Lecture 6

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 compile.ml in lec05.zip

DIRECTLY GENERATING X86

Directly Translating AST to Assembly

- For simple languages, no need for intermediate representation.
  - *e.g.*, the arithmetic expression language from SIMPLE
- Main Idea: ***maintain invariants***
  - e.g., code emitted for a given expression computes the answer into rax
- Key Challenges:
  - storing intermediate values needed to compute complex expressions
  - some instructions use specific registers (*e.g.*, shift)

One Simple Strategy

- Compilation is the process of "emitting" instructions into an instruction stream.
- To compile an expression, we recursively compile sub expressions and then process the results.
- Invariants:
  - Argument (X_i) is stored in a dedicated operand
  - Compilation of an expression yields its result in rax
  - Intermediate values are pushed onto the stack
  - Stack slot is popped after use (so the space is reclaimed)
- Resulting code is wrapped to comply with calling conventions:
- See the compile.ml compile1.

Another Simple Strategy

- Use a stack-oriented *intermediate representation*
  1. translate source expressions to stack instructions
  2. translate stack instructions to x86 assembly

- Compilation Invariants:
  - Argument (X_i) is stored in a dedicated operand
  - Compilation of an expression yields its result on the top of the stack
  - We use dedicated registers to process the stack

  note: each instruction can be translated independently

- Resulting code is wrapped to comply with calling conventions:

- See the compile.ml compile2.

INTERMEDIATE REPRESENTATIONS

Why do something else?

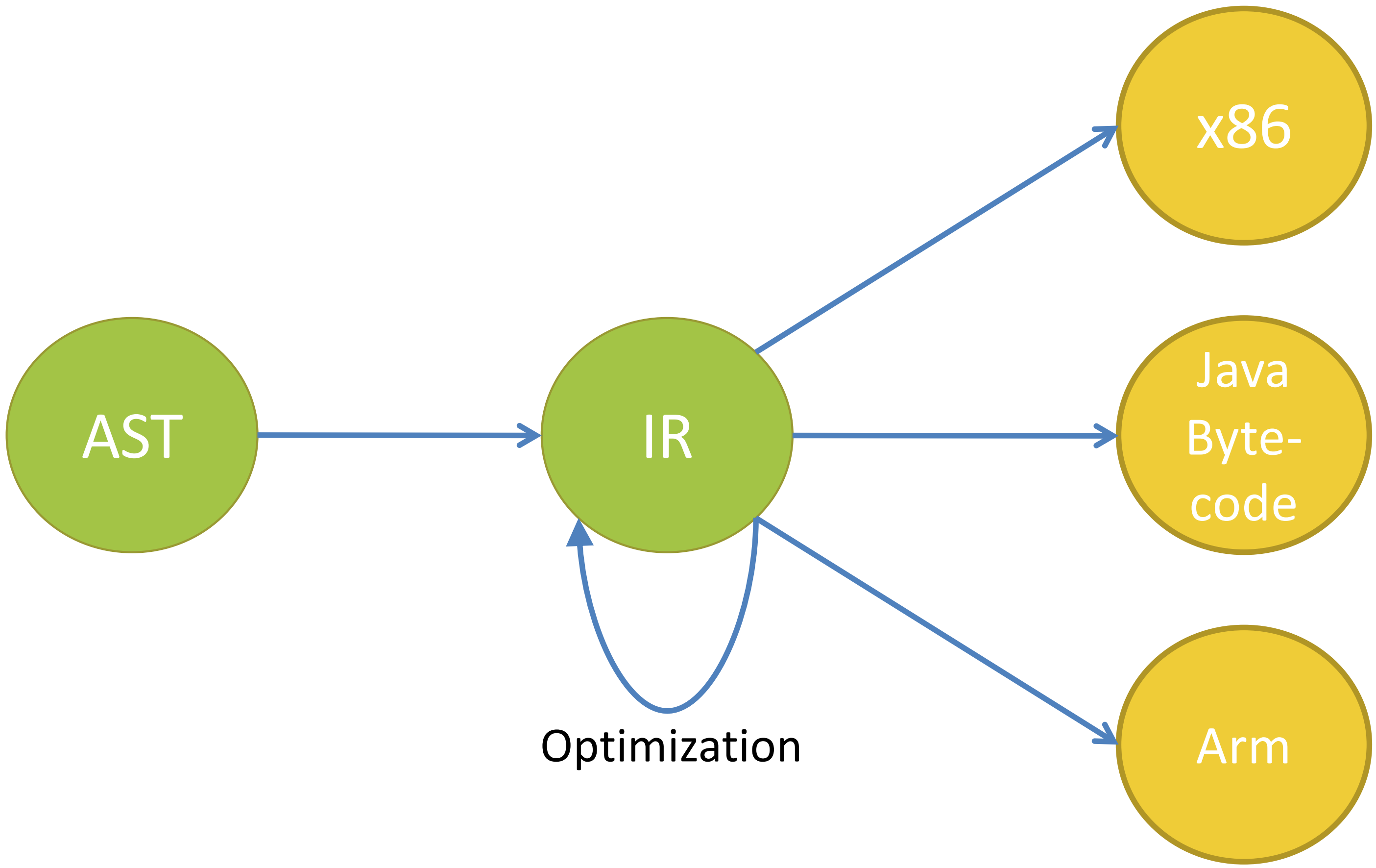
- This is a simple *syntax-directed* translation
  - Input syntax uniquely determines the output, no complex analysis or code transformation is done.
  - It works fine for simple languages.

