Compiler

(CS3104)

Introduction 1

Taken from: https://web.stanford.edu/class/cs143/

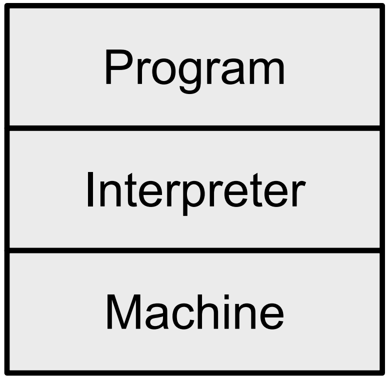
Course Goal

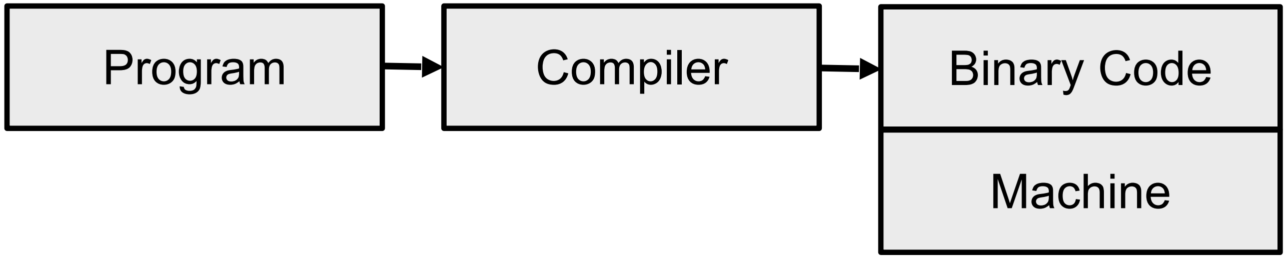
- Open the lid of compilers and see inside
  - Understand what they do
  - Understand how they work
  - Understand how to build them

- **Correctness** over performance
  - Correctness is essential in compilers
  - They must produce correct code
  - Enormous consequences if they do not

How are Languages Implemented?

- Two major strategies:
  - Interpreters run your program
  - Compilers translate your program





Language Implementations

- Compilers dominate low-level languages
  - C, C++, Go, Rust

- Interpreters dominate high-level languages
  - Python, JavaScript

- Many language implementations provide both
  - Java, Javascript, WebAssembly
  - Interpreter + Just in Time (JIT) compiler

History of High-Level Languages

- 1954: IBM develops the 704

- Problem
  - Software costs exceeded hardware costs!

- All programming done in assembly

The Solution

- Enter “Speedcoding”
- An interpreter
- Ran 10-20 times slower than hand-written assembly

FORTRAN I

- Enter John Backus

- Idea
  - Translate high-level code to assembly
  - Many thought this impossible
  - Had already failed in other projects

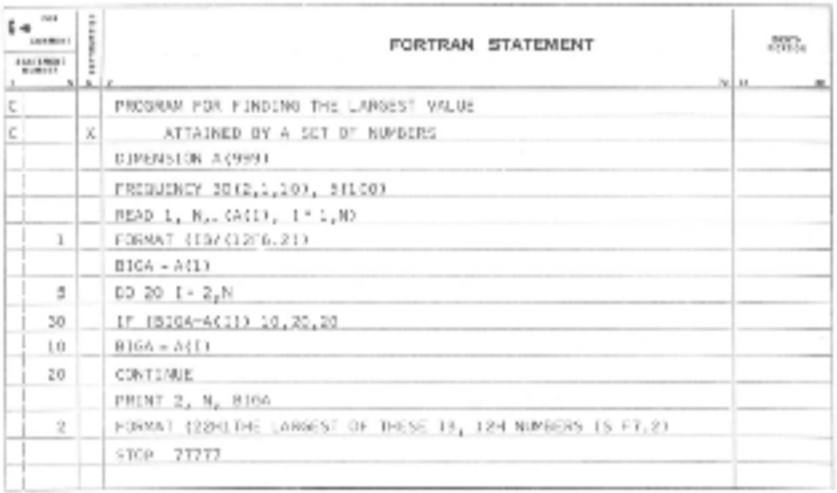
FORTRAN I (Cont.)

