

# CS3300 - Compiler Design

## Introduction

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## Academic Formalities

- Written assignments = 5+5 marks.
- Quiz 1 = 5 marks, Quiz 2 = 5, Final = 40 marks.
- Lab: 6 assignments: 40 marks.
- Extra marks
  - During the lecture time - individuals can get additional 5 marks.
  - How? - Ask a good question, answer a chosen question, make a good point! Take 0.5 marks each. Max one mark per day per person.
- Attendance requirement – as per institute norms. Non compliance will lead to 'W' grade.
  - If you come to the class after 5 minutes - don't.
  - Proxy attendance - is not a help; actually a disservice.
- Plagiarism - A good word to know. A bad act to own.
  - Students Welfare and Disciplinary committee.

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## What, When and Why of Compilers

- **What:**
  - A compiler is a program that can read a program in one language and translates it into an equivalent program in another language.
- **When**
  - 1952, by Grace Hopper for A-0.
  - 1957, Fortran compiler by John Backus and team.
- **Why? Study?**
  - It is good to know how the food (you eat) is cooked.
  - A programming language is an artificial language designed to communicate instructions to a machine, particularly a computer.
  - For a computer to execute programs written in these languages, these programs need to be translated to a form in which it can be executed by the computer.



## Images of the day

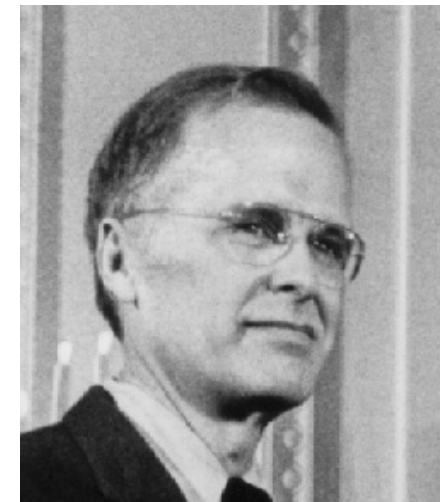


Figure: Grace Hopper and John Backus



Compiler construction is a microcosm of computer science

- **Artificial Intelligence** greedy algorithms, learning algorithms, ...
- **Algo** graph algorithms, union-find, dynamic programming, ...
- **theory** DFAs for scanning, parser generators, lattice theory, ...
- **systems** allocation, locality, layout, synchronization, ...
- **architecture** pipeline management, hierarchy management, instruction set use, ...
- **optimizations** Operational research, load balancing, scheduling, ...

Inside a compiler, all these and many more come together. Has probably the healthiest mix of theory and practise.



For the class to be a mutually learning experience:

- What will be required from the students?
  - An open mind to learn.
  - Curiosity to know the basics.
  - Explore their own thought process.
  - Help each other to learn and appreciate the concepts.
  - Honesty and hard work.
  - Leave the fear of marks/grades.
- What are the students expectations?



A rough outline (we may not strictly stick to this).

- Overview of Compilers
- Regular Expressions and Context Free Grammars (glance)
- Lexical Analysis and Parsing
- Type checking
- Intermediate Code Generation
- Register Allocation
- Code Generation
- Overview of advanced topics.



### Start exploring

- C and Java - familiarity a must - Use eclipse to save you valuable coding and debugging cycles.
- Flex, Bison, JavaCC, JTB – tools you will learn to use.
- Make / Ant / Scripts – recommended toolkit.
- Find the course webpage:  
<http://www.cse.iitm.ac.in/krishna/cs3300/>



These slides borrow liberal portions of text verbatim from Antony L. Hosking @ Purdue, Jens Palsberg @ UCLA, and the Dragon book.

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## A common confusion: Compilers and Interpreters

- What is a compiler?
  - a program that translates an executable program in one language into an executable program in another language
  - we expect the program produced by the compiler to be better, in some way, than the original.
- What is an interpreter?
  - a program that reads an executable program and produces the results of running that program
  - usually, this involves executing the source program in some fashion

This course deals mainly with compilers  
Many of the same issues arise in interpreter

- A common (mis?) statement – XYZ is an interpreted (or compiled) languaged.



