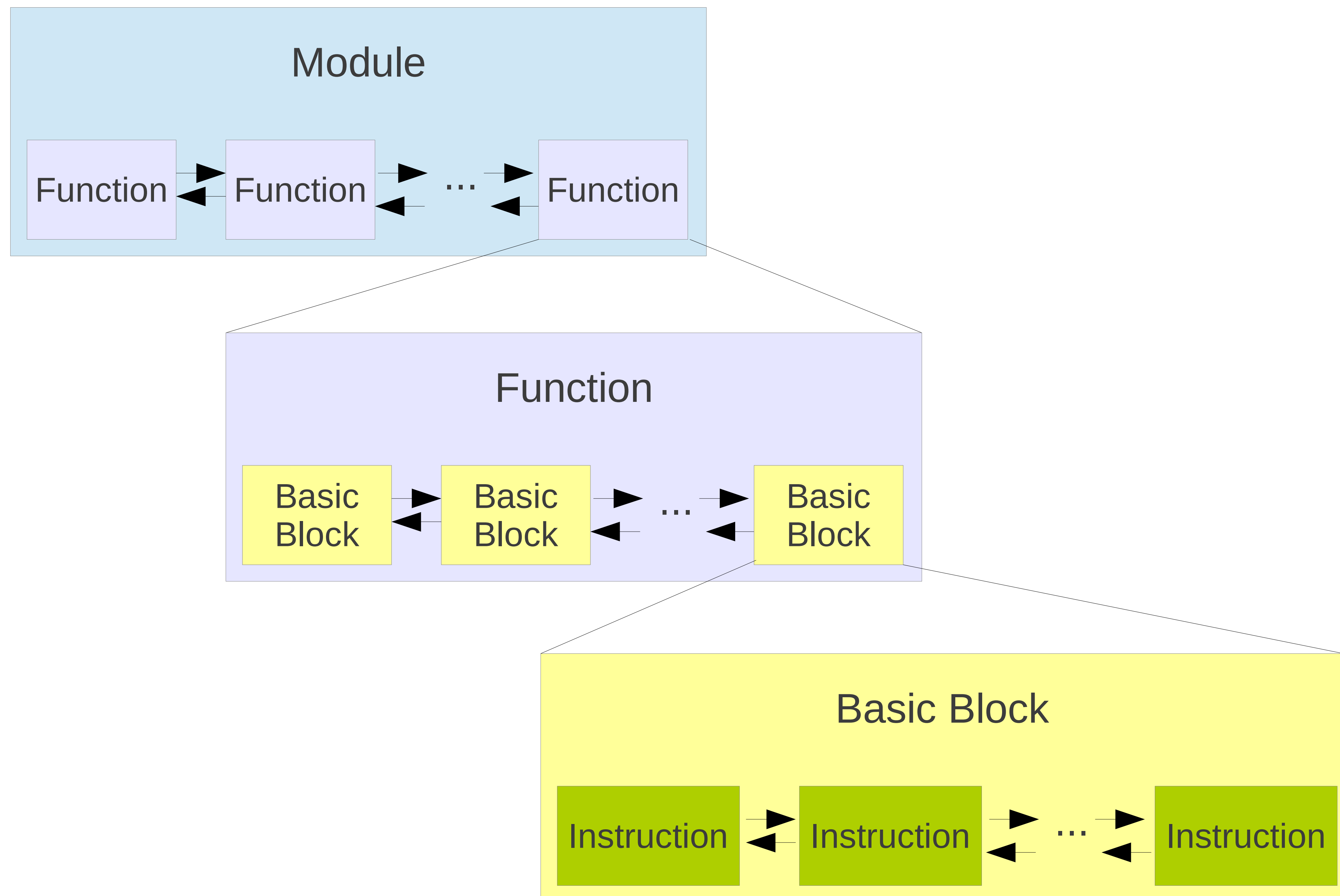
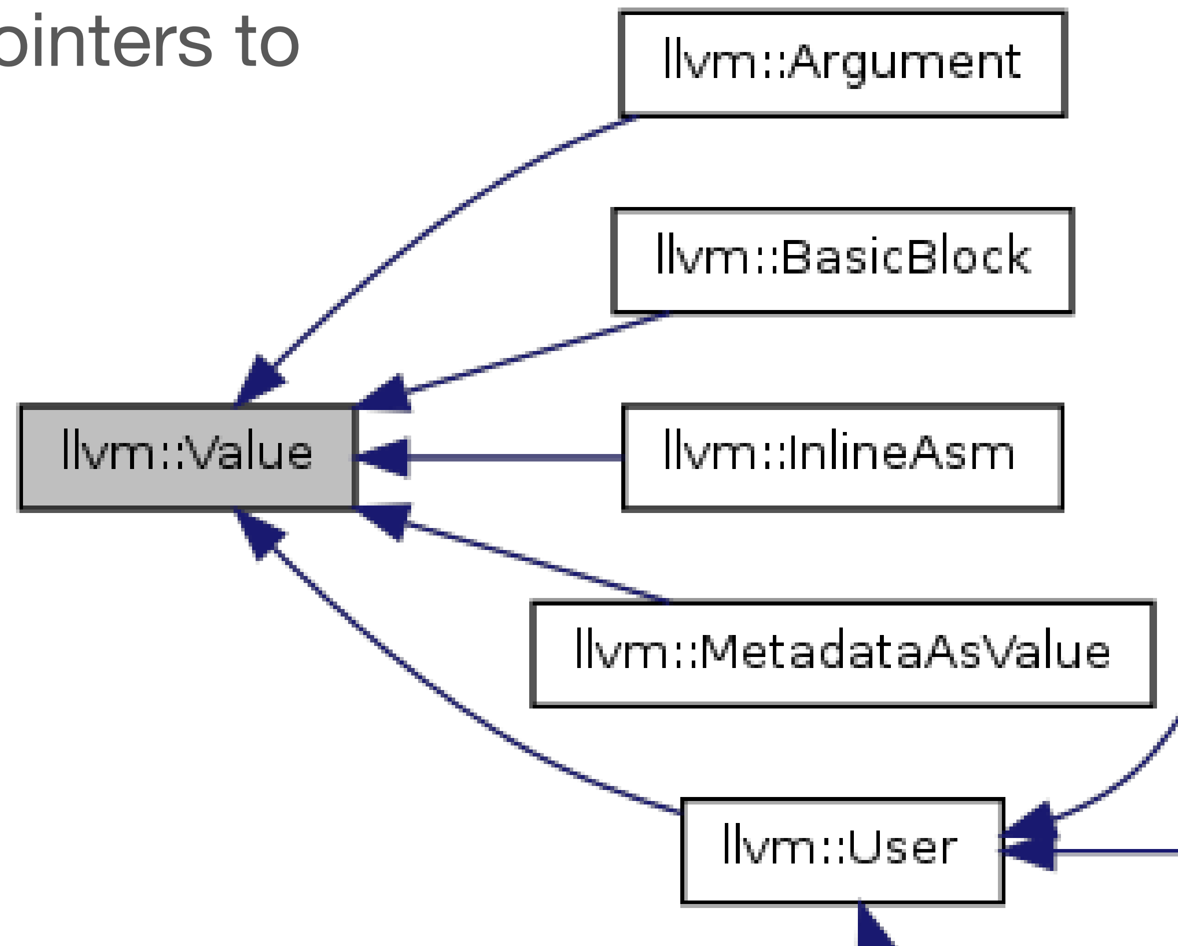
C++ Interface



C++ Interface

- Object oriented
- Instruction doubles as reference for written value
- Every value contains a list of pointers to instructions that use the value



.ll Files

```
; ModuleID = 'llvm.c'
target datalayout = "e-m:o-i64:64-f80:128-n8:16:32:64-S128"
target triple = "x86_64-apple-macosx10.10.0"

; Function Attrs: nounwind ssp uwtable
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  store i32 %x, i32* %1, align 4
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}

attributes #0 = { nounwind ssp uwtable "less-precise-fpmad"="false"
"no-frame-pointer-elim"="true" “no-frame-pointer-elim-non-leaf”… }

!llvm.module.flags = !{!0}
!llvm.ident = !{!1}

!0 = !{i32 1, !"PIC Level", i32 2}
!1 = !{!"Apple LLVM version 7.0.0 (clang-700.0.72)"}
```

http://llvm.org/docs/LangRef.html