# COMP3131/9102: Programming Languages and Compilers

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`http://www.cse.unsw.edu.au/~cs3131`

`http://www.cse.unsw.edu.au/~cs9102`

# Lectures

1. pre-recorded lectures
2. Lecture times: may be used for providing feedback to our assignments (and for consulation purposes)
3. The Microsoft Team for this course:
   - Name: COMP3131/9102 (22T1)
   - Team Code to Join: grez5g2
4. The lecture recording for a lecture can be found in its corresponding channel in the course's Team.


5. Moodle is not used

## Outline

1. Administrivia
2. Subject overview
3. Lexical analysis $\Longrightarrow$ Assignment 1

## Important Facts

- Lecturer + Subject Admin:

| | |
|---|---|
| Name: | Jingling Xue |
| Office: | K17 – 501L |
| Telephone: | x54889 |
| Email: | jingling@cse.unsw.edu.au |

Important messages will be displayed on the subject home page and urgent messages also sent to you by email.

- Check the course emails/notices at least every day
- Check the questions/ansers at the course forum
- Contact me at jingling@cse rather than ~~{cs3131,cs9102}@cse~~

# Handbook Entry

COMP3131/9102: Programming Languages and Compilers

Prerequisite: COMP2911 (or good knowledge on OO, C++ and/or Java)

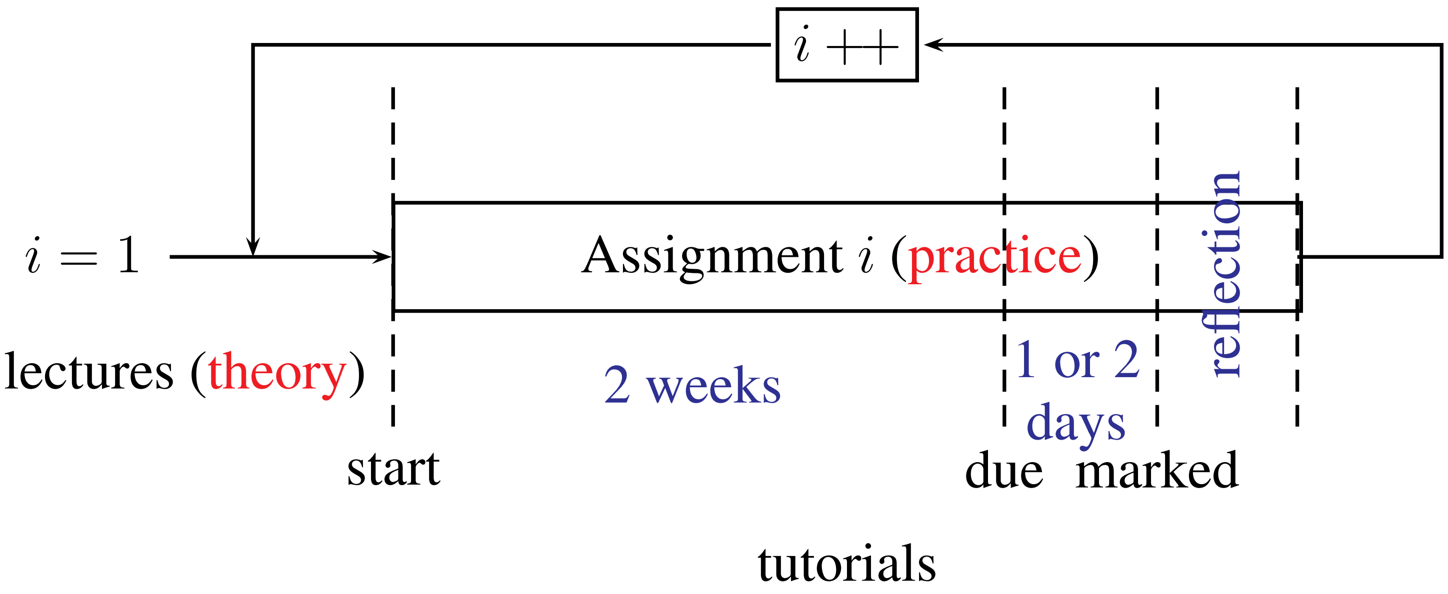
`Covers the fundamental principles in programming languages and implementation techniques for compilers (emphasis on compiler front ends). Course contents selected from: program syntax and semantics, formal translation of programming languages, finite-state recognisers and regular expressions, context-free parsing techniques such as LL(k) and LR(k), attribute grammars, syntax-directed translation, type checking, code optimisation and code generation.`

`Project: implementation of a compiler in a` $\boxed{\texttt{main-stream}}$ `programming language for a` $\boxed{\texttt{non-trivial}}$ `programming language.`

A Variant of C $\Longrightarrow$ VC

Java

# Teaching Strategies




reflection: on $i$ and concepts, fix its bugs, ...

- Project-centered rather than project-augmented
- Strike a balanced approach between theory and practice

## Learning Strategies

- Complete each assignment on time!
- Understand theories introduced in lectures and apply them when implementing your assignment modules
- Tutorials — more examples worked out to ensure your understandings of compiler principles introduced in lectures
- Consultations:
  - Course Forum
  - No fixed consultation hours (but you can reach me during the usual lecture slots via this course's Team)
  - Individual consultations (with me)
    - Ask questions by email
    - Make an individual appointment

## Learning Objectives

- Learn important compiler techniques, algorithms and tools
- Learn to use compilers (and debuggers) more efficiently
- Improve understanding of program behaviour
  (e.g., syntax, semantics, typing, scoping, binding)
- Improve programming and software engineering skills
  (e.g., OO, visitor design pattern)
- Learn to build a large and reliable system
- See many basic CS concepts at work
- Prepare you for some advanced topics, e.g., compiler backend optimisations (for GPUs, FPGAs, multicores, embedded processors)

