# Compiler Design 1

## Introduction to Programming Language Design and to Compilation

## Administrivia

- Lecturer:
  - Kostis Sagonas (Hus 1, 352)
- Course home page:

  http://user.it.uu.se/~kostis/Teaching/KT1-11
- If you want to be enrolled in the course, send mail with your name and UU account to:

  kostis@it.uu.se
- Assistant:
  - Stavros Aronis (stavros.aronis@it.uu.se)
  - responsible for the lessons and the assignments

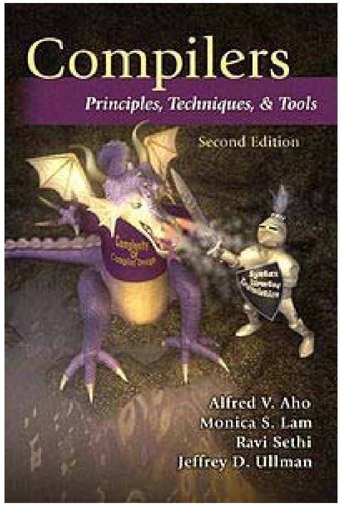


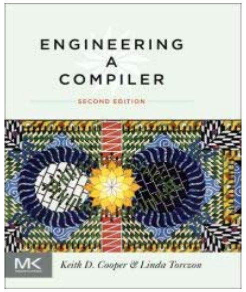
## Course Structure

- Course has theoretical and practical aspects
- Need both in programming languages!
- Written examination = theory (4 points)
- Assignments = practice (1 point)
  - Electronic hand-in to the assistant before the corresponding deadline

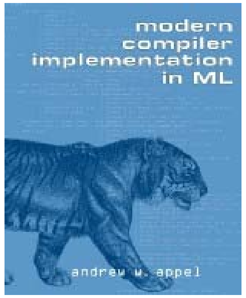


## Course Literature







## Academic Honesty

- For assignments you are allowed to work in pairs (but no threesomes/foursomes/...)
- Don't use work from uncited sources
  - Including old assignments




## The Compiler Project

- A follow-up course
- that will be taught by Sven-Olof Nyström
- in period 3



## How are Languages Implemented?

- Two major strategies:
  - Interpreters (older, less studied)
  - Compilers (newer, much more studied)
- Interpreters run programs "as is"
  - Little or no preprocessing
- Compilers do extensive preprocessing

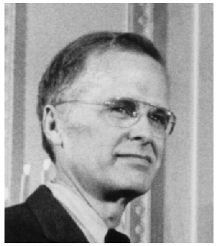


## Language Implementations

- Batch compilation systems dominate
  - gcc
- Some languages are primarily interpreted
  - Java bytecode
  - Postscript
- Some environments (e.g. Lisp) provide both
  - Interpreter for development
  - Compiler for production

## (Short) History of High-Level Languages

- 1953 IBM develops the 701
- Till then, all programming done in assembly
- Problem: Software costs exceeded hardware costs!
- John Backus: "Speedcoding"
  - An interpreter
  - Ran 10-20 times slower than hand-written assembly





## FORTRAN I

- 1954 IBM develops the 704
- John Backus
  - Idea: translate high-level code to assembly
  - Many thought this impossible
    - Had already failed in other projects
- 1954-7 FORTRAN I project
- By 1958, >50% of all software is in FORTRAN
- Cut development time dramatically
  - (2 weeks → 2 hours)



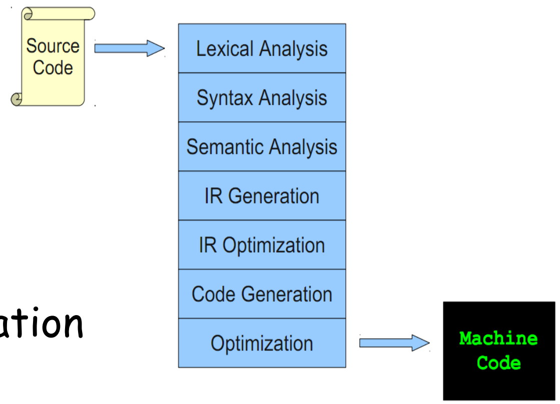
## FORTRAN I

- The first compiler
  - Produced code almost as good as hand-written
  - Huge impact on computer science
- Led to an enormous body of theoretical work
- Modern compilers preserve the outlines of the FORTRAN I compiler



## The Structure of a Compiler

1. Lexical Analysis
2. Syntax Analysis
3. Semantic Analysis
4. IR Optimization
5. Code Generation
6. Low-level Optimization




The first 3, at least, can be understood by analogy to how humans comprehend English.

## Lexical Analysis

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

This is a sentence.

