Compiler Theory

001 - Introduction and Course Outline

Sandro Spina
Department of Computer Science

*Books (**needed** during this course)*

- My slides are based on the three books:
  - Compilers: Principles, techniques and tools.
    - Aho, Lam, Sethi, Ullman
  - Engineering a Compiler, 2nd Edition.
    - Keith Cooper and Linda Torczon
  - Modern compiler implementation in Java.
    - Andrew Appel

- but there are other very good books on compiler theory

- As always, the Internet is another great source of information ...

Course Sequence

- Compiling Theory … (with practice)
  - Front end
  - Back end
- Assignment – You shall be building parts of a compiler (it is very important that you have good programming skills)

Computing

- *Computers are everywhere ... not just in server rooms and offices !!!*
- *On automobiles, telephones (mobiles), televisions, musical instruments, traffic lights, etc.*
- *The software that runs on them provides services such as communication, security, entertainment (eg gaming), amongst others.*
- *Fundumentally everything is based on the theory of computation.*

Heterogeneous Computing

- *Computing hardware has evolved along many directions.*
- *Today we speak about multi-core micro processors, traditional CPUs, FPGAs (reconfigurable hardware), GPUs.*
- *Application software can either be*
  - *Control intensive (eg searching, parsing)*
  - *Data intensive (eg image processing, data mining)*
  - *A mix of both !! (most often)*
- *Nowadays software needs to execute across a range of hardware devices.*

What is a compiler?

- *It is a language processor !!*

- *It is a program that can read a program in one language (Java, C, Lisp, C#, Pascal, C for CUDA, OpenCL, GLSL, HLSL, etc.) – the source language – and translate it into an* ***equivalent*** *program in another language – target language.*

- *Also - a compiler needs to report any errors in the source program that it detects during the translation process. (e.g. a missing semicolon at the end of a statement)*

Brief compiler history (based on Cooper)

- *Appeared first in the 1950s for FORTRAN.*
- *Early 1960s – Algol 60*
- *Complex machine instruction sets were created in order to mimic closely programming language features. CISC architectures.*
- *RISC architectures (1980s) shifted this balance towards the compiler.*
- *Both architectures are still widely used today … E.g. Ipad is based on RISC and Intel's x86 on CISC.*

Compiler Fundamental Principle (Cooper)

THE COMPILER MUST PRESERVE THE MEANING OF THE PROGRAM BEING COMPILED

CORRECTNESS MUST BE GUARANTEED (PROVED)

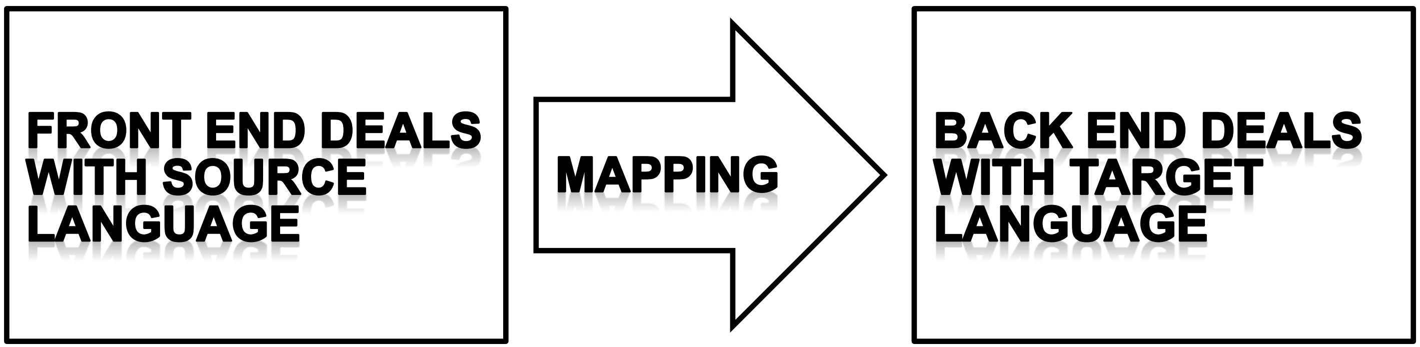
What is an interpreter?

