Lecture 7

CIS 4521/5521: COMPILERS

Announcements

- HW2: X86lite
  - Due: Weds. Feb. 12th at 10:00pm
  - Pair-programming
  - Sign up for teams via github classroom

  - **Please get started!** (I can see who has cloned the git repo!)

- Note: clone the project with `` `--recurse-submodules` `` flag
  - There is a shared, public git submodule to which you will need to push test cases.
  - We may need to adjust permissions on github to make this work, so:
  1. please accept the invitation to join the `upenn-cis5521` organization.
  2. let us know if you don't have access to the `sp25_students` team, which is needed to clone the shared submodule.

see: ir-by-hand.ml, ir<X>.ml in lec06.zip

INTERMEDIATE REPRESENTATIONS

Eliminating Nested Expressions

- Fundamental problem:
  - Compiling complex & nested expression forms to simple operations.

Source

```
((1 + X4) + (3 + (X1 * 5)))
```

AST

```
Add(Add(Const 1, Var X4),
    Add(Const 3, Mul(Var X1,
                     Const 5)))
```

IR

?

- Idea: *name* intermediate values, make order of evaluation explicit.
  - No nested operations.

Translation to SLL

- Given this:

```
Add(Add(Const 1, Var X4),
    Add(Const 3, Mul(Var X1,
                     Const 5)))
```

- Translate to this desired SLL form:

```
let tmp0 = add 1L varX4 in
let tmp1 = mul varX1 5L in
let tmp2 = add 3L tmp1 in
let tmp3 = add tmp0 tmp2 in
  tmp3
```

- Translation makes the order of evaluation explicit.
- Names intermediate values
- Note: introduced temporaries are never modified

Intermediate Representations

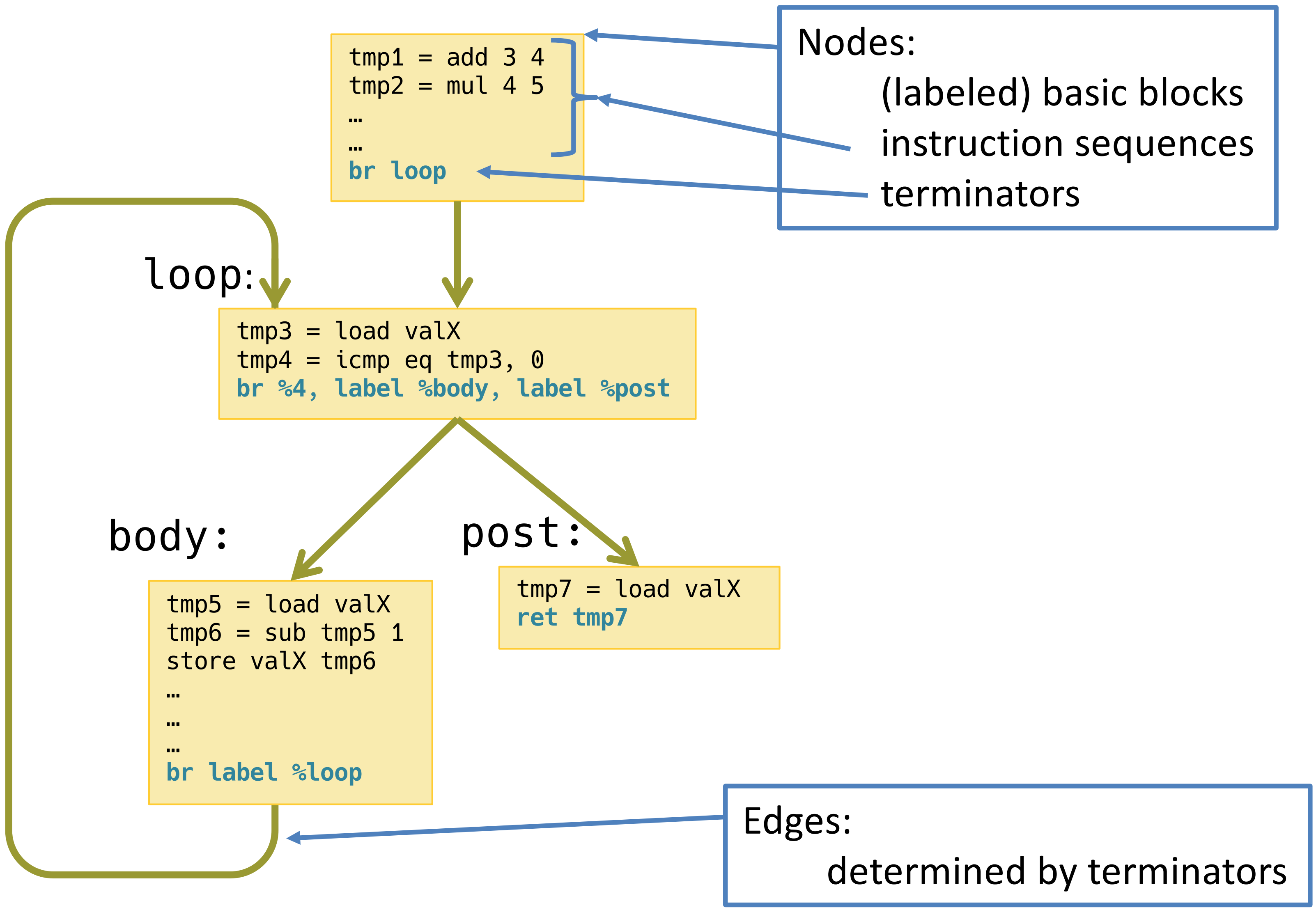
- IR1: Expressions
  - *immutable* global variables
  - simple arithmetic *expressions*
- IR2: Commands
  - *mutable* global variables
  - *commands* for update and sequencing
- IR3: Local control flow
  - *conditional* commands & while *loops*
  - *basic blocks*
- IR4: Procedures (top-level functions)
  - *local variables*
  - *call stack*
- IR5: “almost” LLVM IR
  - missing *phi-nodes* (explained when we get there)

