Compiler Construction
1. Introduction

Oscar Nierstrasz
## Compiler Construction

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<tr>
<th>Lecturers</th>
<th>Prof. Oscar Nierstrasz, Dr. Mircea Lungu</th>
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<tr>
<td>Assistants</td>
<td>Jan Kurš, Boris Spasojević</td>
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<tr>
<td>Lectures</td>
<td>E8 001, Fridays @ 10h15-12h00</td>
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<td>WWW</td>
<td>scg.unibe.ch/teaching/cc</td>
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MSc registration Spring 2015

JMCS students

• Register on Academia for teaching units by March 13, 2015
• Register on Academia for exams by May 15, 2015
• Request reimbursement of travel expenses by June 30, 2015

NB: Hosted JMCS students (e.g. CS bachelor students etc.) must additionally:
• Request for Academia access by February 28, 2015
Roadmap

> Overview
> Front end
> Back end
> Multi-pass compilers
> Example: compiler and interpreter for a toy language

See *Modern compiler implementation in Java* (Second edition), chapter 1.
Roadmap

- Overview
- Front end
- Back end
- Multi-pass compilers
- Example: compiler and interpreter for a toy language

Thanks to Jens Palsberg and Tony Hosking for their kind permission to reuse and adapt the CS132 and CS502 lecture notes.

http://www.cs.ucla.edu/~palsberg/
http://www.cs.purdue.edu/homes/hosking/
Other recommended sources

> **Compilers: Principles, Techniques, and Tools**, Aho, Sethi and Ullman

> **Parsing Techniques**, Grune and Jacobs
  —[http://www.cs.vu.nl/~dick/PT2Ed.html](http://www.cs.vu.nl/~dick/PT2Ed.html)

> **Advanced Compiler Design and Implementation**, Muchnik
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What is a compiler?

A program that translates an *executable* program in one language into an *executable* program in another language.
What is an interpreter?

A program that reads an executable program and produces the results of running that program.
Implementing Compilers, Interpreters …
Why do we care?

Compiler construction is a microcosm of computer science

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<th>greedy algorithms</th>
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<td>hierarchy management</td>
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<td></td>
<td>instruction set use</td>
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*Inside a compiler, all these things come together*
Isn’t it a solved problem?

> **Machines are constantly changing**
  — Changes in architecture ⇒ changes in compilers
  — new features pose new problems
  — changing costs lead to different concerns
  — old solutions need re-engineering

> Innovations in compilers should prompt changes in architecture
  — New languages and features
What qualities are important in a compiler?

- Correct code
- Output runs fast
- Compiler runs fast
- Compile time proportional to program size
- Support for separate compilation
- Good diagnostics for syntax errors
- Works well with the debugger
- Good diagnostics for flow anomalies
- Cross language calls
- Consistent, predictable optimization
A bit of history

> **1952**: First compiler (linker/loader) written by Grace Hopper for **A-0** programming language

> **1957**: First complete compiler for **FORTRAN** by John Backus and team

> **1960**: **COBOL** compilers for multiple architectures

> **1962**: First self-hosting compiler for **LISP**
A compiler was originally a program that “compiled” subroutines [a link-loader]. When in 1954 the combination “algebraic compiler” came into use, or rather into misuse, the meaning of the term had already shifted into the present one.

— Bauer and Eickel [1975]
Abstract view

- recognize legal (and illegal) programs
- generate correct code
- manage storage of all variables and code
- agree on format for object (or assembly) code

Big step up from assembler — higher level notations
Traditional two pass compiler

- front end maps legal code into IR
- intermediate representation (IR)
- back end maps IR onto target machine
- simplifies retargeting
- allows multiple front ends
- multiple passes ⇒ better code
A fallacy!

Front-end, IR and back-end must encode knowledge needed for all $n \times m$ combinations!
Roadmap

- Overview
- **Front end**
- Back end
- Multi-pass compilers
- Example: compiler and interpreter for a toy language
Front end

- recognize legal code
- report errors
- produce IR
- preliminary storage map
- shape code for the back end

*Much of front end construction can be automated*
Scanner

- map characters to *tokens*
- character string value for a token is a *lexeme*
- eliminate white space

\[ x = x + y \]
\[ <\text{id},x> = <\text{id},x> + <\text{id},y> \]
Parser

- recognize context-free syntax
- guide context-sensitive analysis
- construct IR(s)
- produce meaningful error messages
- attempt error correction

Parser generators mechanize much of the work
Context-free syntax is specified with a grammar, usually in Backus-Naur form (BNF)

