INTRODUCTION TO LLVM

Bo Wang
SA 2016 Fall

OUTLINE

- LLVM Basic
- LLVM IR
- LLVM Pass

What is LLVM?

- LLVM is a compiler infrastructure designed as a set of reusable libraries with well-defined interfaces.
  - Implemented in C++
  - Several front-ends
  - Several back-ends
  - First release: 2003
  - The original author: Chris Lattner (PhD of UIUC)
  - Open source http://llvm.org/

LLVM is a Compilation Infrastructure

It is a framework that comes with a lots of tools to compile and optimize code.

```
nightwish@nightwish-TP [02:30:42 PM] [~/code/git/newest_llvm/llvm/build/bin] [master *]
-> % ls
arcmt-test              llvm-config       llvm-PerfectShuffle
bugpoint                llvm-cov          llvm-profdata
c-arcmt-test            llvm-c-test       llvm-ranlib
c-index-test            llvm-cxxdump      llvm-readobj
clang                   llvm-cxxfilt      llvm-rtdyld
clang++                 llvm-diff         llvm-size
clang-4.0               llvm-dis          llvm-split
clang-check             llvm-dsymutil     llvm-stress
clang-cl                llvm-dwarfdump    llvm-symbolizer
clang-cpp               llvm-dwp          llvm-tblgen
clang-format            llvm-extract      not
clang-offload-bundler   llvm-lib          obj2yaml
clang-tblgen            llvm-link         opt
count                   llvm-lit          sancov
diagtool                llvm-lto          sanstats
FileCheck               llvm-lto2         scan-build
llc                     llvm-mc           scan-view
lli                     llvm-mcmarkup     verify-uselistorder
lli-child-target        llvm-nm           yaml2obj
llvm-ar                 llvm-objdump      yaml-bench
llvm-as                 llvm-opt-report
```

A First Look

1. PATH/clang –emit-llvm –c hello.c –o hello.bc
2. PATH/lli hello.bc
3. PATH/llvm-dis < hello.bc | less

   or

   PATH/llvm-dis hello.bc

   or

   PATH/clang –emit-llvm –S hello.c

Why to learn LLVM?

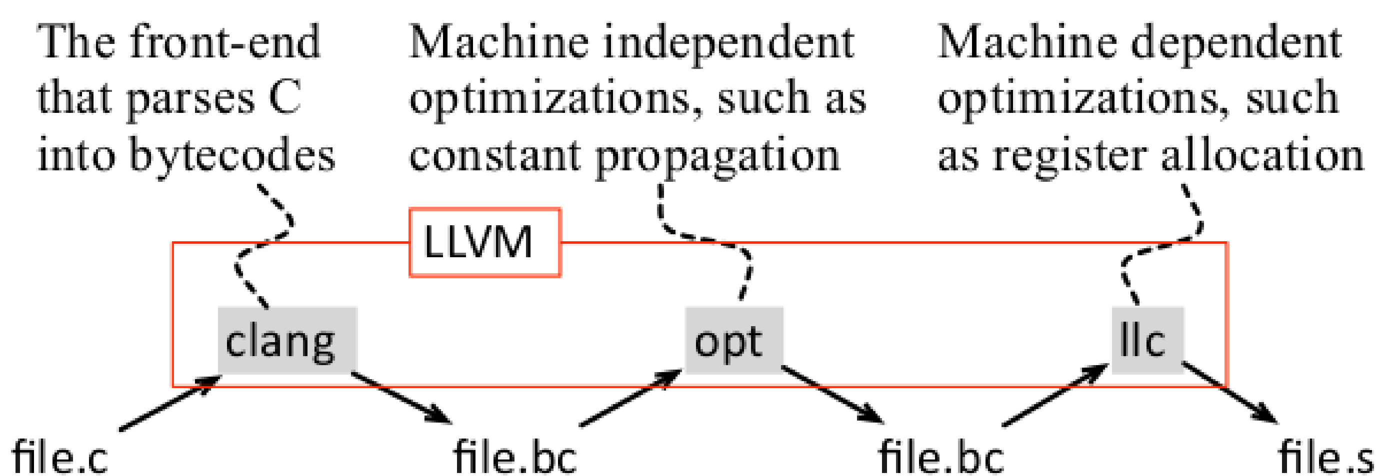
- Intensively used in the academia:

  > LLVM: A compilation framework for lifelong program analysis & transformation
  > C Lattner, V Adve - Code Generation and Optimization, 2004. …, 2004 - ieeexplore.ieee.org
  > ABSTRACT This paper describes LLVM (Low Level Virtual Machine), a compiler framework designed to support transparent, lifelong program analysis and transformation for arbitrary programs, by providing high-level information to compiler transformations at compile-time, ...
  > 被引用次数：2641 相关文章 所有 60 个版本 引用 保存

- Widely used in the industry
  - LLVM is supported by Apple
  - ARM, NVIDIA, Mozilla, etc.
- Clean and modular interfaces
- Awards: ACM Software System Award 2012
  - UNIX, TCP/IP, WWW, Java, Apahe, Eclipse, gcc, make, Vmware, LLVM...

