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

- Compilers: Principles, Techniques, & Tools
- Engineering a Compiler
- Crafting a Compiler
- Modern Compiler Implementation in ML
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

PLAGIARISM
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)

This line is a longer sentence

article noun verb article adjective noun

noun phrase

noun phrase verb phrase

sentence
Diagramming a Sentence (2)

This line is a longer sentence

article noun verb article adjective noun

subject object sentence
Parsing Programs

• Parsing program expressions is the same

• Consider:

\[
\text{If (}x \text{ == } y\text{) then } z = 1; \text{ else } z = 2;
\]

• Diagrammed:

\[
\begin{align*}
x & \quad == \
\quad \text{relation} & 
\quad z & \quad = \quad 1 \\
\quad \text{predicate} & 
\quad z & \quad = \quad 2 \\
\quad \text{then-stmt} & 
\quad \text{else-stmt} & 
\quad \text{if-then-else}
\end{align*}
\]
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.

```cpp
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

\[ X = Y \times 0 \text{ is the same as } X = 0 \]

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

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<td>Simplicity</td>
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<tr>
<td>Data types</td>
<td>YES</td>
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<tr>
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<td>YES</td>
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<tr>
<td>Abstraction</td>
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<td>Expressivity</td>
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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