## Compilers – A closed area?

“Optimization for scalar machines was solved years ago”

Machines have changed drastically in the last 20 years

Changes in architecture  $\Rightarrow$  changes in compilers

- new features pose new problems
- changing costs lead to different concerns
- old solutions need re-engineering

Changes in compilers should prompt changes in architecture

- New languages and features



# Expectations

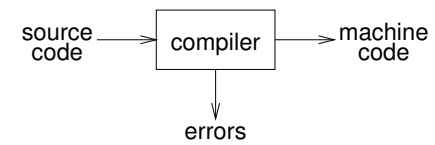
What qualities are important in a compiler?

- 1 Correct code
- 2 Output runs fast
- 3 Compiler runs fast
- 4 Compile time proportional to program size
- 5 Support for separate compilation
- 6 Good diagnostics for syntax errors
- 7 Works well with the debugger
- 8 Good diagnostics for flow anomalies
- 9 Cross language calls
- 10 Consistent, predictable optimization

Each of these shapes your expectations about this course



# Abstract view



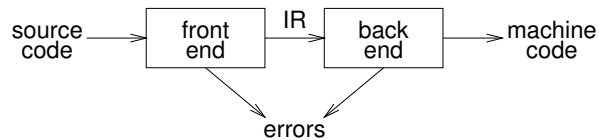
Implications:

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

Big step up from assembler — higher level notations



# Traditional two pass compiler



Implications:

- intermediate representation (IR). Why do we need it?
- front end maps legal code into IR
- back end maps IR onto target machine
- simplify retargeting
- allows multiple front ends
- multiple passes  $\Rightarrow$  better code

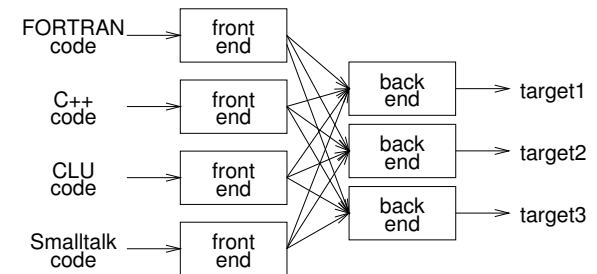
A rough statement: Most of the problems in the Front-end are simpler (polynomial time solution exists).

Most of the problems in the Back-end are harder (many problems are NP-complete in nature).

**Our focus:** Mainly front end and little bit of back end.



A Clarification:



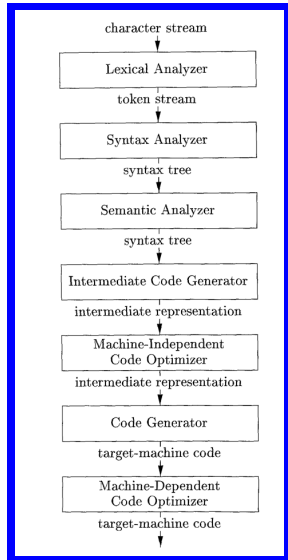
Can we build  $n \times m$  compilers with  $n + m$  components?

- must encode all the knowledge in each front end
- must represent all the features in one IR
- must handle all the features in each back end

Limited success with low-level IRs



# Phases inside the compiler



## Front end responsibilities:

- Recognize syntactically legal code; report errors.
- Recognize semantically legal code; report errors.
- Produce IR.

## Back end responsibilities:

- Optimizations, code generation.

## Our target

- five out of seven phases.
- glance over optimizations – attend the graduate course, if interested.



