ECE 573: Compilers & Translation Systems Engineering

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http://www.engineering.purdue.edu/~milind/ece573/2011fall
Announcements

- “Problem Set” 0 online
- Short questionnaire
- Project step 0 due this Friday
  - Use subject line “ECE 573: Project Step 0”
  - Let me know if you plan to work with a partner
    - Send me an email even if you don’t!
What is a compiler?

- Traditionally: Program that analyzes and translates from a high level language (e.g., C++) to low-level assembly language that can be executed by hardware

```c
int a, b;
a = 3;
if (a < 4) {
    b = 2;
} else {
    b = 3;
}
```

```assembly
var a
var b
mov 3 a
mov 4 r1
cmpi a r1
jge l_e
mov 2 b
jmp l_d
l_e:    mov 3 b
l_d:    ;done
```
Compilers are *translators*

- Fortran
- C
- C++
- Java
- Text processing language
- HTML/XML
- Command & Scripting Languages
- Natural language
- Domain specific languages

- Machine code
- Virtual machine code
- Transformed source code
- Augmented source code
- Low-level commands
- Semantic components
- Another language
Compilers are *optimizers*

- Can perform optimizations to make a program more efficient

```c
int a, b, c;
b = a + 3;
c = a + 3;
```

```asm
var a
var b
var c
mov a r1
addi 3 r1
mov r1 b
mov a r2
addi 3 r2
mov r2 c
```
Why do we need compilers?

- Compilers provide *portability*

- Old days: whenever a new machine was built, programs had to be rewritten to support new instruction sets

- IBM System/360 (1964): Common Instruction Set Architecture (ISA) — programs could be run on any machine which supported ISA

- Common ISA is a huge deal (note continued existence of x86)

- But still a problem: when new ISA is introduced (EPIC) or new extensions added (x86-64), programs would have to be rewritten

- Compilers bridge this gap: write new compiler for an ISA, and then simply recompile programs!
Why do we need compilers? (II)

- Compilers enable **high performance and productivity**
- Old: programmers wrote in assembly language, architectures were simple (no pipelines, caches, etc.)
  - Close match between programs and machines — easier to achieve performance
- New: programmers write in high level languages (Ruby, Python), architectures are complex (superscalar, out-of-order execution, multicore)
- Compilers are needed to bridge this *semantic gap*
  - Compilers let programmers write in high level languages and still get good performance on complex architectures
Semantic Gap

```ruby
def index
  @posts = Post.find(:all)

  respond_to do |format|
    format.html # index.html.erb
    format.xml { render :xml => @posts }
  end
end
```

Snippet of Ruby-on-rails code

AMD Barcelona architecture
def index
  @posts = Post.find(:all)

  respond_to do |format|
    format.html # index.html.erb
    format.xml { render :xml => @posts }
  end
end

This would be impossible without compilers!

Snippet of Ruby-on-rails

AMD Barcelona architecture

Semantic Gap
Some common compiler types

1. High level language $\Rightarrow$ assembly language (e.g., gcc)

2. High level language $\Rightarrow$ machine independent bytecode (e.g., javac)

3. Bytecode $\Rightarrow$ native machine code (e.g., java’s JIT compiler)

4. High level language $\Rightarrow$ high level language (e.g., domain specific languages, many research languages—including mine!)
HLL to Assembly

- Compiler converts program into assembly
- Assembler is machine-specific translator which converts assembly into machine code
  
  \[
  \text{add } $7 \text{ } $8 \text{ } $9 \Rightarrow 000000 \text{ 00111 01000 01001 0000 100000}
  \]

- Conversion is usually one-to-one with some exceptions
  - Program locations
  - Variable names
HLL to Bytecode

- Compiler converts program into machine independent bytecode
  - e.g., javac generates Java bytecode, C# compiler generates CIL
- Interpreter then executes bytecode “on-the-fly”
  - Bytecode instructions are “executed” by invoking methods of the interpreter, rather than directly executing on the machine
- Aside: what are the pros and cons of this approach?
Compiler converts program into machine independent bytecode

- e.g., javac generates Java bytecode, C# compiler generates CIL

Just-in-time compiler compiles code while program executes to produce machine code

- Is this better or worse than a compiler which generates machine code directly from the program?
Structure of a Compiler
Scanner

- Compiler starts by seeing only program text

```java
if (a < 4) {
    b = 5
}
```
Scanner

- Compiler starts by seeing only program text

```plaintext
'i' 'f' ' ' ' ' ( ' ' 'a' ' ' '<' ' ' '4' ' ' ) ' 
' ' ' '{' ' ' \n' ' ' \t' ' ' 'b' ' ' '=' ' ' '5' ' 
' ' ' \n' ' ' '} '
```
• Compiler starts by seeing only program text
• Scanner converts program text into string of tokens

```
'i' 'f' ' ' '(' 'a' '<' '4' ')
' ' '{' '
' 't' 'b' '=' '5'
' '
' '}'
```
Scanner

- Compiler starts by seeing only program text
- Scanner converts program text into string of tokens

But we still don’t know what the syntactic structure of the program is

```plaintext
if ( ID(a) OP(<) LIT(4) )
{
    ID(b) = LIT(5)
}
```
Parser

• Converts string of tokens into a parse tree or an abstract syntax tree.