Basic Blocks

- A sequence of instructions that is always executed starting at the first instruction and always exits at the last instruction.
  - Starts with a label that names the *entry point* of the basic block.
  - Ends with a control-flow instruction (e.g., branch or return) the "link"
  - Contains no other control-flow instructions
  - Contains no interior label used as a jump target

- Basic blocks can be arranged into a *control-flow graph*
  - Nodes are basic blocks
  - There is a directed edge from node A to node B if the control flow instruction at the end of basic block A might jump to the label of basic block B.

Control-flow Graphs



See llvm.org

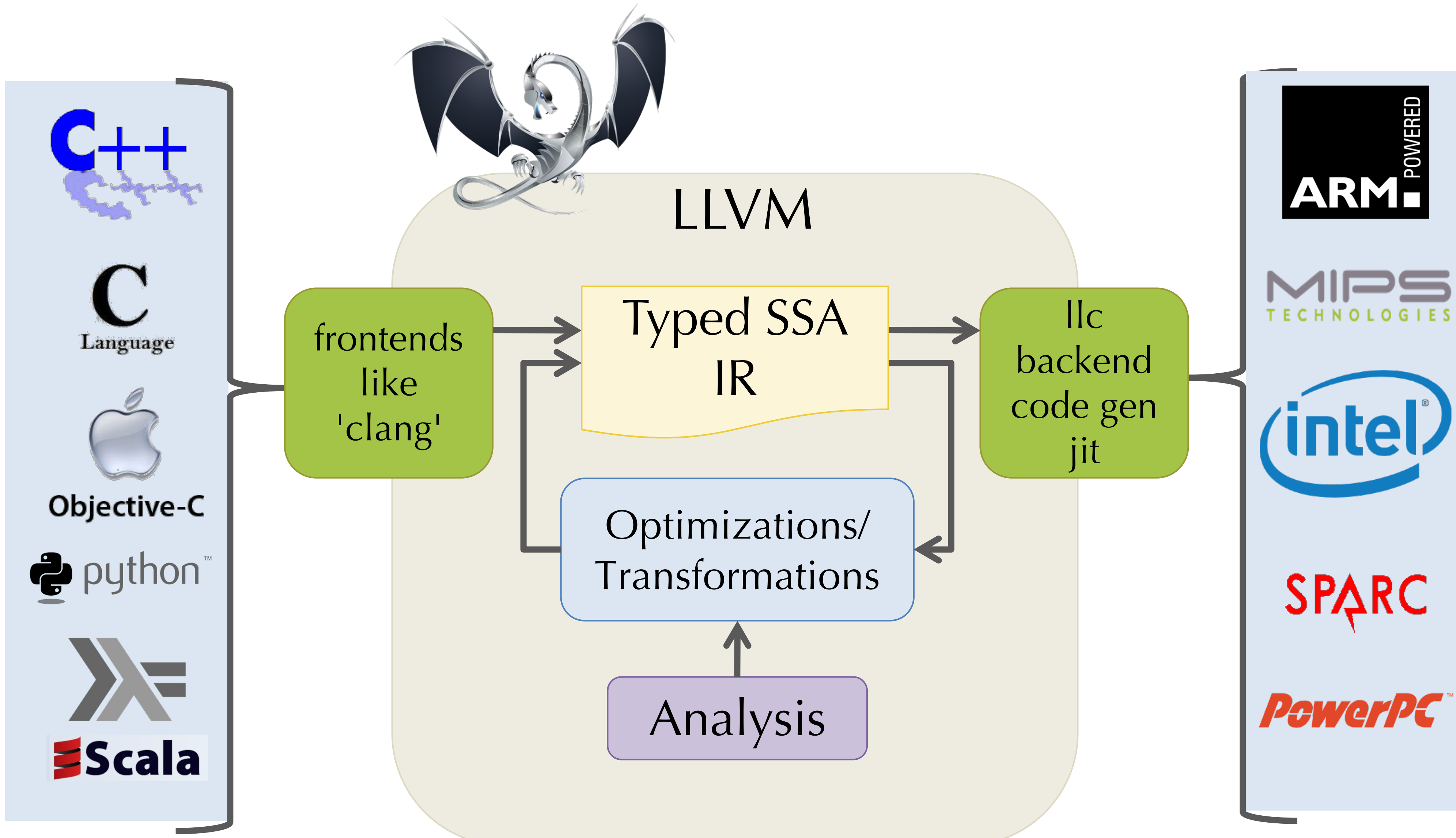
LLVM

Low-Level Virtual Machine (LLVM)

- Open-Source Compiler Infrastructure
  - see llvm.org for full documentation
- Created by Chris Lattner (advised by Vikram Adve) at UIUC
  - LLVM: An infrastructure for Mult-stage Optimization, 2002
  - LLVM: A Compilation Framework for Lifelong Program Analysis and Transformation, 2004
- 2005: Adopted by Apple for XCode 3.1
- Front ends:
  - llvm-gcc (drop-in replacement for gcc)
  - Clang: C, objective C, C++ compiler supported by Apple
  - various languages: Swift, ADA, Scala, Haskell, …
- Back ends:
  - x86 / Arm / Power / etc.
