Compiling Techniques

Lecture 2: The view from 35000 feet

Christophe Dubach

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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-84-059

Actually more a sort of linker than what we call 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,
     $13H 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

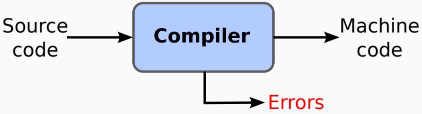
source: "null0", CC BY-SA 2.0, via Wikimedia Commons

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

(Fortran) Imperative ⟷ Functional (Lisp)

High-level view

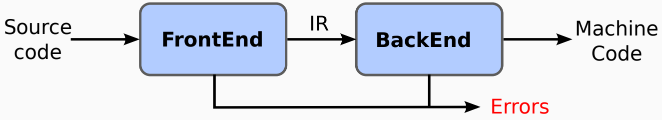
High-level view of a compiler



- 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

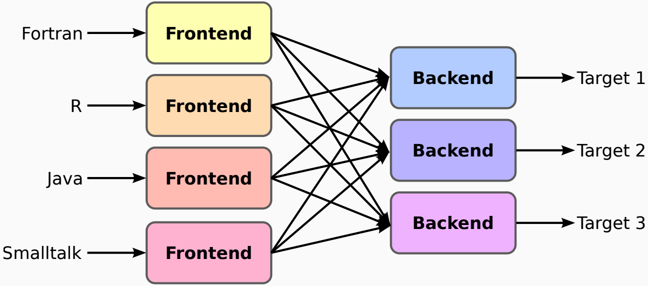
Big step up from assembly language; use higher level notations

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



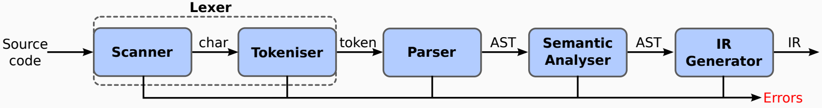
- Can we build n x m compilers with n+m components?
- Must encode all language specific knowledge in each front end
- Must encode all features in a single IR
- Must encode all target specific knowledge in each back end
- Limited success in systems with very low-level IRs (e.g. LLVM)
- Active research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

Front End

Front End

Passes

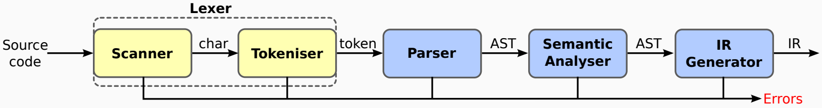
The Frontend



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

Much of front end construction can be automated

The Lexer

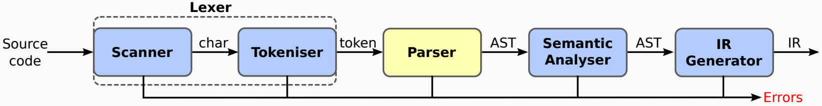


Lexical analysis

- Recognises words in a character stream
- Produces tokens (words) from lexeme
- Collect identifier information (*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)

The Parser



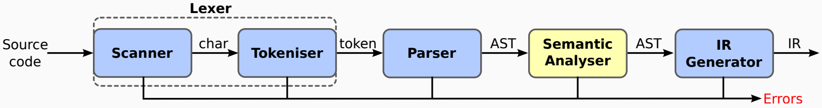
Parsing

- 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



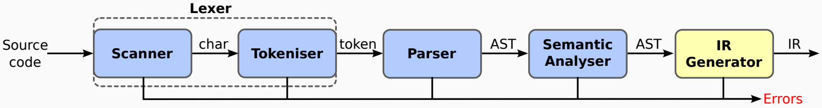
Semantic Analysis

- 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		$\mid$	$term$
4	$term$	$\rightarrow$	$number$
5		$\mid$	id
6	op	$\rightarrow$	$+$
7		$\mid$	$-$

