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 IDENTIFIER(x) EQUAL IDENTIFIER(y) 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 Analyzer

- Guides context-sensitive ("semantic") analysis
- Checks variable and function declared before use
- Type checking
IR Generator

- Generates the IR used by the rest of the compiler
- Sometimes the AST is the IR
Simple Expression Grammar

- 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

\[
\begin{align*}
goal & \rightarrow \ expr \\
expr & \rightarrow \ expr \ op \ term \mid term \\
term & \rightarrow \ number \mid id \\
op & \rightarrow \ + \mid - \\
\end{align*}
\]

\[
\begin{align*}
S &= \ text{goal} \\
T &= \{ \text{number, id , +, - } \} \\
N &= \{ \text{goal , expr , term , op } \} \\
P &= \{ \ 1, 2, 3, 4, 5, 6, 7 \ \} \\
\end{align*}
\]
Derivations

Given a CFG, we can derive sentence by repeated substitution

<table>
<thead>
<tr>
<th>Production</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>goal</td>
</tr>
<tr>
<td>0</td>
<td>expr</td>
</tr>
<tr>
<td>1</td>
<td>expr op term</td>
</tr>
<tr>
<td>2</td>
<td>expr op y</td>
</tr>
<tr>
<td>3</td>
<td>expr - y</td>
</tr>
<tr>
<td>4</td>
<td>expr op term - y</td>
</tr>
<tr>
<td>5</td>
<td>expr op 2 - y</td>
</tr>
<tr>
<td>6</td>
<td>expr + 2 - y</td>
</tr>
<tr>
<td>7</td>
<td>term + 2 - y</td>
</tr>
<tr>
<td>8</td>
<td>x + 2 - y</td>
</tr>
</tbody>
</table>

To recognise a valid sentence in a CFG, we reverse this process and build up a parse tree.
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 Backend

- 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

- 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
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
The Optimizer

- 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

![Diagram of the Optimizer process]

Errors
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
- Optimizations 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 (real start of compiler course)
  - Decomposition of the input into a stream of tokens
  - Construction of scanners from regular expressions