- Used in many academic/research projects
  - Here at Penn: SoftBound, Vellvm

LLVM Compiler Infrastructure

[Lattner et al.]



IR3/4/5 vs. LLVM

IR3/4/5

- “`let - in`” and OCaml-style identifiers:

```
let tmp1 = add 3L 4L in
```

- OCaml-style “let-rec” and functions for blocks:

```
let rec entry () =
  let tmp1 = …
and foo () =
  let tmp2 = …
```

- OCaml-style global variables:
  `let varX = ref 0L`

LLVM

- Omits let/in and prefixes local identifiers with %:

```
%tmp1 = add i64 3, i64 4
```

- Uses lighter-weight colon notation:

```
entry:
  %tmp1 = …
foo:
  %tmp2 = …
```

- Prefixes globals with @
  `define @X = i64 0`

Example LLVM Code

- LLVM offers a textual representation of its IR
  - files ending in `.ll`

factorial64.c

```
#include <stdio.h>
#include <stdint.h>

int64_t factorial(int64_t n) {
  int64_t acc = 1;
  while (n > 0) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}
```

factorial-pretty.ll

```
define @factorial(%n) {
  %1 = alloca
  %acc = alloca
  store %n,  %1
  store 1,  %acc
  br label %start

start:
  %3 = load %1
  %4 = icmp sgt %3, 0
  br %4, label %then, label %else

then:
  %6 = load %acc
  %7 = load %1
  %8 = mul %6, %7
  store %8, %acc
  %9 = load %1
  %10 = sub %9, 1
  store %10, %1
  br label %start

else:
  %12 = load %acc
  ret %12
}
```