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

- 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

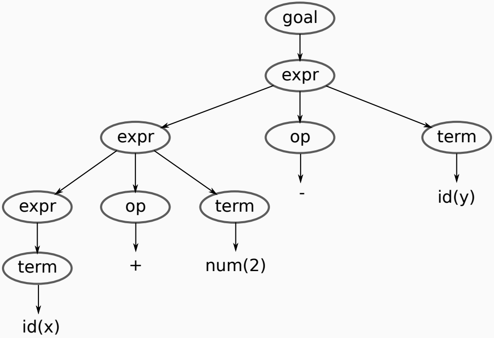
Given a CFG, we can derive sentences by repeated substitution

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

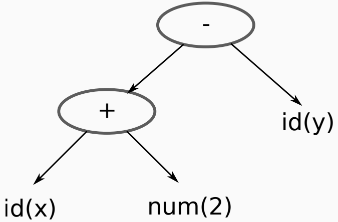
Parse tree

`x + 2 - y`



This contains a lot of unnecessary information.

Abstract Syntax Tree (AST)

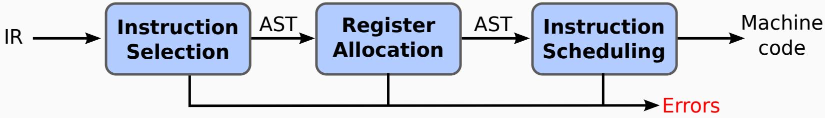


The AST summarises grammatical structure, without including detail about the derivation.

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

Back end

The Back end

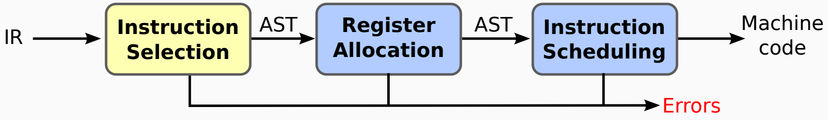


- Translate IR into target machine code
- Choose instructions to implement each IR operation
- Decide which value to keep in registers
- Ensure conformance with system interfaces
- Automation has been less successful in the back end

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
```

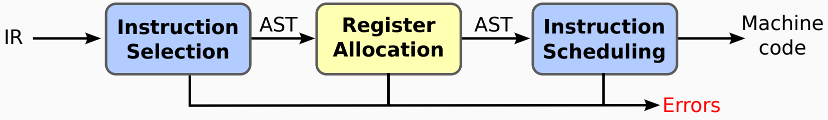
option 2

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

Back end

Register Allocation

Register Allocation

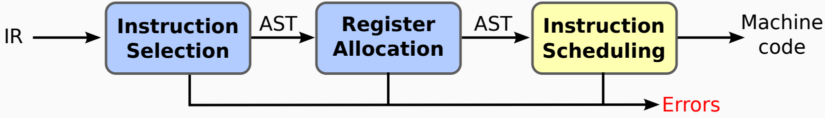


- Have each value in a register when it is used
- Manage a limited set of resources
- Can change instruction choices & insert LOADs & STOREs (spilling)
- Optimal allocation is NP-Complete (1 or k registers)
  - Graph colouring problem
  - Compilers approximate solutions to NP-Complete problems

Back end

Instruction Scheduling

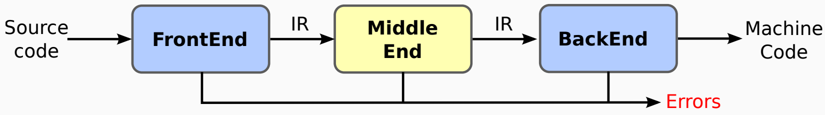
Instruction Scheduling



- 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

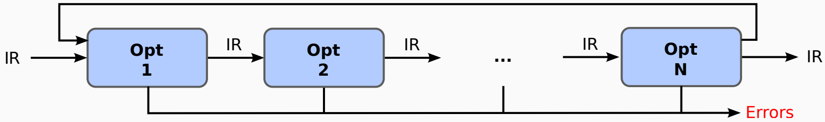


Compiler Optimization (or code improvement):

- 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

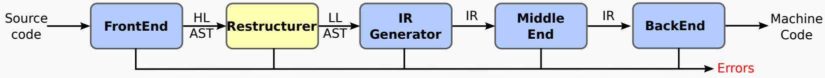
The Optimiser

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