Compiler Design

Lecture 2: The view from 35000 feet

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First Compilers & Programming Languages

First “Compiler”: 1952

First “compiler”: A-0 System. The term “compiler” was coined by Grace Hopper in the 1950s.

Automatic Coding for Digital Computers, Grace Hopper, 1955:

> *“Compiling [...] which withdraw subroutines from a library and operate upon them, finally linking the pieces together to deliver, as output, a complete specific program.”*

Grace Hopper, US Navy

source: James S. Davis - Image released by the United States Navy with the ID DN-SC-84-05971

Actually more a sort of linker than what we call a compiler today.

Fortran, 1957

- First "high-level" programming language.
- Fortran = **For**mula **tran**slation

Simple Fortran II program

```
C AREA OF A TRIANGLE - HERON'S FORMULA
C INPUT - CARD READER UNIT 5, INTEGER INPUT
C OUTPUT -
C INTEGER VARIABLES START WITH I,J,K,L,M OR N

    READ(5,501) IA,IB,IC
501 FORMAT(3I5)
    IF(IA.EQ.0 .OR. IB.EQ.0 .OR. IC.EQ.0) STOP 1
    S = (IA + IB + IC) / 2.0
    AREA = SQRT( S * (S - IA) * (S - IB) * (S - IC) )
    WRITE(6,601) IA,IB,IC,AREA
601 FORMAT(4H A=,I5,5H B=,I5,5H C=,I5,
           8H AREA=,F10.2,$13H SQUARE UNITS)
    STOP
    END
```

source: Wikipedia

John Bakus,
IBM

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Lisp, 1958

- Lisp = **Lis**t **p**rocessing language

Simple Lisp 1 program

```
((Y (LAMBDA (FN)
      (LAMBDA (X)
        (IF (ZEROP  X) 1 (* X (FN (- X 1)))))))
 6)
```

source: Technical Issues of Separation in Function Cells and Value Cells

John McCarthy, MIT

source: "null0", CC BY-SA 2.0, via Wikimedia Commons

Fortran and Lisp are the oldest, and most influencial programming languages. Both are still in use today!

(Fortran) Imperative ⟷ Functional (Lisp)

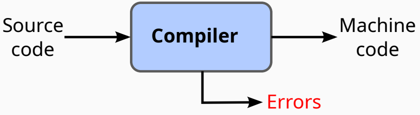
- Fortran is imperative: you tell the machine what to do at every step, pretty much like assembly.
- Lisp is functional: based on Lambda calculus, computation is performed by "substitution" (at least at the abstract level).

In this class, we will mostly study how imperative languages are compiled.

But this will also be applicable to functional languages, since eventually everything has to be turned into sequences of assembly instructions.

High-level view

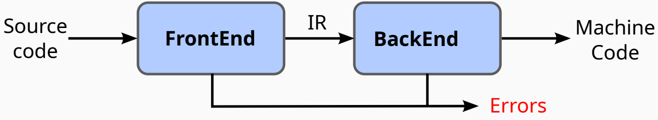
High-level view of a compiler



- 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

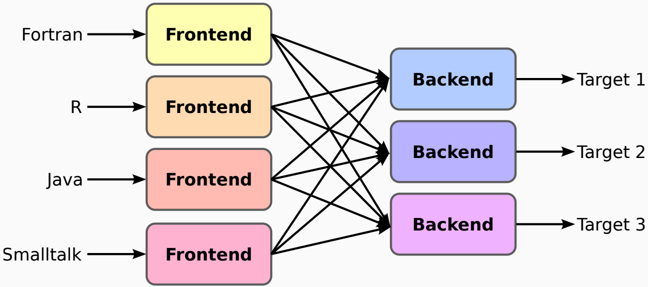
Big step up from assembly language; use higher level notations

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



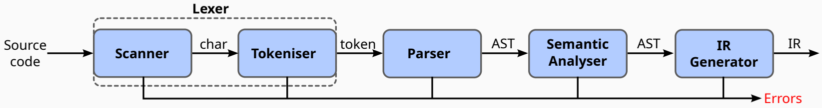
- Can we build n x m compilers with n+m components?
- Must encode all language specific knowledge in each front end
- Must encode all features in a single IR
- Must encode all target specific knowledge in each back end
- Limited success in systems with very low-level IRs (e.g. LLVM)
- Active research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