But…

- The resulting code quality is poor.
- Richer source language features are hard to encode
  - Structured data types, objects, first-class functions, etc.
- It's hard to optimize the resulting assembly code.
  - The representation is too concrete – *e.g.*, it has committed to using certain registers and the stack
  - Only a fixed number of registers
  - Some instructions have restrictions on where the operands are located
- Control-flow is not structured:
  - Arbitrary jumps from one code block to another
  - Implicit fall-through makes sequences of code non-modular (*i.e.*, you can't rearrange sequences of code easily)
- Retargeting the compiler to a new architecture is hard.
  - Target assembly code is hard-wired into the translation

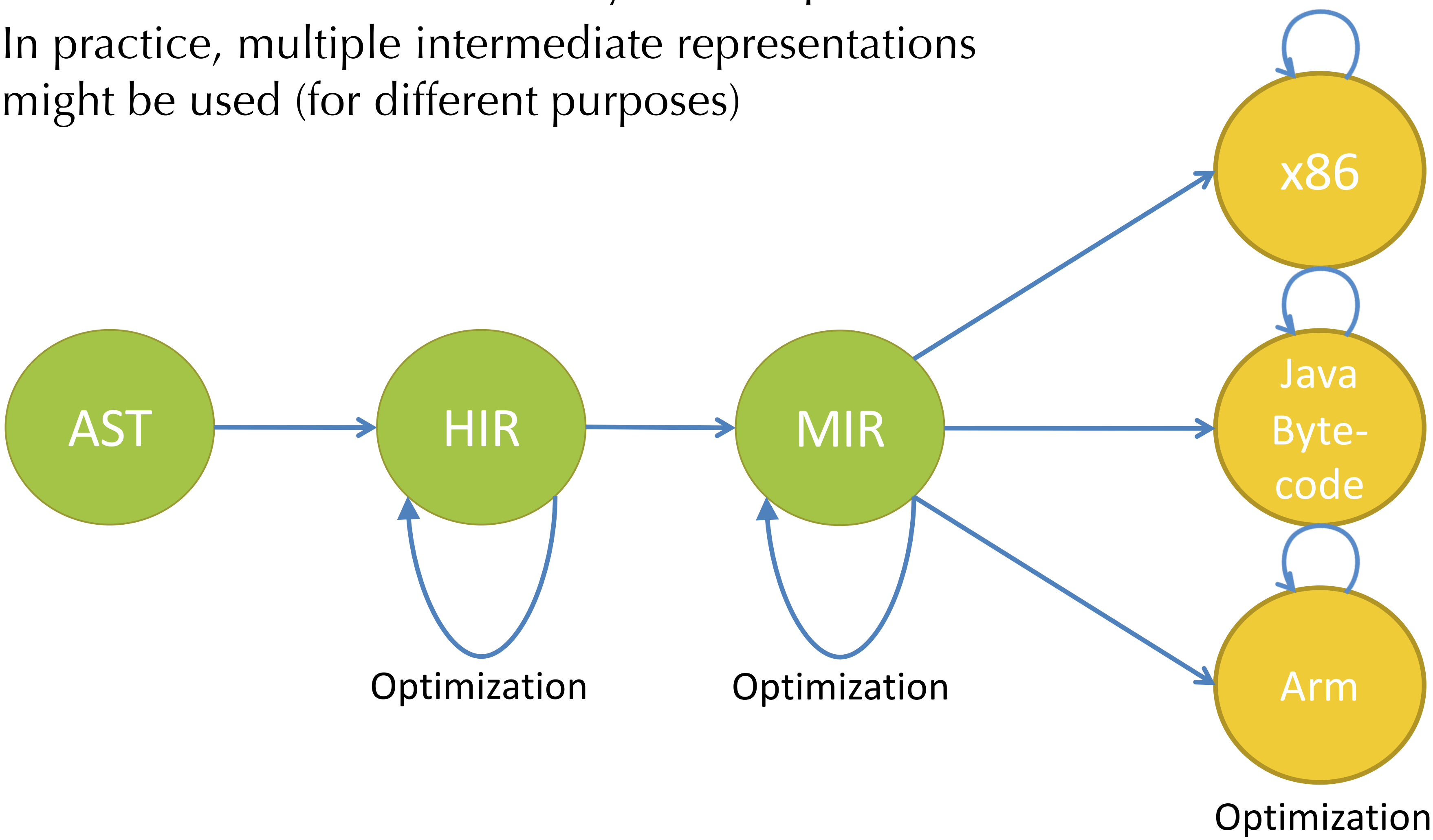
Intermediate Representations (IR's)