- *An interpreter is also a language processor*
- *However - instead of producing a target program, it directly executes the operations specified in the source program on inputs supplied by the user.*
- *A typical example of an interpreter is the JVM.*
  - *Java compiler translates Java source code into byte code … which is then interpreted by a virtual machine (JIT compilers which can during runtime compile to machine code directly)*

Two blocks !!

- *Clearly a compiler **must** understand the syntax (valid forms) and semantics (meaning) of the input language.*

- *It also needs to understand the rules, syntax and meaning of the output language.*



Stages of a compiler (in brief) …

- Source Program (Character Stream)
  - Lexical Analysis
- Tokens (Token Stream)
  - Parser, Syntax Analyzer
- Abstract Syntax (Syntax Tree)
  - Semantic Analysis – Symbol Table

Stages of a compiler (in brief) ...

- Syntax Tree
  - Intermediate Code Generator
- Intermediate Representation
  - Machine independent Optimisations
- Intermediate Representation
  - Code Generator > Target Machine Code

Eg from Aho showing compiler phases

- IMAGE FROM AHO Pg5/7
- Expression (in source code)
  - *position = initial + rate * 60*

Lexical Analysis (scanning)

- *The 1st phase of the compiler is lexical analysis (scanning)*
- *It reads a stream of characters (source program) and groups the characters into meaningful sequences called <u>lexemes</u>.*
- *For each lexeme, the lexical analyzer produces output tokens of the form*
  - *< token-name, attribute-value>*
  - *Eg <**id**,1> <=> <**id**,2> <+> <**id**,3> <*> <60>*
- ***id** indicates to the syntax analysis phase that we have an identifier (variable) and it's value it located in symbol table at position 1.*

Syntax Analysis (parsing)

- *The parser uses the first component of the tokens produced by the lexical analyzer to create a tree-like intermediate representation that depicts the grammatical structure of the token stream.*
- *Syntax trees are usually used where each interior node represents an operation and the children of the node represent the arguments of the operation.*

Semantic Analysis

- *The semantic analyzer uses the syntax tree and the information in the symbol table to check the source program for semantic consistency with the language definition.*
- *Type Checking !!*
- *Type conversions (coercions) … eg if operator is applied to int and float, the compiler may convert (coerce) the integer into a floating-point.*

Intermediate Code Generation

- *Many compilers generate an explicit low-level (machine-like) intermediate representation.*

- *Properties*
  - *Easy to produce*
  - *Easy to translate into target machine*

- Eg. Three-address code (linear representation)
  - < X = y **op** z >   format
  - T2 = id3 * t1
  - T3 = id2 + t2

- We'll see how this step is useful for code optimization

Code Optimization (i)

- *This stage of compilation attempts to improve the intermediate code so that better target code is generated.*
- *Better = faster, smaller !!*
- *But could also mean that target consumes less power (eg mobile phone, pda apps)*
- *We shall eventually look at machine-dependent and machine-independent optimizations in some detail.*

Code Optimization (ii)

- *Compiler optimization must meet the following design objectives:*
  - *It must be correct, that is, preserve the meaning of the compiled program.*
  - *It must improve the performance of many programs (not just a few !!)*
  - *Compilation time must be kept reasonable, and*
  - *Engineering effort required must be manageable*

Code Generation

- *The code generator takes as input an intermediate representation of the source program and maps it into the target language.*

- *If target language is machine code, registers or memory locations are selected for each of the variables … the assignment of registers to hold variables is very important!*

- *Output might look like :*
  - *LDF R2, id3*
  - *MULF R2, R2, #60.0 (# means 60.0 is a constant)*
  - *LDF R1, id2*
  - *ADDF R1, R1, R2*

Instruction Scheduling

- *An important task during code generation is instruction scheduling.*
- *This is because the execution time of different operations can vary according to the target machine's specific performance constraints.*
- *Clearly, an operation cannot begin to execute until its operands are ready ... But can start multiple new operations which do not need the result of currently executing operations.*
- *The intuition here is that by re-ordering certain operations, the compiler minimizes the number of cycles wasted waiting for operands ...*
- E.g. [load r1, add r1, load r2, mult r2, load r3, add r3]   can be reordered to [load r1, load r2, load r3, add r1, mult r2, add r3]

Some important concepts (i)

- *So far we have seen (very very briefly) the phases of a compiler !!*
- *In the next few slides we shall look at important concepts you should be aware of with respect to programming languages + compilers*