Big Picture of LLVM

- LLVM implements the entire compilation flow.
  - Front-end, e.g., clang (C), clang++ (C++)
  - Middle-end, e.g., analyses and optimizations
  - Back-end, for different computer architectures, e.g., MIPS, x86, ARM



Middle-end: LLVM IR

- IR: Intermediate Representation
  - RISC like instruction set
  - Well typed representation
  - SSA format: Each variable noun has only one definition
  - Three types of format
    - in memory (JIT)
    - byte code (.bc)
    - human readable (.ll)

A First Look at IR

CMD : YOUR_BUILD_PATH/bin/clang -emit-llvm -S 1st.c

```c
int foo(int a){
        int res;
        if(a > 0){
                res = 1;
        }else{
                res = 0;
        }
        return res;
}
```

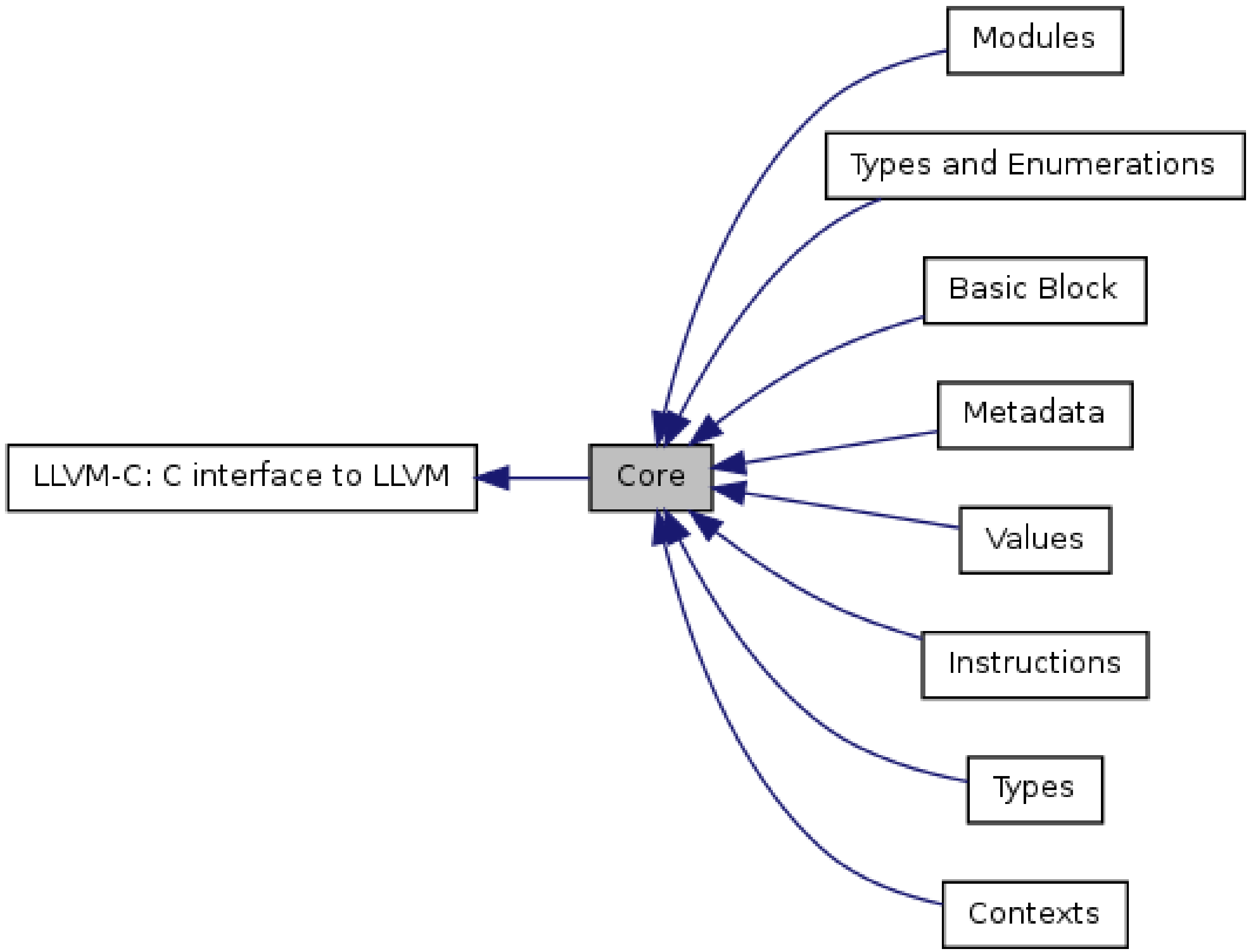
1st.c

```llvm
; Function Attrs: nounwind uwtable
define i32 @foo(i32 %a) #0 {
entry:
  %a.addr = alloca i32, align 4
  %res = alloca i32, align 4
  store i32 %a, i32* %a.addr, align 4
  %0 = load i32, i32* %a.addr, align 4
  %cmp = icmp sgt i32 %0, 0
  br i1 %cmp, label %if.then, label %if.else

if.then:
  store i32 1, i32* %res, align 4
  br label %if.end

if.else:
  store i32 0, i32* %res, align 4
  br label %if.end

if.end:
  %1 = load i32, i32* %res, align 4
  ret i32 %1
}
```