Front End

Front End

Passes

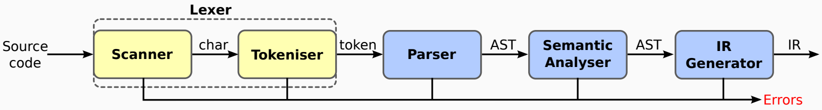
The Frontend



- Recognise legal (& illegal) programs
- Report errors in a useful way
- Produce IR
- Shape the code for the back end

Much of front end construction can be automated

The Lexer

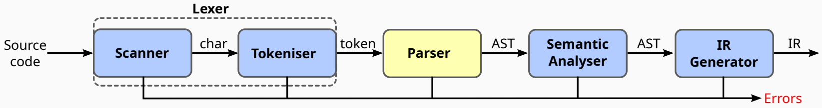


Lexical analysis

- Recognises words in a character stream
- Produces tokens (words) from lexeme
- Collect identifier information (*e.g.* variable names)
- Typical tokens include number, identifier, $+$, $-$, `new`, `while`, `if`
- Lexer eliminates white space (including comments)

Example: `x = y+2;`
becomes: IDENTIFIER(x) EQUAL IDENTIFIER(y) PLUS CST(2) SC

The Parser



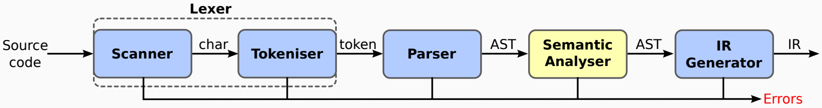
Parsing

- Recognises context-free syntax & reports errors
- Builds an AST (Astract Syntax Tree)
- Hand-coded parsers are fairly easy to build
- Most books advocate using automatic parser generators

In the course project, you will build your own parser

- Will teach you more than using a generator!
- Once you know how to build a parser by hand, using a parser generator becomes easy

Semantic Analyser



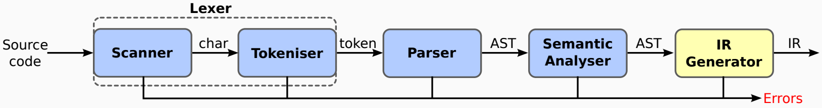
Semantic Analysis

- Guides context-sensitive (“semantic”) analysis
- Checks variable and function declared before use
- Type checking

Type checking example:

```
int foo(int a) = {...}
void main() {
  float f;
  f = foo(1,2); // type error
}
```

Intermediate Representation (IR) Generator



- Generates the IR (Intermediate Representation) used by the rest of the compiler.
- Sometimes the AST is the IR.

Front End

Representations

Simple Expression Grammar

1	*goal*	$\rightarrow$	*expr*
2	*expr*	$\rightarrow$	*expr op term*
3		|	*term*
4	*term*	$\rightarrow$	*number*
5		|	*id*
6	*op*	$\rightarrow$	+
7		|	-

$S = goal$
$T = \{number, id, +, -\}$
$N = \{goal, expr, term, op\}$
$P = \{1, 2, 3, 4, 5, 6, 7\}$

- 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

Derivations

Given a CFG, we can derive sentences by repeated substitution

Productions:

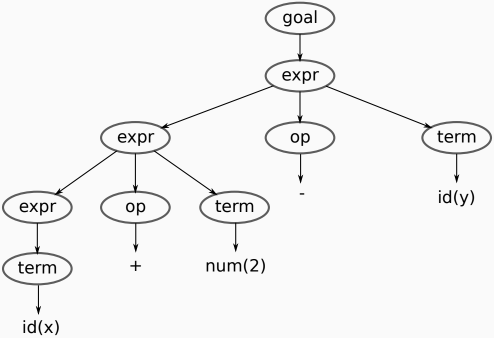
1	*goal*	→	*expr*
2	*expr*	→	*expr op term*
3		|	*term*
4	*term*	→	*number*
5		|	*id*
6	*op*	→	+
7		|	−

Production	Result
	goal
1	expr
2	expr op term
5	expr op y
7	expr - y
2	expr op term - y
4	expr op 2 - y
6	expr + 2 - y
3	term + 2 - y
5	x + 2 - y

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

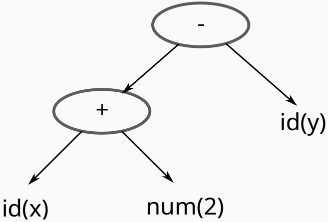
Parse tree

x + 2 - y



This contains a lot of unnecessary information.