- Note the
  - Capital "T" (start of sentence symbol)
  - Blank " " (word separator)
  - Period "." (end of sentence symbol)



## More Lexical Analysis

- Lexical analysis is not trivial. Consider:

ist his ase nte nce

- Plus, programming languages are typically more cryptic than English:

*p->f ++ = -.12345e-5



## And More Lexical Analysis

- Lexical analyzer divides program text into "words" or "tokens"

if (x == y) then z = 1; else z = 2;

- Units:

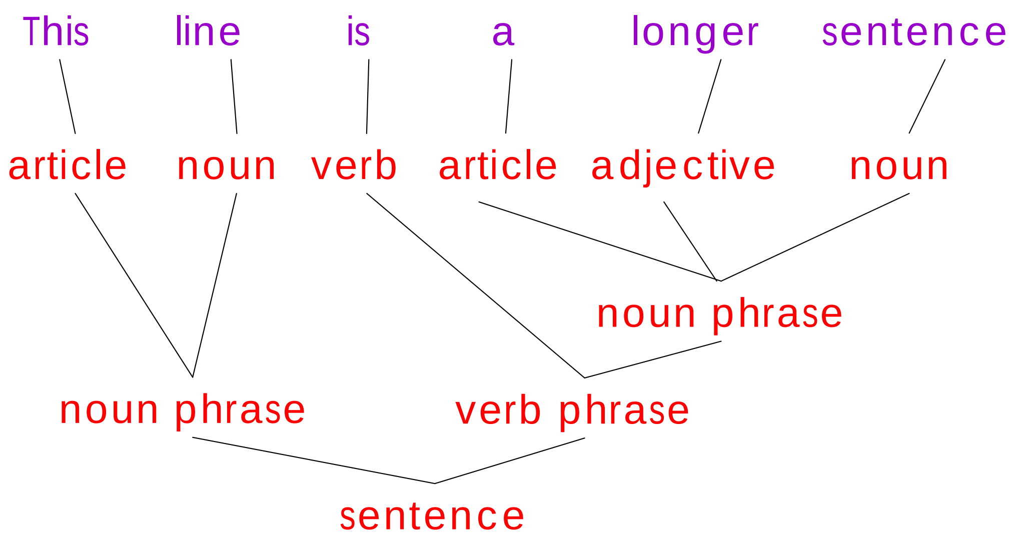
if, (, x, ==, y, ), then, z, =, 1, ;, else, z, =, 2, ;



## Parsing

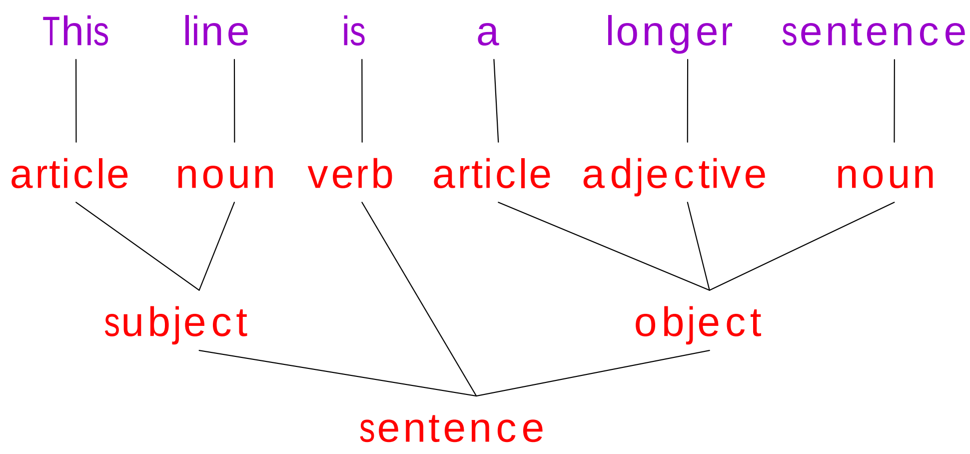
- Once words are understood, the next step is to understand the sentence structure
- Parsing = Diagramming Sentences
  - The diagram is a tree

## Diagramming a Sentence (1)






## Diagramming a Sentence (2)



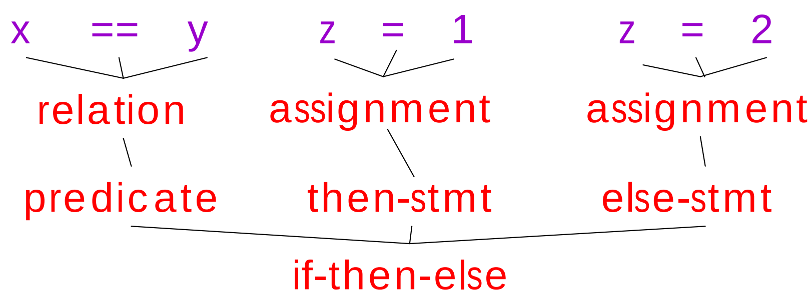



## Parsing Programs

- Parsing program expressions is the same
- Consider:

  If (x == y) then z = 1; else z = 2;

- Diagrammed:






## Semantic Analysis

- Once sentence structure is understood, we can try to understand its "meaning"
  - But meaning is too hard for compilers
- Most compilers perform limited analysis to catch inconsistencies
- Some optimizing compilers do more analysis to improve the performance of the program

## Semantic Analysis in English

- Example:

  Jack said Jerry left his assignment at home.