- 1954-7
  - FORTRAN I project

- 1958
  - >50% of all software is in FORTRAN

- Development time halved

- Performance close to hand-written assembly!



FORTRAN STATEMENT

```
C        PROGRAM FOR FINDING THE LARGEST VALUE
C      X     ATTAINED BY A SET OF NUMBERS
         DIMENSION A(999)
         FREQUENCY 30(2,1,10), 5(100)
         READ 1, N, (A(I), I = 1,N)
    1    FORMAT (I3/(12F6.2))
         BIGA = A(1)
    5    DO 20 I = 2,N
   30    IF (BIGA-A(I)) 10,20,20
   10    BIGA = A(I)
   20    CONTINUE
         PRINT 2, N, BIGA
    2    FORMAT (22H1THE LARGEST OF THESE I3, 12H NUMBERS IS F7.2)
         STOP 77777
```

FORTRAN I

- The first compiler
  - Huge impact on computer science
- Led to an enormous body of theoretical and practical work
- Modern compilers preserve the outlines of FORTRAN I
- Can you name a modern compiler?

The Structure of a Compiler

1. Lexical Analysis — identify words
2. Parsing — identify sentences
3. Semantic Analysis — analyse sentences
4. Optimization — editing
5. Code Generation — translation

Can be understood by analogy to how humans comprehend English.

Lexical Analysis

- First step: recognize words.
  - Smallest unit above letters

This is a sentence.

More Lexical Analysis

- Lexical analysis is not trivial.

- Suppose we scramble the whitespaces:

  ist his ase nte nce

- Suppose we replace whitespace with z:

  iszthiszazsentence

And More Lexical Analysis

- Lexical analyzer divides program text into “words” or “tokens”

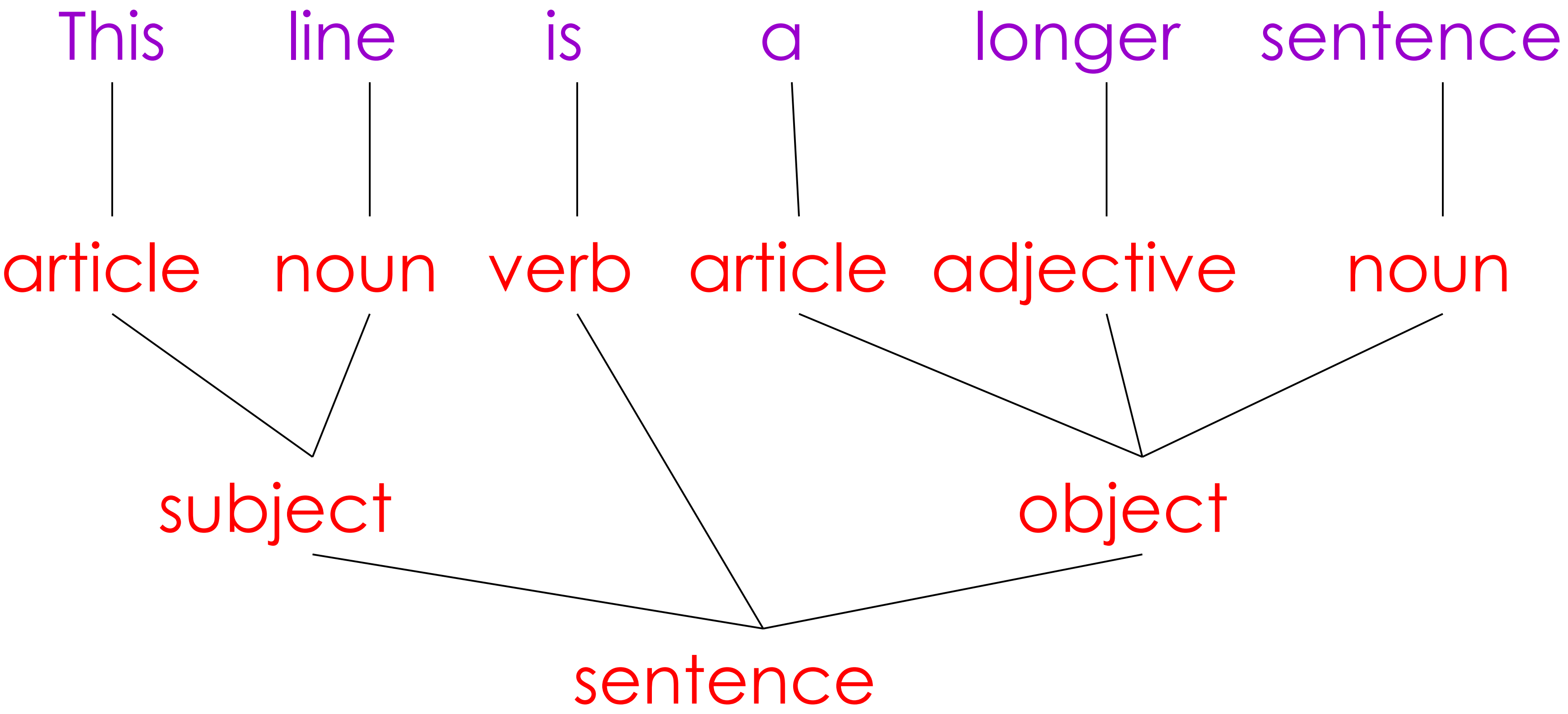
```
if x == y then z = 1; else z = 2;
```