1. `<goal>` := `<expr>`
2. `<expr>` := `<expr>` `<op>` `<term>`
3. | `<term>`
4. `<term>` := `number`
5. | `id`
6. `<op>` := `+`
7. | `−`

A grammar $G = (S,N,T,P)$
- $S$ is the **start-symbol**
- $N$ is a set of **non-terminal symbols**
- $T$ is a set of terminal symbols
- $P$ is a set of **productions** $− P: N \rightarrow (N \cup T)^*$
Deriving valid sentences

<table>
<thead>
<tr>
<th>Production</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;goal&gt;</td>
</tr>
<tr>
<td>1</td>
<td>&lt;expr&gt;</td>
</tr>
<tr>
<td>2</td>
<td>&lt;expr&gt; &lt;op&gt; &lt;term&gt;</td>
</tr>
<tr>
<td>5</td>
<td>&lt;expr&gt; &lt;op&gt; y</td>
</tr>
<tr>
<td>7</td>
<td>&lt;expr&gt; - y</td>
</tr>
<tr>
<td>2</td>
<td>&lt;expr&gt; &lt;op&gt; &lt;term&gt; - y</td>
</tr>
<tr>
<td>4</td>
<td>&lt;expr&gt; &lt;op&gt; 2 - y</td>
</tr>
<tr>
<td>6</td>
<td>&lt;expr&gt; + 2 - y</td>
</tr>
<tr>
<td>3</td>
<td>&lt;term&gt; + 2 - y</td>
</tr>
<tr>
<td>5</td>
<td>x + 2 - y</td>
</tr>
</tbody>
</table>

Given a grammar, valid sentences can be derived by repeated substitution.

To recognize a valid sentence in some CFG, we reverse this process and build up a parse.
Parse trees

A parse can be represented by a tree called a *parse tree* (or *syntax tree*).

*Obviously, this contains a lot of unnecessary information*
Abstract syntax trees

So, compilers often use an abstract syntax tree (AST).

ASTs are often used as an IR.
Roadmap

- Overview
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- **Back end**
- Multi-pass compilers
- Example: compiler and interpreter for a toy language
Back end

- translate IR into target machine code
- choose instructions for each IR operation
- decide what to keep in registers at each point
- ensure conformance with system interfaces

Automation has been less successful here
Instruction selection

- produce compact, fast code
- use available addressing modes
- pattern matching problem
  - *ad hoc techniques*
  - *tree pattern matching*
  - *string pattern matching*
  - *dynamic programming*
Register allocation

- have value in a register when used
- limited resources
- changes instruction choices
- can move loads and stores
- optimal allocation is difficult

Modern allocators often use an analogy to graph coloring
Roadmap

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Traditional three-pass compiler

- analyzes and changes IR
- goal is to reduce runtime \textit{(optimization)}
- must preserve results
Modern optimizers are usually built as a set of passes

- constant expression propagation and folding
- code motion
- reduction of operator strength
- common sub-expression elimination
- redundant store elimination
- dead code elimination
The MiniJava compiler
## Compiler phases

<table>
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<tr>
<th>Phase</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Lex</td>
<td>Break source file into individual words, or <em>tokens</em></td>
</tr>
<tr>
<td>Parse</td>
<td>Analyse the phrase structure of program</td>
</tr>
<tr>
<td>Parsing Actions</td>
<td>Build a piece of <em>abstract syntax tree</em> for each phrase</td>
</tr>
<tr>
<td>Semantic Analysis</td>
<td>Determine what each phrase means, relate uses of variables to their definitions, check types of expressions, request translation of each phrase</td>
</tr>
<tr>
<td>Frame Layout</td>
<td>Place variables, function parameters, etc., into activation records (stack frames) in a machine-dependent way</td>
</tr>
<tr>
<td>Translate</td>
<td>Produce <em>intermediate representation trees</em> (IR trees), a notation that is not tied to any particular source language or target machine</td>
</tr>
<tr>
<td>Canonicalize</td>
<td>Hoist side effects out of expressions, and clean up conditional branches, for convenience of later phases</td>
</tr>
<tr>
<td>Instruction Selection</td>
<td>Group IR-tree nodes into clumps that correspond to actions of target-machine instructions</td>
</tr>
<tr>
<td>Control Flow Analysis</td>
<td>Analyse sequence of instructions into <em>control flow graph</em> showing all possible flows of control program might follow when it runs</td>
</tr>
<tr>
<td>Data Flow Analysis</td>
<td>Gather information about flow of data through variables of program; e.g., <em>liveness analysis</em> calculates places where each variable holds a still-needed (live) value</td>
</tr>
<tr>
<td>Register Allocation</td>
<td>Choose registers for variables and temporary values; variables not simultaneously live can share same register</td>
</tr>
<tr>
<td>Code Emission</td>
<td>Replace temporary names in each machine instruction with registers</td>
</tr>
</tbody>
</table>
Roadmap