Real LLVM

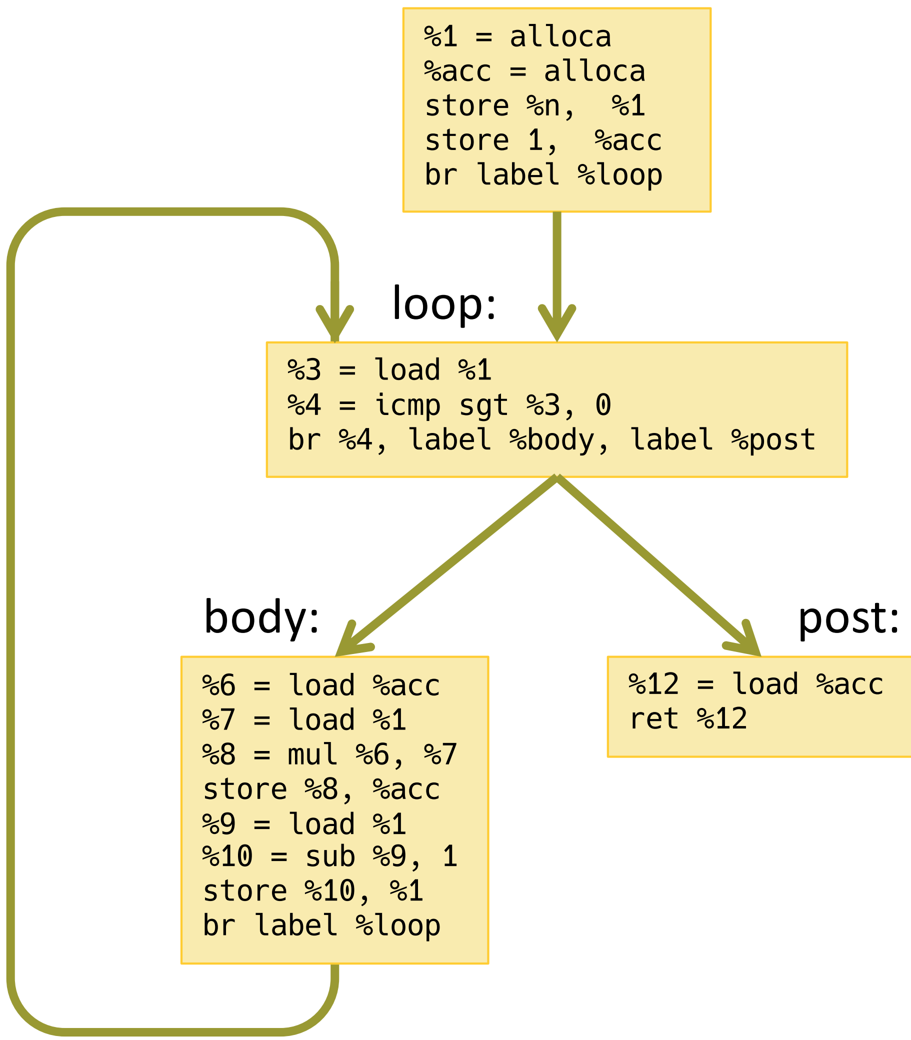
- Decorates values with type information
  `i64`
  `i64*`
  `i1`
- Permits numeric identifiers
- Has alignment annotations
- Keeps track of entry edges for each block: `preds = %5, %0`

factorial.ll

```
; Function Attrs: nounwind ssp
define i64 @factorial(i64 %n) #0 {
  %1 = alloca i64, align 8
  %acc = alloca i64, align 8
  store i64 %n, i64* %1, align 8
  store i64 1, i64* %acc, align 8
  br label %2

; <label>:2                                      ; preds = %5, %0
  %3 = load i64* %1, align 8
  %4 = icmp sgt i64 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                                      ; preds = %2
  %6 = load i64* %acc, align 8
  %7 = load i64* %1, align 8
  %8 = mul nsw i64 %6, %7
  store i64 %8, i64* %acc, align 8
  %9 = load i64* %1, align 8
  %10 = sub nsw i64 %9, 1
  store i64 %10, i64* %1, align 8
  br label %2

; <label>:11                                     ; preds = %2
  %12 = load i64* %acc, align 8
  ret i64 %12
}
```

Example Control-flow Graph

```
define @factorial(%n) {
```




```
}
```

LL Basic Blocks and Control-Flow Graphs

- LLVM enforces (some of) the basic block invariants syntactically.
- Representation in OCaml:

```
type block = {
   insns : (uid * insn) list;
   term  : (uid * terminator)
}
```

- A *control flow graph* is represented as a list of labeled basic blocks with these invariants:
  - No two blocks have the same label
  - All terminators mention only labels that are defined among the set of basic blocks
  - There is a distinguished, unlabeled, entry block:

```
type cfg = block * (lbl * block) list
```

LL Storage Model: Locals

- Several kinds of storage:
  - Local variables (or temporaries): `%uid`
  - Global declarations (*e.g.*, for string constants): `@gid`
  - Abstract locations: references to (stack-allocated) storage created by the `alloca` instruction
  - Heap-allocated structures created by external calls (*e.g.*, to `malloc`)

- Local variables:
  - Defined by the instructions of the form `%uid = …`
  - Must satisfy the ***static single assignment*** invariant
    - *Each* `%uid` *appears on the left-hand side of an assignment only once in the entire control flow graph.*
  - The value of a `%uid` remains unchanged throughout its lifetime
  - Analogous to "`let %uid = e in` …" in OCaml
- Intended to be an abstract version of machine registers.
- We'll see later how to extend SSA to allow richer use of local variables
  - ***phi nodes***

LL Storage Model: `alloca`

- `alloca` instruction allocates stack space and returns a reference to it.
  - The returned reference is stored in local:

    ```
    %ptr = alloca type
    ```

  - The amount of space allocated is determined by the type

- The contents of the slot are accessed via the `load` and `store` instructions:

```
%acc = alloca i64                  ; allocate a storage slot
store i64 4521/5521, i64* %acc     ; store the integer value 4521/5521
%x = load i64, i64* %acc           ; load the value 4521/5521 into %x
```

- Gives an abstract version of stack slots