Parsing

- Once words are understood, the next step is to understand sentence structure

- Parsing = Diagramming Sentences
  - The diagram is a tree

Diagramming a Sentence

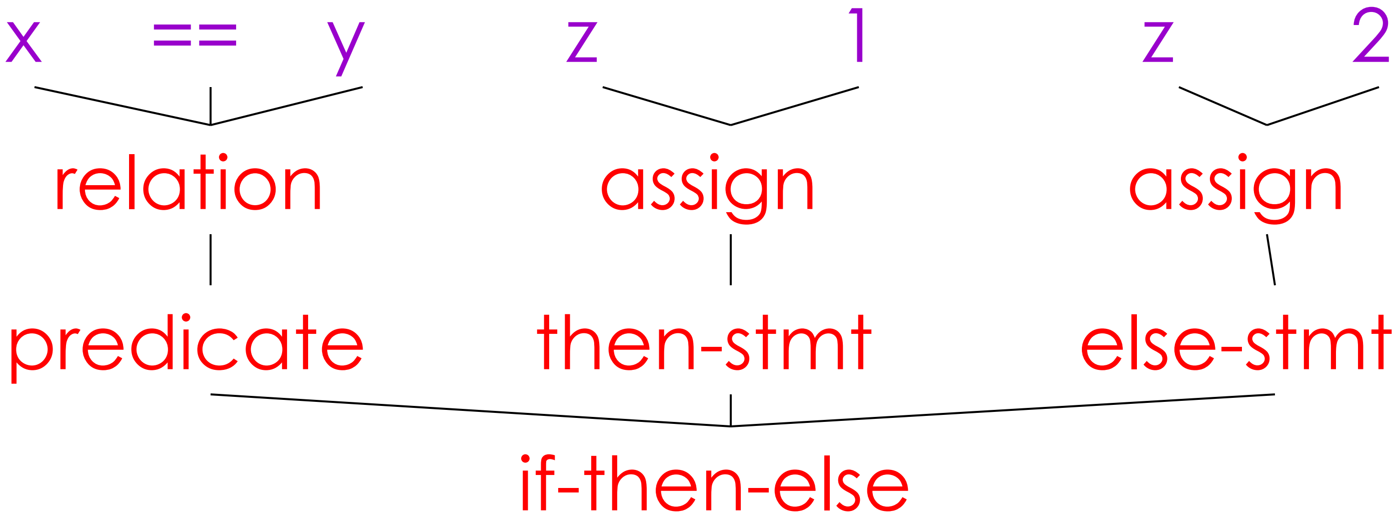


Parsing Programs

- Parsing program expressions is the same
- Consider:

  if x == y then z = 1 else z = 2

- Diagrammed:



x == y z 1 z 2

relation assign assign

predicate then-stmt else-stmt

if-then-else

Semantic Analysis

- Once sentence structure is understood, we can try to understand “meaning”
  - But meaning is too hard for compilers

- Compilers perform limited semantic analysis to catch inconsistencies

Semantic Analysis in English

- Example:

Jack said Jerry left his assignment at home.

What does “his” refer to? Jack or Jerry?

- Even worse:

Jill said Jill left her assignment at home?

How many Jills are there?

Which one left the assignment?

Semantic Analysis in Programming

- Programming languages define strict rules to avoid such ambiguities

- This C++ code prints "4"; the inner definition is used

```
{
   int i = 3;
   {
        int i = 4;
        cout << i;
   }
}
```

More Semantic Analysis

- Compilers perform many semantic checks besides variable bindings

- Example:

  Jack left her homework at home.

- Possible type mismatch between her and Jack
  - If Jack is male

Optimization

- Akin to editing
  - Minimize reading time
  - Minimize items the reader must keep in short-term memory

- Automatically modify programs so that they
  - Run faster
  - Use less memory
  - In general, to conserve some resource

Optimization Example

x = y * 0 is the same as x = 0

(the * operator is annihilated by zero)

Is this optimization legal?

Code Generation

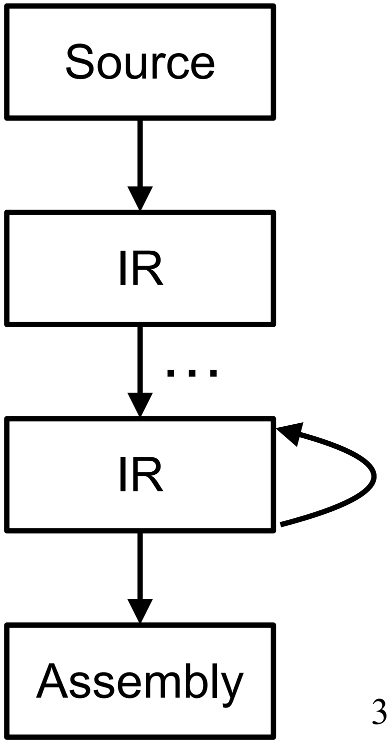
- Typically produces assembly code

- Generally a translation into another language
  - Analogous to human translation

Intermediate Representations (IR)

- Compilers typically perform translations between successive intermediate languages
  - All but first and last are intermediate representations (IR) internal to the compiler

- IRs are generally ordered in descending level of abstraction
  - Highest is source
  - Lowest is assembly



Intermediate Representations (IR) (Cont.)

- IRs are useful because lower levels expose features hidden by higher levels
  - registers
  - memory layout
  - raw pointers
  - etc.

- But lower levels obscure high-level meaning
  - Classes
  - Higher-order functions
  - Even loops…

Issues

- Compiling is almost this simple, but there are many pitfalls

- Example: How to handle erroneous programs?

- Language design has a big impact on the compiler
  - Determines what is easy and hard to compile
  - Course theme: many trade-offs in language design

Compilers Today

- The overall structure of almost every compiler adheres to our outline

- The proportions have changed since FORTRAN
  - Early: lexing and parsing most complex/expensive
  - Today: optimization dominates all other phases, lexing and parsing are well understood and cheap

- Compilers are now also found inside libraries:
  - XLA, TVM, Halide, DBMS, …