- Overview
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- Multi-pass compilers
- **Example: compiler and interpreter for a toy language**
A straight-line programming language (no loops or conditionals):

\[
\begin{align*}
\text{Stm} & \rightarrow \text{Stm} ; \text{Stm} \\
\text{Stm} & \rightarrow \text{id} := \text{Exp} \\
\text{Stm} & \rightarrow \text{print( ExpList )} \\
\text{Exp} & \rightarrow \text{id} \\
\text{Exp} & \rightarrow \text{num} \\
\text{Exp} & \rightarrow \text{Exp Binop Exp} \\
\text{Exp} & \rightarrow ( \text{Stm, Exp} ) \\
\text{ExpList} & \rightarrow \text{Exp, ExpList} \\
\text{ExpList} & \rightarrow \text{Exp} \\
\text{Binop} & \rightarrow + \\
\text{Binop} & \rightarrow - \\
\text{Binop} & \rightarrow \times \\
\text{Binop} & \rightarrow / \\
\end{align*}
\]

\[
a := 5 + 3; \ b := (\text{print}(a,a-1),10\times a); \ \text{print}(b)
\]

prints 8 7 80
a := 5 + 3; b := (print(a, a−1), 10×a); print(b)
Straightline Interpreter and Compiler Files

Source files

- «Grammar spec»
  - slpl.jj

- «Compiler source»
  - CompilerVisitor ...

- «Interpreter source»
  - InterpreterVisitor ...

- «Abstract Machine for Interpreter»
  - Machine

Generated files

- «Grammar spec with actions»
  - jtb.out.jj

- «Default visitors and interfaces»
  - Visitor ...

- «Syntax Tree Nodes»
  - Goal ...

- «Parser source»
  - StraightLineParser ...

- «Bytecode»
  - StraightLineParser ...

Key
- JavaCC produces
- JTB visits
- JavaC generates
abstract class Stm {}  
class CompoundStm extends Stm {  
    Stm stm1, stm2;  
    CompoundStm(Stm s1, Stm s2)  
        {stm1=s1; stm2=s2;}  
}  
class AssignStm extends Stm {  
    String id; Exp exp;  
    AssignStm(String i, Exp e)  
        {id=i; exp=e;}  
}  
class PrintStm extends Stm {  
    ExpList exps;  
    PrintStm(ExpList e) {exps=e;}  
}  
abstract class Exp {}  
class IdExp extends Exp {  
    String id;  
    IdExp(String i) {id=i;}
}  
class NumExp extends Exp {  
    int num;  
    NumExp(int n) {num=n;}
}  
class OpExp extends Exp {  
    Exp left, right; int oper;  
    final static int Plus=1, Minus=2, Times=3, Div=4;  
    OpExp(Exp l, int o, Exp r)  
        {left=l; oper=o; right=r;}
}  
class EseqExp extends Exp {  
    Stm stm; Exp exp;  
    EseqExp(Stm s, Exp e) {stm=s; exp=e;}
}  
abstract class ExpList {}  
class PairExpList extends ExpList {  
    Exp head; ExpList tail;  
    public PairExpList(Exp h, ExpList t)  
        {head=h; tail=t;}
}  
class LastExpList extends ExpList {  
    Exp head;  
    public LastExpList(Exp h) {head=h;}
}
Straightline Interpreter and Compiler Runtime

Examples

«Straightline source code» -> StraightLineParser

Goal ...

InterpreterVisitor ...

instructs

Machine

output

CompilerVisitor ...

uses

«Bytecode generation library»

bcel.jar

bytecode

output

Key

generates
What you should know!

-) What is the difference between a compiler and an interpreter?
-) What are important qualities of compilers?
-) Why are compilers commonly split into multiple passes?
-) What are the typical responsibilities of the different parts of a modern compiler?
-) How are context-free grammars specified?
-) What is “abstract” about an abstract syntax tree?
-) What is intermediate representation and what is it for?
-) Why is optimization a separate activity?
Can you answer these questions?

- Is Java compiled or interpreted? What about Smalltalk? Ruby? PHP? Are you sure?
- What are the key differences between modern compilers and compilers written in the 1970s?
- Why is it hard for compilers to generate good error messages?
- What is “context-free” about a context-free grammar?
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