1st.ll

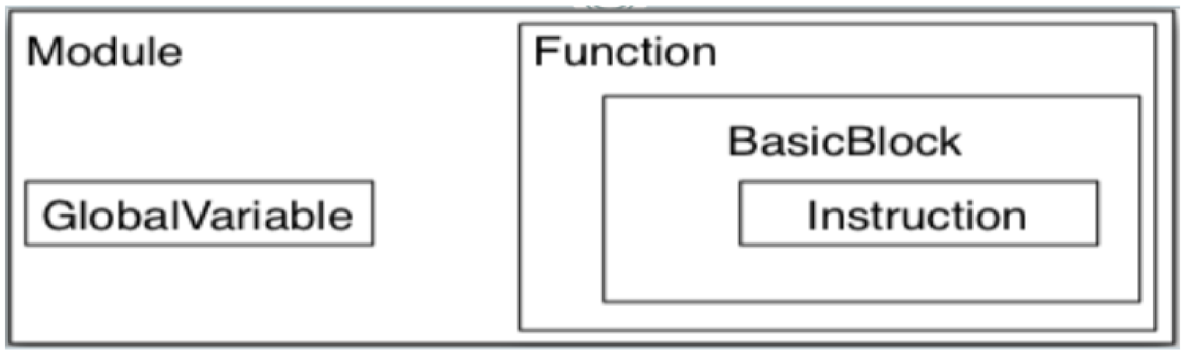
- All the types of IR:
  - llvm/include/llvm/IR/Instruction.def
- Document:
  - http://llvm.org/docs/LangRef.html

LLVM-IR Core



LLVM-C: C interface to LLVM
Core
Modules
Types and Enumerations
Basic Block
Metadata
Values
Instructions
Types
Contexts

LLVM Core Hierarchy



- Module contains Functions/GlobalVariables
  - Module is unit of compilation/analysis/optimization
- Function contains BasicBlocks/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
  - All operands have types
  - Instruction result is typed

The Module

- What is the modules?
  - Modules represent the top-level structure in an LLVM program.
  - An LLVM module is effectively a translation unit or a collection of translation units merged together.
- Why C need modules?
  - Python : interpreter-based
  - Java : All members of a class within a java src
  - C/C++ : linkage, the scope of identifiers

The Function

- Name
- Argument list
- Return type
- Extends from *GlobalValue*, has properties of linkage visibility.

The Value

- Value: can be treated as arbitrary num of registers.
- Locals start with %, globals with @
- All instructions that produce values can have a name (Not assignments: *store, br*)

Type

- Not exactly what PL people think of as types
- All values have a static type
- Integer: iN; for C --- i1, i8, i16, i32, i64…
- Float: float, double, half
- Arrays: can get num of elements
- Structures: can get members, like {i32, i32, i8}
- Pointers: can get the pointed value
- Void

Note on Integer Types

- There are no signed or unsigned integers
- LLVM views integers as bit vectors
- Frontends destroyed signed/unsigned information
- Operations are interpreted as signed or unsigned based on instructions they are used in
  - icmp sgt v.s. icmp ugt
  - sdiv v.s. udiv

BasicBlock & Instruction

- Classify Instructions
  - Terminator Instructions: ret, switch, br (cond & uncond)...
  - Binary operators: add, sub…
  - Logical operators: and, or, shl…
  - Memory operators: alloca, load, store...
  - Cast operators …
  - Others: icmp, phi, call...
- Contains a list of Instructions
- In general, every basic block must end with a Terminator Instruction

