1DL321: Kompilatorteknik I
(Compiler Design 1)

Introduction to Programming
Language Design and to Compilation
Administrivia

• Lecturer:
  - Kostis Sagonas (kostis@it.uu.se)

• Course home page:
  http://www.it.uu.se/edu/course/homepage/komp/ht16

• 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 credits)
  - first exam scheduled for 19th December 2016

- Four assignments = practice (1 credit)
  - Electronic hand-in to the assistant before the corresponding deadline
  - You can submit one late assignment, if you need to, but it cannot be later than the deadline of the next assignment (for 1-3) or Dec. 20th (for 4th)
Course Literature

  - Alfred V. Aho
  - Monica S. Lam
  - Ravi Sethi
  - Jeffrey D. Ullman

- *Engineering a Compiler* (Second Edition)
  - Keith D. Cooper & Linda Torczon

- *Crafting a Compiler*

- *Modern Compiler Implementation in ML*
  - Andrew W. Appel
Academic Honesty

• For assignments you are allowed to work in pairs (but no threesomes/foursomes/...)
• Don’t share your work with others
  • e.g. post on public repositories
• Don’t use work from non-cited sources
  • including old assignments
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

- Today, batch compilation systems dominate
  - `gcc`, `clang`, ...

- Some languages are primarily interpreted
  - Java bytecode compiler (`javac`)
  - Scripting languages (`perl`, `python`, `javascript`, `ruby`)

- Some languages (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 is 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 phases can be understood by analogy to how humans comprehend natural languages (e.g. Swedish or English).
First Step: Lexical Analysis

• 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"
  
  ```plaintext
  if (x == y) then z = 1; else z = 2;
  ```

- Units:
  ```plaintext
  if, (, x, ==, y, ), then, z, =, 1, ;, else, z, =, 2, ;
  ```
Second Step: Syntax Analysis (Parsing)

• Once words are identified, 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 program expressions is the same
• Consider:

  \[
  \text{if (} x == y \text{) then } z = 1; \text{ else } z = 2; 
  \]
• Diagrammed:

```
  x == y  z = 1  z = 2
    \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\     \|--\      
```

```}

- relation
- assignment
- assignment
- predicate
- then-stmt
- else-stmt
- if-then-else

```
Third Step: Semantic Analysis

• Once the 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 42; the inner definition is used

```cpp
int Jack = 17;
{
    int Jack = 42;
    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
    - avoid some source code redundancy
    - exploit the underlying hardware more effectively
  - Use less memory/cache/power
  - In general, conserve some resource more economically
Optimization Example

\[ X = Y \times 0 \] 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

- Intermediate languages 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:
    • lexical analysis and parsing are well-understood and cheap
    • semantic analysis and optimization dominate
    • focus on concurrency/parallelism and interactions with the memory model of the underlying platform
    • optimization for code size and energy consumption
Current Trends in Compilation

• Compilation for speed is less interesting. However, there are exceptions:
  - scientific programs
  - advanced processors (Digital Signal Processors, advanced speculative architectures, GPUs)

• Ideas from compilation used for improving code reliability:
  - memory safety
  - detecting data races
  - security properties
  - ...
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
  - *Web programming*: scripts that run everywhere
  - *Multicores*: concurrency and parallelism
  - 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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Readability</td>
</tr>
<tr>
<td>Simplicity</td>
<td>YES</td>
</tr>
<tr>
<td>Data types</td>
<td>YES</td>
</tr>
<tr>
<td>Syntax design</td>
<td>YES</td>
</tr>
<tr>
<td>Abstraction</td>
<td></td>
</tr>
<tr>
<td>Expressivity</td>
<td>YES</td>
</tr>
<tr>
<td>Type checking</td>
<td></td>
</tr>
<tr>
<td>Exceptions</td>
<td></td>
</tr>
</tbody>
</table>
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 your knowledge of common programming constructs and their properties
- Improve your understanding of program execution
- Increase your ability to learn new languages
- Learn how languages are implemented
- Learn new (programming) techniques
- See many basic CS concepts at work