  What does "his" refer to? Jack or Jerry?

- Even worse:

  Jack said Jack left his assignment at home?

  How many Jacks are there?

  Which one left the assignment?



## Semantic Analysis in Programming Languages

- Programming languages define strict rules to avoid such ambiguities

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

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



## More Semantic Analysis

- Compilers perform many semantic checks besides variable bindings

- Example:

  Arnold left her homework at home.

- A "type mismatch" between her and Arnold; we know they are different people
  - Presumably Arnold is male



## Optimization

- No strong counterpart in English, but akin to editing
- Automatically modify programs so that they
  - Run faster
  - Use less memory/power
  - In general, conserve some resource more economically
- The compilers project has no optimization component
  - for those interested there is KT2 !

## Optimization Example

X = Y * 0 is the same as X = 0

**NO!**

Valid for integers, but not for floating point numbers



## Code Generation

- Produces assembly code (usually)
- A translation into another language
  - Analogous to human translation



## Intermediate Languages

- Many compilers perform translations between successive intermediate forms
  - All but first and last are *intermediate languages* internal to the compiler
  - Typically there is one IL
- IL's generally ordered in descending level of abstraction
  - Highest is source
  - Lowest is assembly



## Intermediate Languages (Cont.)

- IL's are useful because lower levels expose features hidden by higher levels
  - registers
  - memory/frame layout
  - etc.
- But lower levels obscure high-level meaning

## Issues

- Compiling is almost this simple, but there are many pitfalls
- Example: How are erroneous programs handled?
- Language design has big impact on 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:
    - lexical analysis, parsing most complex, expensive
  - Today:
    - semantic analysis and optimization dominate all other phases; lexing and parsing are well-understood and cheap



## Current Trends in Compilation

- Compilation for speed is less interesting. But:
  - scientific programs
  - advanced processors (Digital Signal Processors, advanced speculative architectures, GPUs)
- Ideas from compilation used for improving code reliability:
  - memory safety
  - detecting data races
  - ...



## Programming Language Economics

- Programming languages are designed to fill a void
  - enable a previously difficult/impossible application
  - orthogonal to language design quality (almost)
- Programming training is the dominant cost
  - Languages with a big user base are replaced rarely
  - Popular languages become ossified
  - but it is easy to start in a new niche...

## Why so many Programming Languages?

- Application domains have distinctive (and sometimes conflicting) needs
- Examples:
  - ***Scientific computing***: High performance
  - ***Business***: report generation
  - ***Artificial intelligence***: symbolic computation
  - ***Systems programming***: efficient low-level access
  - Other special purpose languages...



## Topic: Language Design

- No universally accepted metrics for design
- "A good language is one people use"
- NO !
  - Is COBOL the best language?
- Good language design is hard



## Language Evaluation Criteria

| Characteristic | Criteria | | |
|---|---|---|---|
| | Readability | Writeability | Reliability |
| Simplicity | YES | YES | YES |
| Data types | YES | YES | YES |
| Syntax design | YES | YES | YES |
| Abstraction | | YES | YES |
| Expressivity | | YES | YES |
| Type checking | | | YES |
| Exceptions | | | YES |



## History of Ideas: Abstraction

- Abstraction = detached from concrete details
- Necessary for building software systems
- Modes of abstraction:
  - Via languages/compilers
    - higher-level code; few machine dependencies
  - Via subroutines
    - abstract interface to behavior
  - Via modules
    - export interfaces which hide implementation
  - Via abstract data types
    - bundle data with its operations

## History of Ideas: Types

- Originally, languages had only few types
  - FORTRAN: scalars, arrays
  - LISP: no static type distinctions
- Realization: types help
  - provide code documentation
  - allow the programmer to express abstraction
  - allow the compiler to check among many frequent errors and sometimes guarantee various forms of safety
- More recently:
  - experiments with various forms of parameterization
  - best developed in functional languages



## History of Ideas: Reuse

- Exploits common patterns in software development
- Goal: mass produced software components
- Reuse is difficult
- Two popular approaches (combined in C++)
  - Type parameterization (List(Int) & List(Double))
  - Class and inheritance: C++ derived classes
- Inheritance allows:
  - specialization of existing abstractions
  - extension, modification and information hiding



## Current Trends

- **Language design**
  - Many new special-purpose languages
  - Popular languages to stay
- **Compilers**
  - More needed and more complex
  - Driven by increasing gap between
    - new languages
    - new architectures
  - Venerable and healthy area



## Why study Compiler Design?

- Increase knowledge of common programming constructs and their properties
- Improve understanding of program execution
- Increase ability to learn new languages

- Learn how to build a large and reliable system
- Learn new (programming) techniques
- See many basic CS concepts at work