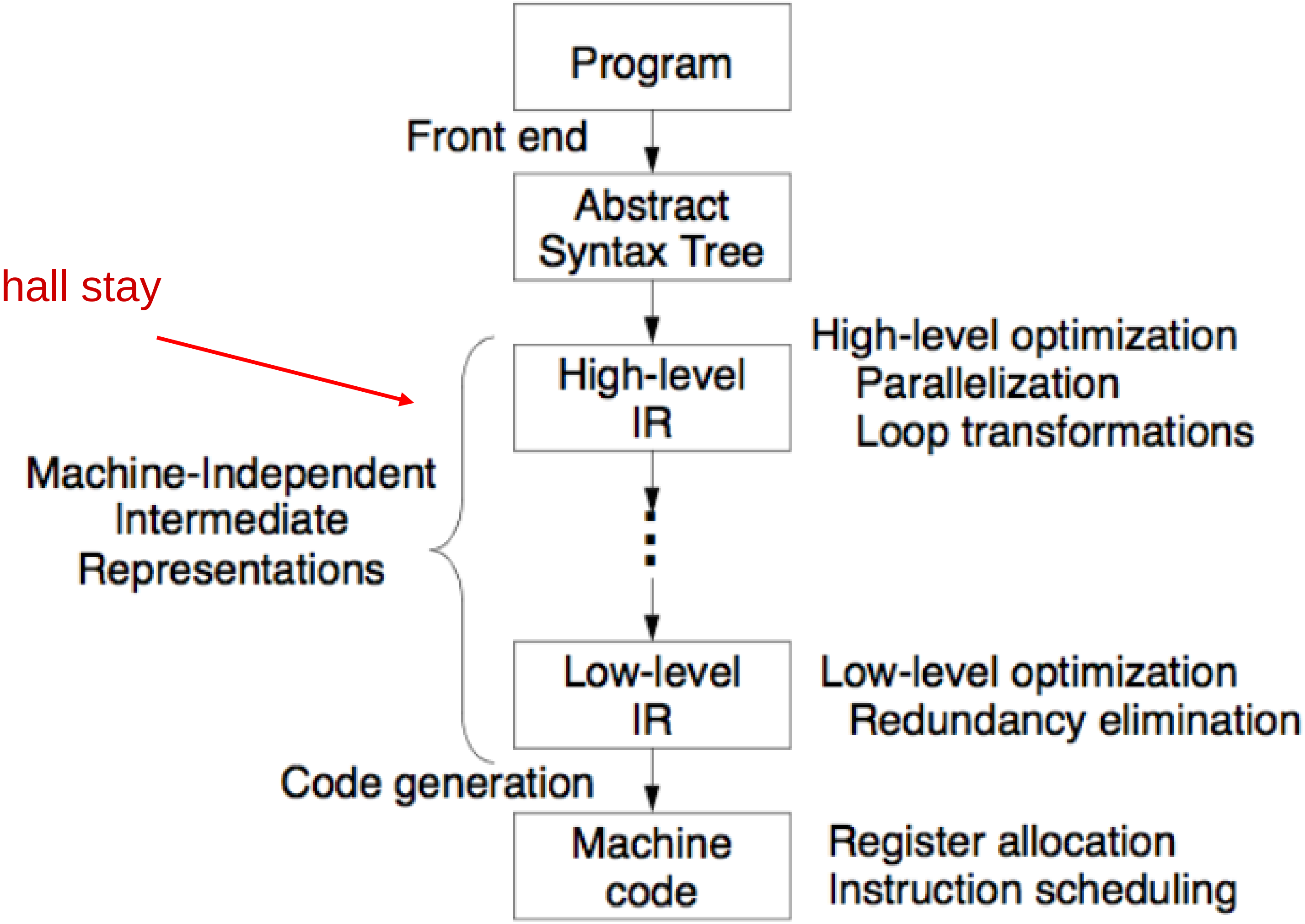
More Detail of Phi nodes

- 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

LLVM Pass

- Normal Compiler Organization

Passes shall stay here!