# Lexical analysis

- Also known as scanning.
- Reads a stream of characters and groups them into meaningful sequences, called lexems.
- Eliminates white space
- For each lexeme, the scanner produces an output of the form:  $\langle \text{token-type, attribute-values} \rangle$
- Example token-types: identifier, number, string, operator and ...
- Example attribute-types: token index, token-value, line and column number and ...
- Example scanning:

• `position = initial + rate * 60`

- For a typical language like C/Java the following lexemes and their values can be identified:

lexeme	token	lexeme	token
		+	$\langle \text{op, +} \rangle$
position	$\langle \text{id, position} \rangle$	rate	$\langle \text{id, rate} \rangle$
=	$\langle \text{op, =} \rangle$	*	$\langle \text{op, *} \rangle$
initial	$\langle \text{id, initial} \rangle$	60	$\langle \text{num, 60} \rangle$



# Specifying patterns

Q: How to specify patterns for the scanner?

## Examples:

- white space

```

<ws> ::= <ws> ' '
        | <ws> '\t'
        | ' '
        | '\t'
  
```

- keywords and operators  
specified as literal patterns: `do`, `end`



# Specifying patterns

A scanner must recognize the units of syntax

- identifiers  
alphabetic followed by  $k$  alphanumerics (., \$, &, ...)
- numbers
  - integers: 0 or digit from 1-9 followed by digits from 0-9
  - decimals: integer | '.' | digits from 0-9
  - reals: (integer or decimal) | 'E' | (+ or -) digits from 0-9
  - complex: | '(' | real | ',' | real | ')' | —

We need a powerful notation to specify these patterns



# Regular Expressions

Patterns are often specified as regular languages

Notations used to describe a regular language (or a regular set) include both regular expressions and regular grammars

Regular expressions (over an alphabet  $\Sigma$ ):

- 1  $\epsilon$  is a RE denoting the set  $\{\epsilon\}$
- 2 if  $a \in \Sigma$ , then  $a$  is a RE denoting  $\{a\}$
- 3 if  $r$  and  $s$  are REs, denoting  $L(r)$  and  $L(s)$ , then:
  - $(r)$  is a RE denoting  $L(r)$
  - $(r) | (s)$  is a RE denoting  $L(r) \cup L(s)$
  - $(r)(s)$  is a RE denoting  $L(r)L(s)$
  - $(r)^*$  is a RE denoting  $L(r)^*$



# Examples of Regular Expressions

- identifier
  - letter  $\rightarrow (a | b | c | \dots | z | A | B | C | \dots | Z)$
  - digit  $\rightarrow (0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9)$
  - id  $\rightarrow \text{letter} ( \text{letter} | \text{digit} )^*$
- numbers
  - integer  $\rightarrow (+ | - | \epsilon) (0 | (1 | 2 | 3 | \dots | 9) \text{digit}^*)$
  - decimal  $\rightarrow \text{integer} . ( \text{digit} )^*$
  - real  $\rightarrow ( \text{integer} | \text{decimal} ) \mathbb{E} (+ | -) \text{digit}^*$
  - complex  $\rightarrow ' ( ' \text{real} , \text{real} ' ) '$

Most tokens can be described with REs  
We can use REs to build scanners automatically



# Generic examples of REs

Let  $\Sigma = \{a, b\}$

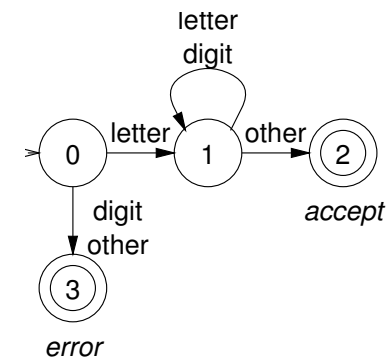
- $a|b$  denotes  $\{a, b\}$
- $(a|b)(a|b)$  denotes  $\{aa, ab, ba, bb\}$   
i.e.,  $(a|b)(a|b) = aa|ab|ba|bb$
- $a^*$  denotes  $\{\epsilon, a, aa, aaa, \dots\}$
- $(a|b)^*$  denotes the set of all strings of  $a$ 's and  $b$ 's (including  $\epsilon$ )  
i.e.,  $(a|b)^* = (a^*b^*)^*$
- $a|a^*b$  denotes  $\{a, b, ab, aab, aaab, aaaab, \dots\}$