Abstract Syntax Tree (AST)

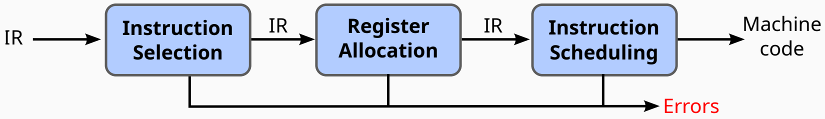


The AST summarises grammatical structure, without including detail about the derivation.

- Compilers often use an abstract syntax tree
- This is much more concise
- ASTs are one kind of IR

Back end

The Back end

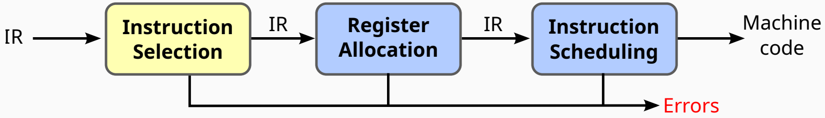


- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which value to keep in registers
- Ensure conformance with system interfaces
- Automation has been less successful in the back end

Back end

Instruction Selection

Instruction Selection



- Produce fast, compact code
- Take advantage of target features such as addressing modes
- Usually viewed as a pattern matching problem

Example: `d = a * b + c`

option 1

```
MUL rt, ra, rb
ADD rd, rt, rc
```

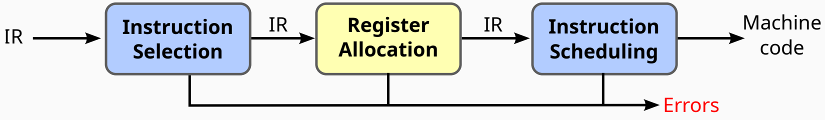
option 2

```
MADD rd, ra, rb, rc
```

Back end

Register Allocation

Register Allocation

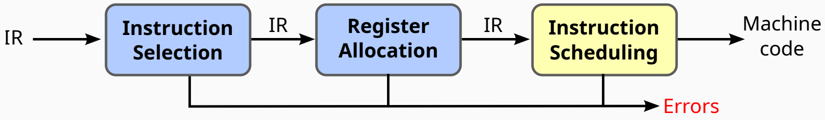


- Have each value in a register when it is used
- Manage a limited set of resources
- Can change instruction choices & insert LOADs & STOREs (spilling)
- Optimal allocation is NP-Complete
  - Graph colouring problem
  - Compilers approximate solutions to NP-Complete problems

Back end

Instruction Scheduling

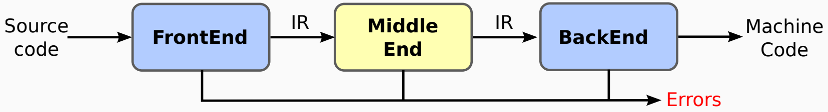
Instruction Scheduling



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

Optimiser

Three Pass Compiler

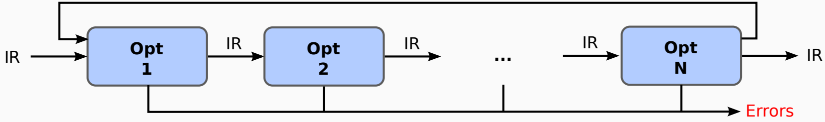


Compiler Optimization (or code improvement):

- Analyses IR and rewrites/transforms IR
- Primary goal is to reduce running time of the compiled code
  - May also improve code size, power consumption, …
- Must preserve “meaning” of the code
  - Measured by values of named variables
- Subject of Compiler Optimisation course

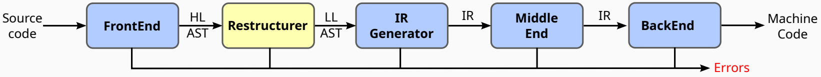
The Optimiser

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
- ...

Modern Restructuring Compiler



Translate from high-level (HL) IR to low-level (LL) IR

- Blocking for memory hierarchy and data reuse
- Parallelisation (including vectorization)

All of above is based on data dependence analysis

- Also full and partial inlining

Compiler optimizations are not covered in this course

Role of the runtime system

- Memory management services
    - Allocate, in the heap or on the stack
    - 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