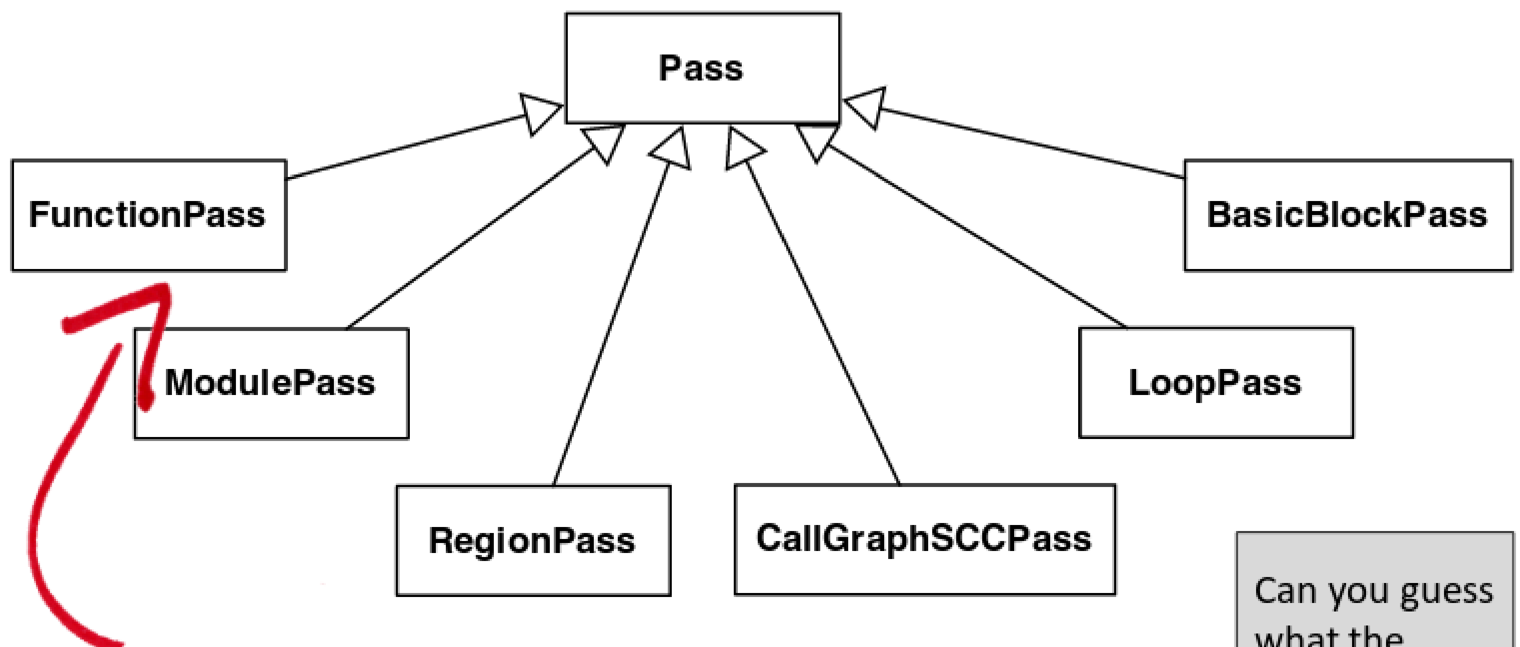


LLVM Pass

- LLVM applies a chain of analyses and transformations on the target program.
- Each of these analyses or transformations is called a ***pass***.
- Some passes, which are machine independent, are invoked by *opt*.
- A pass may require information provided by other passes. Such dependencies must be explicitly stated.

LLVM Pass

- A pass is an instance of the LLVM class *Pass*
- There are many kinds of passes



In this lesson we will focus on Function Passes, which analyze whole functions.

Can you guess what the other passes are good for?

A First Look at LLVM Passes

- Memory To Register (-mem2reg)

```
int foo(int a){
        int res;
        if(a > 0){
                res = 1;
        }else{
                res = 0;
        }
        return res;
}
```

1

YOURPATH/clang -emit-llvm -S 1st.c -o 1st.ll

```
; Function Attrs: nounwind uwtable
define i32 @foo(i32 %a) #0 {
entry:
  %a.addr = alloca i32, align 4
  %res = alloca i32, align 4
  store i32 %a, i32* %a.addr, align 4
  %0 = load i32, i32* %a.addr, align 4
  %cmp = icmp sgt i32 %0, 0
  br i1 %cmp, label %if.then, label %if.else

if.then:
  store i32 1, i32* %res, align 4
  br label %if.end

if.else:
  store i32 0, i32* %res, align 4
  br label %if.end

if.end:
  %1 = load i32, i32* %res, align 4
  ret i32 %1
}
```

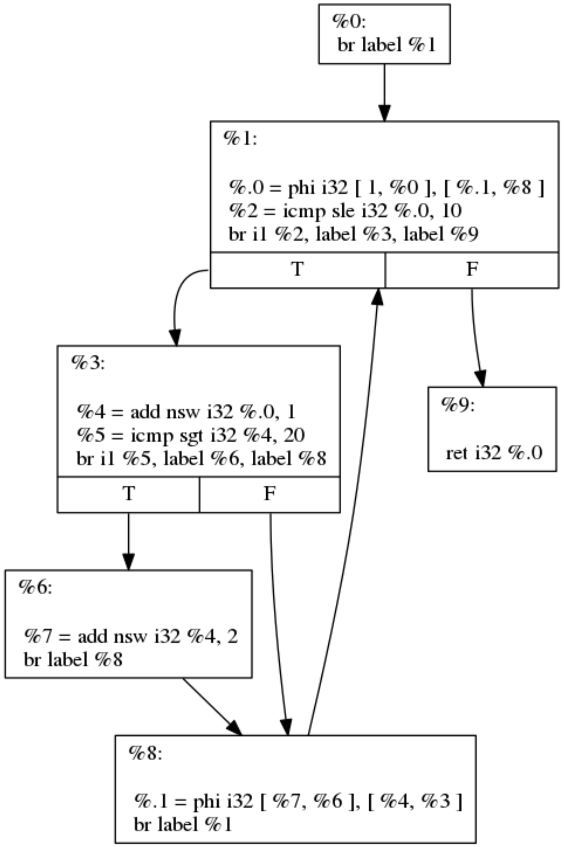
2

```
; Function Attrs: nounwind uwtable
define i32 @foo(i32 %a) #0 {
entry:
  %cmp = icmp sgt i32 %a, 0
  br i1 %cmp, label %if.then, label %if.else

if.then:                                                ;
  br label %if.end

if.else:                                                ;
  br label %if.end

if.end:                                                 ;
  %res.0 = phi i32 [ 1, %if.then ], [ 0, %if.else ]
  ret i32 %res.0
}
```