# Recognizers

From a regular expression we can construct a deterministic finite automaton (DFA)

Recognizer for identifier:



## Code for the recognizer

Given an automata, can we write a recognizer for a token?

```

ch=nextChar();
state=0; // initial state
done=false;
tokenVal=""// empty
while (not done) {
  class=charClass[ch];
  state=
  nextState[class,state];
  switch(state) {
  case 1:
    tokenVal=tokenVal+ch;
    char=nextChar();
    break;
  case 2: // accept state
    tokenType=id;
    done = true;
    break;
  case 3: // error
    tokenType=error;
    done=true;
    break;
  } // end switch
} // end while
return tokenType;

```



## Tables for the recognizer

Two tables control the recognizer

charClass:		a-z	A-Z	0-9	other
value	letter	letter	digit	other	
class	0	1	2	3	
nextState:	letter	1	1	—	—
	digit	3	1	—	—
	other	3	2	—	—

To change languages, we can just change tables



## So what is hard?

Language features that can cause problems:

*reserved words*

PL/I had no reserved words

```

if then then then = else; else else =
then;

```

*significant blanks*

FORTRAN and Algol68 ignore blanks

```

do 10 i = 1,25
do 10 i = 1.25

```

*string constants*

special characters in strings

```

newline,tab,quote,comment delimiter

```

*finite closures*

some languages limit identifier lengths

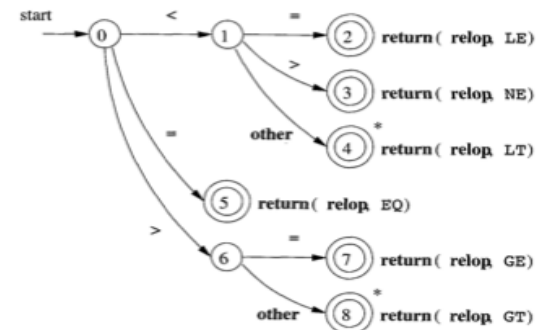
adds states to count length

FORTRAN 66 → 6 characters



## Considerations when building lexical analyzer

- How to combine multiple DFAs?
  - Try all (in parallel?), take the longest.
- Some of the patterns may have common prefixes. e.g. <, <=, <>



- Create a transition diagram.

- Reserved words: example then, thenVar
  - Identify as an identifier and if the value matches a reserved word, change their "type".
  - Let it be identified as both reserved word and identifier. Higher priority to reserved words.



## Error recovery

- It is hard to tell (without the aid of other components), if there is a source code error.
- For example:  
`fi (a = f(x))`  
If `fi` a misspelling for “`if`”, or a function identifier?
- Since `fi` is a valid lexeme for the token `id`, the lexer must return the token  $\langle id, fi \rangle$ .
- A later phase (parser or semantic analyzer) may be able to catch the error.

Recovery (if the lexer is unable to proceed, that is):

- Panic and stop!
- Delete one character!
- Many other one character related fixes (examples?)



## Automatic construction

Scanner generators automatically construct code from RE-like descriptions

- construct a DFA
- use state minimization techniques
- emit code for the scanner  
(table driven or direct code)

A key issue in automation is an interface to the parser

`lex/flex` is a scanner generator

- Takes a specification of all the patterns as a RE.
- emits C code for scanner
- provides macro definitions for each token  
(used in the parser)



## Limits of regular languages

Not all languages are regular

One cannot construct DFAs to recognize these languages:

- $L = \{p^k q^k\}$
- $L = \{wcw^r \mid w \in \Sigma^*\}$

Note: neither of these is a regular expression!

(DFAs cannot count!)

But, this is a little subtle. One can construct DFAs for:

- alternating 0's and 1's  
 $(\epsilon \mid 1)(01)^* (\epsilon \mid 0)$
- sets of pairs of 0's and 1's  
 $(01 \mid 10)^+$

