Compiling Techniques
Lecture 2: The view from 35000 feet

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Table of contents

1. High-level view
2. Front End
   - Passes
   - Representations
3. Back end
   - Instruction Selection
   - Register Allocation
   - Instruction Scheduling
4. Optimiser
High-level view of a compiler

- Must recognise legal (and illegal) programs
- Must generate correct code
- Must manage storage of all variables (and code)
- Must agree with OS & linker on format for object code
- Big step up from assembly language; use higher level notations
Traditional two-pass compiler

- Use an intermediate representation (IR)
- Front end maps legal source code into IR
- Back end maps IR into target machine code
- Admits multiple front ends & multiple passes
- Typically, front end is $O(n)$ or $O(n \log n)$, while back end is NPC (NP-complete)
A common fallacy two-pass compiler

- Can we build $n \times m$ compilers with $n+m$ components?
- Must encode all language specific knowledge in each front end
- Must encode all features in a single IR
- Must encode all target specific knowledge in each back end
- Limited success in systems with very low-level IRs (e.g. LLVM)
- Active research area (e.g. Graal, Truffle)
The Frontend

- Recognise legal (& illegal) programs
- Report errors in a useful way
- Produce IR & preliminary storage map
- Shape the code for the back end
- Much of front end construction can be automated
The Lexer

- **Lexical analysis**
- Recognises words in a character stream
- Produces tokens (words) from lexeme
- Collect identifier information
- Typical tokens include number, identifier, +, −, new, while, if
- Example: \( x = y + 2; \) becomes
  \[ \text{IDENTIFIER}(x) \text{ EQUAL IDENTIFIER}(y) \text{ PLUS CST}(2) \]
- Lexer eliminates white space (including comments)
The Parser

- Recognises context-free syntax & reports errors
- Hand-coded parsers are fairly easy to build
- Most books advocate using automatic parser generators
Semantic Analyser

- Guides context-sensitive ("semantic") analysis
- Checks variable and function declared before use
- Type checking
Generates the IR used by the rest of the compiler.
Sometimes the AST is the IR.
This grammar defines simple expressions with addition & subtraction over “number” and “id”

This grammar, like many, falls in a class called “context-free grammars”, abbreviated CFG
Given a CFG, we can derive sentences by repeated substitution

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

To recognise a valid sentence in a CFG, we reverse this process and build up a parse tree.
$x + 2 - y$

This contains a lot of unnecessary information.
Abstract Syntax Tree (AST)

The AST summarises grammatical structure, without including detail about the derivation.

- Compilers often use an abstract syntax tree
- This is much more concise
- ASTs are one kind of intermediate representation (IR)
The Back end

- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which value to keep in registers
- Ensure conformance with system interfaces
- Automation has been less successful in the back end
Instruction Selection

- Produce fast, compact code
- Take advantage of target features such as addressing modes
- Usually viewed as a pattern matching problem
- Ad hoc methods, pattern matching, dynamic programming
- Example: madd instruction
Register Allocation

- Have each value in a register when it is used
- Manage a limited set of resources
- Can change instruction choices & insert LOADs & STOREs (spilling)
- Optimal allocation is NP-Complete (1 or k registers)
- Graph colouring problem
- Compilers approximate solutions to NP-Complete problems
Instruction Scheduling

- Avoid hardware stalls and interlocks
- Use all functional units productively
- Can increase lifetime of variables (changing the allocation)
- Optimal scheduling is NP-Complete in nearly all cases
- Heuristic techniques are well developed
Three Pass Compiler

- Code Improvement (or Optimisation)
- Analyses IR and rewrites (or transforms) IR
- Primary goal is to reduce running time of the compiled code
  - May also improve space, power consumption, ...
- Must preserve meaning of the code
  - Measured by values of named variables
- Subject of UG4 Compiler Optimisation
Modern optimisers are structured as a series of passes e.g. LLVM

- Discover & propagate some constant value
- Move a computation to a less frequently executed place
- Specialise some computation based on context
- Discover a redundant computation & remove it
- Remove useless or unreachable code
- Encode an idiom in some particularly efficient form
Modern Restructuring Compiler

- Translate from high-level (HL) IR to low-level (LL) IR
- Blocking for memory hierarchy and register reuse
- Vectorisation
- Parallelisation
- All based on dependence
- Also full and partial inlining
- Not covered in this course
Role of the runtime system

- Memory management services
  - Allocate, in the heap or in an activation record (stack frame)
  - Deallocate
  - Collect garbage
- Run-time type checking
- Error processing
- Interface to the operating system (input and output)
- Support for parallelism (communication and synchronization)
Programs related to compilers

- **Pre-processor:**
  - Produces input to the compiler
  - Processes Macro/Directives (e.g. `#define`, `#include`)

- **Assembler:**
  - Translate assembly language to actual machine code (binary)
  - Performs actual allocation of variables

- **Linker:**
  - Links together various compiled files and/or libraries
  - Generate a full program that can be loaded and executed

- **Debugger:**
  - Tight integration with compiler
  - Uses meta-information from compiler (e.g. variable names)

- **Virtual Machines:**
  - Executes virtual assembly
  - Typically embedded a just-in-time (jit) compiler
Next lecture

- Introduction to Lexical Analysis
- Decomposition of the input into a stream of tokens
- Construction of scanners from regular expressions