YOURPATH/opt -mem2reg 1st.bc -S -o 1stm2r.ll

A First Look at LLVM Passes

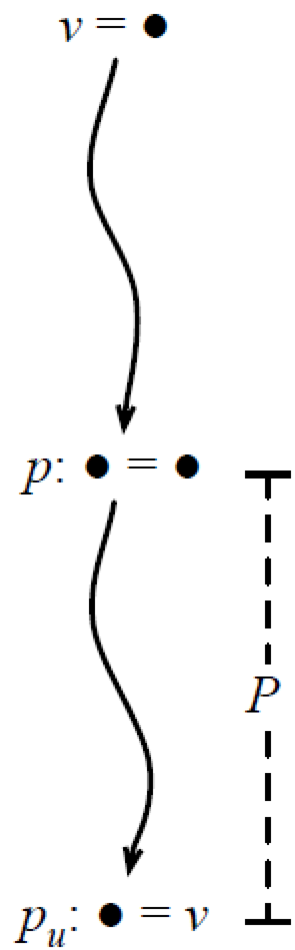
- Draw a CGF (-mem2reg)
  1. sudo apt-get install graphviz
  2. opt –dot-cfg hello.bc
  3. dot –Tpng –o cfg.png cfg.foo.dot



CFG for 'foo' function

Review: Liveness Analysis

- If we assume an infinite supply of registers, then a variable *v* should be in a register at a program point *p*, whenever:
  1. There is a path *P* from *p* to another program point p_u, where *v* is used.
  2. The path *P* does not go across any definition of *v*.



Why is the second condition really necessary?

Can you define the liveness problem more formally?

Review: Textbook Liveness Analysis

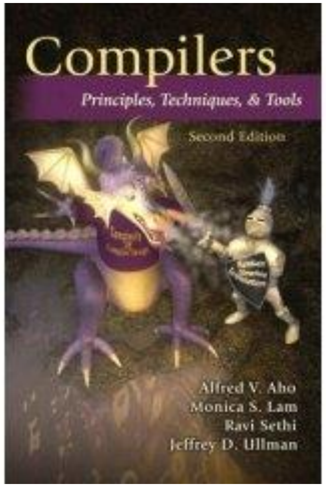
- Liveness analysis: Backwards, may, union.

Algorithm

for each node n in CFG
    in[n] = ∅; out[n] = ∅   — Initialize solutions

repeat
    for each node n in CFG **in reverse topsort order**
        in'[n] = in[n]
        out'[n] = out[n]   — Save current results
        out[n] = $\bigcup_{s \in succ[n]}$ **in[s]**
        in[n] = use[n] ∪ (out[n] – def[n])   — Solve data-flow equations