Some important concepts (ii) – Symbol Table

- *Compilers need to record the variable names used in the source program together with various attributes of each name (eg type, storage allocated, scope)*

- *Procedure names are also stored together with attributes such as number of parameters, type of arguments and method of passing each argument (by value or by reference)*

- *It is 'clearly' very important that the data structure which stores this information is efficient in terms of retrieval and storage of data.*

Concepts (iii) – Parameter Passing

- *All programming languages have a notion of a procedure (in Java we have methods, functions in C)*

- *Most programming languages use either call by value, call by reference or both*

- *Call by Value :- the actual parameter is evaluated (if it is an expression) or copied (if it is a variable). Both C and Java use call by value however with C we can pass a pointer to a variable and with Java many variables are really references (pointers) to arrays, strings and objects !!*

Concepts (iv) – Parameter Passing

- *All programming languages have a notion of a procedure (in Java we have methods, functions in C)*

- *Call by reference is usually an option in many programming languages (call by value is much more used)*

- *Call by Reference :- Changes to the formal parameter appear as changes in the actual parameter !! Eg Pascal incr (var x : int)*

Concepts (v) – Memory Hierarchies

- *A memory hierarchy consists of several levels of storage with different speeds and sizes, with the levels closest to the processor (registers, caches) being the fastest but smallest.*

- *A processor usually has a small number of registers consisting of hundreds of bytes, several levels of caches containing kilobytes to megabytes, physical memory containing megabytes to gigabytes and beyond.*

- *Using registers effectively is probably the single most important problem in optimizing a program.*

- *The compiler can improve the effectiveness of the memory hierarchy by changing the layout of the data.*

Concepts (vi) – Software Tools

- *Lexical Analysis – LeX, FLeX, JLeX*
- *Syntax Anaysis – JavaCC, SableCC*
- *Semantic Analysis – JavaCC, SableCC*
- *MiniJava programming language (Appel Book)*

The language of straight-line programs !

- Check Appel Pg 7
- Made up of simple statements and expressions (no loops or if stmts)
- Bottom up:
  - Binop,
  - Exp,
  - ExpList,
  - Stm.

An embedded compiler !!

- We know what a compiler is.
- Embedding with respect to language … for example one can easily embed a parser in Haskell or Java.
- A compiler would 'slightly' be more hairy to embed because you would need to generate executable at run-time using it.
- We usually think of compile-time and run-time are two separate stages but really one can be compiling at run-time !!!
- Let's take for example Janino … (next slide)

Janino - The embedded Java compiler … eg

```
ExpressionEvaluator ee = new ExpressionEvaluator(
        "c > d ? c : d",                // expression
        int.class,                      // expressionType
        new String[] { "c", "d" }, // parameterNames
        new Class[] { int.class, int.class } // parameterTypes
);
// Evaluate it with varying parameter values; very fast.
Integer res = (Integer) ee.evaluate(
        new Object[] {                  // parameterValues
                new Integer(10),
                new Integer(11),
        }
);
System.out.println("res = " + res);
```

Janino embedded in Sunflow (GI Rendering Engine)

- Janino is used in Sunflow in order to compile shaders at run-time.
- Different shaders describing different reflection models can be loaded at run-time … then compiled using Janino … and executed in the same memory space of the currently executing VM.
- DirectX and OpenGL also have compilers which compile at run-time vertex and pixel shaders before loading them on the GPU.

- The point to understand here is that compilers have an extremely vast range of applicability. Not just the traditional source -> compile -> execute trace.
- Although we'll be looking mainly at those because the main concepts remain the same.

Compiler Construction Topics

- *Compiler construction is a complex task !!! It combines together many aspects of Computer Science*
  - *Formal language theory*
  - *Artificial intelligence (greedy algorithms and heuristic techniques)*
  - *Computer architecture*
- *We shall cover many aspects, but will focus mostly on the front end.*
- *At the end of this course you will be able to take a formal specification of a language (using e.g. EBNF) and be able to use tools (compiler compilers) to generate a source-to-source compiler.*

Next ...

- *Chapter 2 from Dragon Book*

- *A simple syntax-directed translator will be used to briefly introduce*
  - *Lexical Analysis*
  - *Syntax Analysis*
  - *Parsing*
  - *Intermediate Code*