- Abstract machine code: hides details of the target architecture
- Allows machine independent code generation and optimization.



Multiple IR's

- Goal: get program closer to machine code without losing the information needed to do analysis and optimizations
- In practice, multiple intermediate representations might be used (for different purposes)



What makes a good IR?

- Easy translation target (from the level above)
- Easy to translate (to the level below)
- Narrow interface
  - Fewer constructs means simpler phases/optimizations

- Example: Source language might have `while`, `for`, and `foreach` loops (and maybe more variants)
  - IR might have only `while` loops and sequencing
  - Translation eliminates `for` and `foreach`

```
⟦for(pre; cond; post) {body}⟧
              =
⟦pre; while(cond) {body;post}⟧
```
*

*Here the notation ⟦cmd⟧ denotes the “translation” or “compilation” of the command cmd.

IR's at the extreme

- High-level IR's
  - Abstract syntax + new node types not generated by the parser
    - e.g., Type checking information or disambiguated syntax nodes
  - Typically preserves the high-level language constructs
    - Structured control flow, variable names, methods, functions, etc.
    - May do some simplification (e.g., convert `for` to `while`)
  - Allows high-level optimizations based on program structure
    - e.g., inlining "small" functions, reuse of constants, etc.
  - Useful for semantic analyses like type checking

- Low-level IR's
  - Machine dependent assembly code + extra pseudo-instructions
    - e.g., a pseudo instruction for interfacing with garbage collector or memory allocator (parts of the language runtime system)
    - e.g., (on x86) a `imulq` instruction that doesn't restrict register usage
  - Source structure of the program is lost:
    - Translation to assembly code is straightforward
  - Allows low-level optimizations based on target architecture
    - e.g., register allocation, instruction selection, memory layout, etc.

- What's in between?

Mid-level IR's: Many Varieties

- Intermediate between AST (abstract syntax) and assembly
- May have unstructured jumps, abstract registers or memory locations
- Convenient for translation to high-quality machine code
  - Example: all intermediate values might be named to facilitate optimizations that attempt to minimize stack/register usage

- Many examples:
  - Triples: `OP a b`
    - Useful for instruction selection on X86 via "tiling"
  - Quadruples: `a = b OP c` (RISC-like "three address form")
  - SSA static single assignment `a = op b c`
    - variant of quadruples where each variable is assigned exactly once
    - Easy dataflow analysis for optimization
    - e.g., LLVM IR: industrial-strength IR, based on SSA
  - Stack-based:
    - Easy to generate
    - e.g., Java Bytecode, UCODE

Growing an IR

- Develop an IR in detail… starting from the very basic.

- Start: a (very) simple intermediate representation for the arithmetic language
  - Very high level
  - No control flow

- Goal: A simple subset of the LLVM IR
  - LLVM = "Low-level Virtual Machine"
  - Used in HW3+

- Add features needed to compile rich source languages

SIMPLE LET-BASED IR

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