until in'[n]=in[n] and out'[n]=out[n] for all n   — Test for convergence

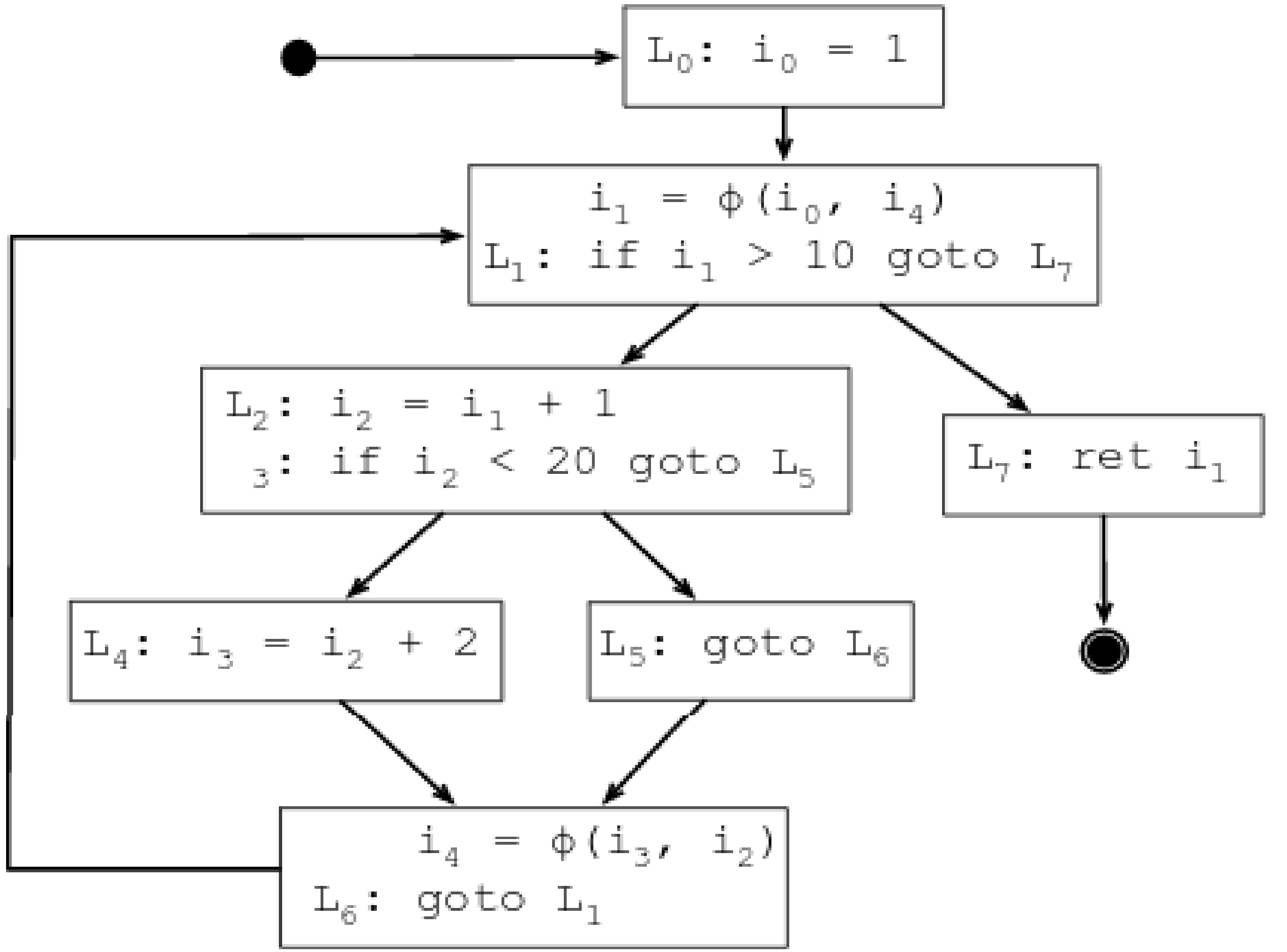


Review: Textbook Liveness Analysis

- Complexity
- Time
  - Worst case: $O(n^4)$
  - Typical case: $O(N)$ to $O(N^2)$
- Space
  - $O(N^2)$

SSA Form Liveness Analysis

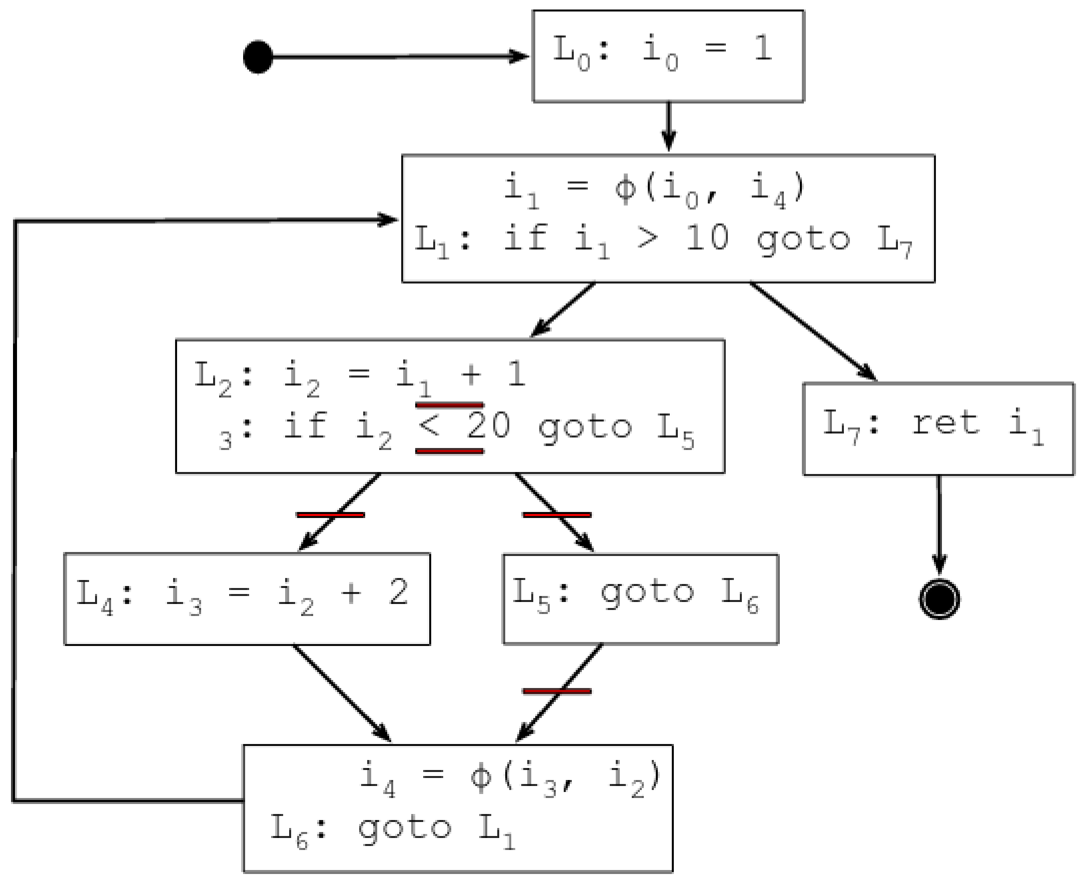
Can you point where i2 is alive in this program?