• Captures syntactic structure of code (i.e., “this is an if statement, with a then-block”)

```plaintext
if (ID(a) OP(<) LIT(4) )
{
  ID(b) = LIT(5)
}
```
Parser

• Converts string of tokens into a *parse tree* or an *abstract syntax tree*.

• Captures syntactic structure of code (i.e., “this is an if statement, with a then-block”)

```
if-stmt
  cond-expr
    <
      lhs
      rhs 4
    stmt_list
      then-clause
      assign_stmt
        lhs
        rhs

a
4
stmt_list
assign_stmt
b
5
```
Semantic actions

- Interpret the *semantics* of syntactic constructs
- Note that up until now we have only been concerned with what the *syntax* of the code is
- What’s the difference?
Syntax vs. Semantics

• Syntax: “grammatical” structure of language
  • What symbols, in what order, is a legal part of the language?
  • But something that is syntactically correct may mean nothing!
    • “colorless green ideas sleep furiously”

• Semantics: meaning of language
  • What does a particular set of symbols, in a particular order, mean?
    • What does it mean to be an if statement?
    • “evaluate the conditional, if the conditional is true, execute the then clause, otherwise execute the else clause”
A note on semantics

• How do you define semantics?
  • Static semantics: properties of programs
    • All variables must have a type
    • Expressions must use consistent types
    • Can define using attribute grammars
  • Execution semantics: how does a program execute?
    • Can define an operational or denotational semantics for a language
    • Not covered in this class (take CS 565)
  • For many languages, “the compiler is the specification”
Semantic actions

• Actions taken by compiler based on the semantics of program statements
  • Building a symbol table
  • Generating intermediate representations
Symbol tables

- A list of every declaration in the program, along with other information
- Variable declarations: types, scope
- Function declarations: return types, # and type of arguments

Program Example

Integer ii;
...
ii = 3.5;
...
print ii;

Symbol Table

Name  Type  Scope
ii     int   global
...
Intermediate representation

- Also called IR
- A (relatively) low level representation of the program
- But not machine-specific!
- One example: *three address code*

```
bge a, 4, done
mov 5, b
```
```
done: //done!
```
- Each instruction can take at most three operands
  (variables, literals, or labels)
- Note: no registers!
Optimizer

- Transforms code to make it more efficient
- Different kinds, operating at different levels
  - High-level optimizations
    - Loop interchange, parallelization
    - Operates at level of AST, or even source code
  - Scalar optimizations
    - Dead code elimination, common sub-expression elimination
    - Operates on IR
  - Local optimizations
    - Strength reduction, constant folding
    - Operates on small sequences of instructions
Code generation

- Generate assembly from intermediate representation
- Select which instructions to use
- Schedule instructions
- Decide which registers to use

```
ld a, r1
mov 4, r2
cmp r1, r2
bge done
mov 5, r3
st r3, b
done:
```
Code generation

- Generate assembly from intermediate representation
- Select which instructions to use
- Schedule instructions
- Decide which registers to use

bge a, 4, done
mov 5, b
done: //done!

mov 4, r1
ld a, r2
cmp r1, r2
blt done
mov 5, r1
st r1, b
done:
Overall structure of a compiler

- Use regular expressions to define tokens. Can then use scanner generators such as lex or flex.
- Define language using context free grammars. Can then use parser generators such as yacc or bison.
- Semantic routines done by hand. But can be formalized.
- Written manually. Automation is an active research area (e.g., dataflow analysis frameworks)
- Written manually
Use *regular expressions* to define tokens. Can then use scanner generators such as lex or flex.

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Written manually.

Many of these passes can be combined.
Design considerations (I)

• Compiler and language designs influence each other
  • Higher level languages are harder to compile
    • More work to bridge the gap between language and assembly
  • Flexible languages are often harder to compile
    • Dynamic typing (Ruby, Python) makes a language very flexible, but it is hard for a compiler to catch errors (in fact, many simply won’t)
Design considerations (II)

• Compiler design is influenced by architectures
  • CISC vs. RISC
  • CISC designed for days when programmers wrote in assembly
    • For a compiler to take advantage of string manipulation instructions, it must be able to recognize them
  • RISC has a much simpler instruction model
    • Easier to compile for