SSA Form Liveness Analysis

Can you point where
i2 is alive in this program?

Why the phi-node i4
is excluded?



SSA Form Liveness Analysis

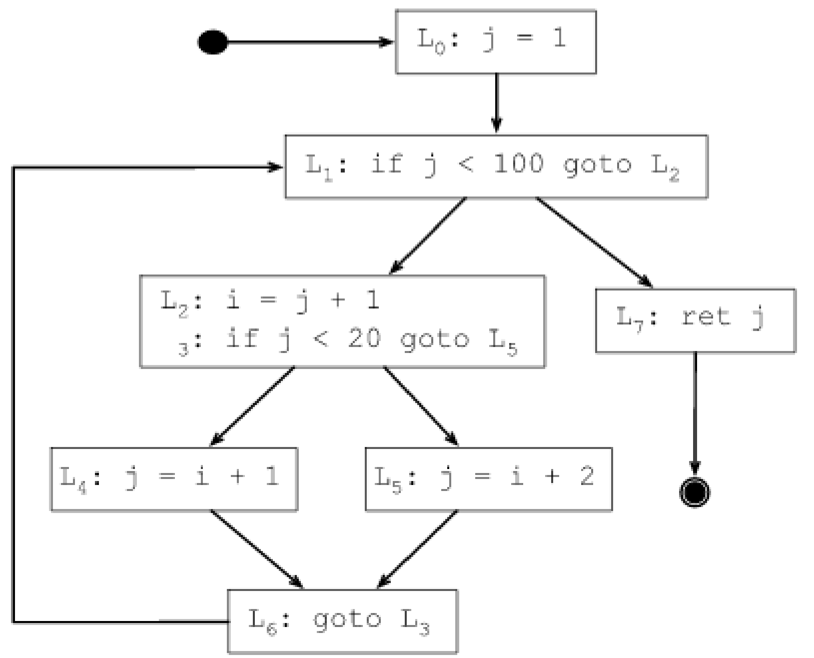
Without traversing the CFG to reach a fixed point.

Space: O(N)
Time: O(N) to O(N^2)

```
For each statement S in the program:
    IN[S] = OUT[S] = {}

For each variable v in the program:
    For each statement S that uses v:
        live(S, v)

live(S, v):
    IN[S] = IN[S] ∪ {v}
    For each P in pred(S):
        OUT[P] = OUT[P] ∪ {v}
        if P does not define v
            live(P, v)
```

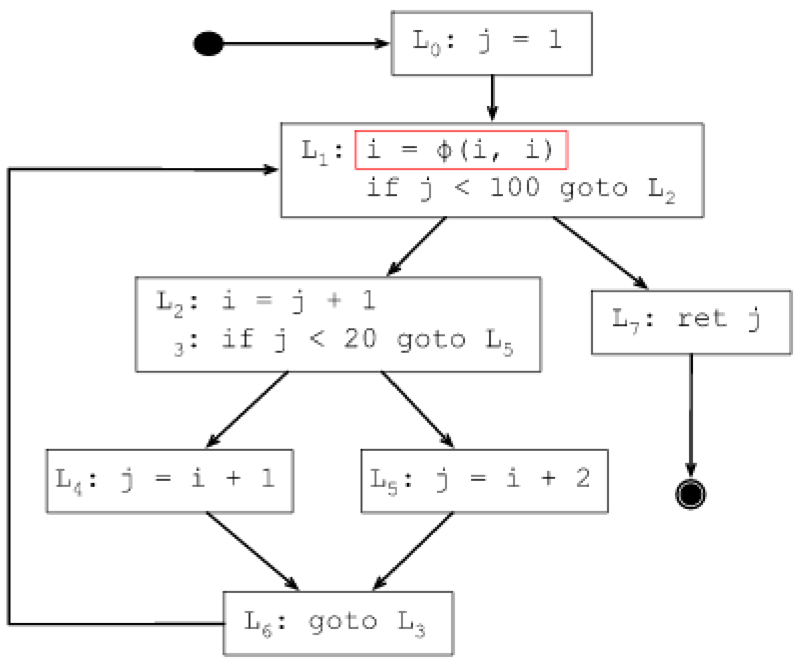
Is Traditional DA Useless?

- Where should we add a phi-function for the defination of *i* at *L2*.



Is Traditional DA Useless?

- The phi-function at *L1* exists even though it is not useful at all.
- We can add a liveness check to the algorithm that inserts phi-functions.



The LLVM Pass in Action

- Naive Liveness Analysis for LLVM IR
- Function Pass
- LLVM API
  - Iterating basic blocks, instructions and operands.
  - Instruction casting
  - ...
- The code
  - http://pan.baidu.com/s/1pLRfCEn