## Knowledge Outcomes

- finite state automata and how they relate to regular expressions
- context free grammars and how they relate to context-free parsing
- formal language specification strategies
- top-down and bottom-up parsing styles
- attribute grammars
- type checking
- Java virtual machine (JVM)
- code generation techniques
- visitor design pattern

## Skill Outcomes

- ability to write scanners, parsers, semantic analysers and code generators
- ability to use compiler construction tools: lexers + parsers
- understand how to specify the syntax and semantics of a language
- understand code generation
- understand and use the data structures and algorithms employed within the compilation process
- ability to write reasonably large OO programs in Java using packages, inheritance, dynamic dispatching and visitor design pattern
- understand virtual machines, in particular, JVM

## Studying Materials

- Textbook:

  Alfred V. Aho, Monica S. Lam, Ravi Sethi and Jeffrey D. Ullman, Compilers: Principles, Techniques, and Tools, 2/E, Addison Wesley, 2007. ISBN-10: 0321486811. ISBN-13: 9780321486813.

- `http://www.cse.unsw.edu.au/~cs3131`:
  `http://www.cse.unsw.edu.au/~cs9102`:
  - Overhead transparencies
  - Supplementary on-line materials
- Reading: suggested in the lecture notes each week

But lecture notes + tutorial questions and solutions + assignment specs should be roughly sufficient for all programming assignments

## Textbook (not Compulsory)

- 1st edition: The Red Dragon Book
- 2nd edition: The Purple Dragon Book
- A reference to, say, Section 3.1 of Dragon book means a reference to both books.
- Otherwise, a specific reference such as “See Section 3.1 of Red Dragon Book or Section 3.3 of Purple Dragon Book” will be used.

## Programming Assignments

- Five compulsory programming assignments
  - Very detailed specifications
  - Need to follow the specs quite closely
- One optional bonus programming assignment
  - Minimal specification
  - Justify your design decisions (if required)

# Basic Programming Assignments

Writing a compiler in Java to translate VC into Java bytecode:

1. Scanner – reads text and produces tokens
2. Recogniser – reads tokens and checks syntax errors
3. Parser– builds abstract syntax tree (AST)
4. Static Semantics – checks semantics at compile time
5. Code Generator – generates Java bytecode

Notes:

- A description of VC is already available on the home page.
- The recogniser is part of the parser; separating both simplifies the construction of the parsing component.

# Compiler Project Policies

- Policies
  - All are individual assignments
  - No illegal collaborations allowed
  - Penalties applied to late assignments
  - No incompletes – assignment $k$ depends on assignment $k - 1$!
- Class discussions:
  - Course forum: on-line

## Plagiarism

- CSE will adopt a uniform set of penalties for all programming assignments in all courses
- A wide range of penalties
- See the “Course Outlinelink of the course home page

## Extensions

- Very few in the past (only genuine reasons considered)
- Why not?
  - Each assignment builds on the previous ones
  - Each assignment will usually be marked within 48 hours of its submission deadline
- The same practice this year

## Marking Criteria for Programming Assignments

- Evaluated on correctness by using various test cases.
- Some are provided with each assignment but you are expected to design your own (see `http://www.cse.unsw.edu.au/~cs3131/22T1/Info/FAQs.html`)
- No subjective marking

# Lectures

- 10 weeks
- Week 6
  - no lectures
  - no tutorials
- Week 10 (Monday – Easter Holiday): no lecture

## Tutorials

- More on mastering the fundamental principles of the subject
- Tutorials starts from week 2
- Solutions for week $k$ available on-line in week $k + 1$
- Tutor: Dr Samad Saadatmand

# Assessment (Due Dates Tentative)

| Component | Marks | Due |
|---|---|---|
| Scanner | 12 | Week 2 |
| Recogniser | 12 | Week 3 |
| Parser | 18 | Week 5 |
| Static Semantics | 30 | Week 8 |
| Code Generator | 28 | Week 10 |
| Final Exam | 100 | April/May |

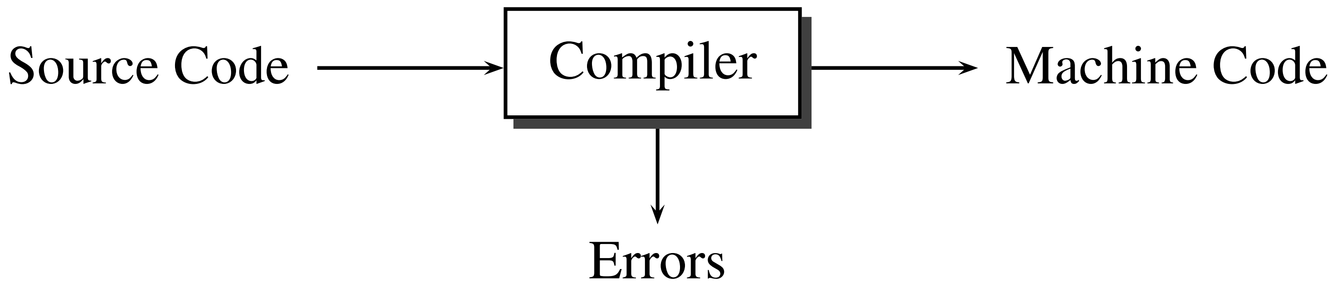
- PROGRAMMING: your marks for all assignments (out of 100)
- EXAM: your marks for the exam (out of 100)
- BONUS: your bonus marks (out of 5)
- final mark = $\min(\frac{2 \times P \times E}{P + E} + B, 100)$

Recogniser and Parser are two different components of the same assignment.

## Outline

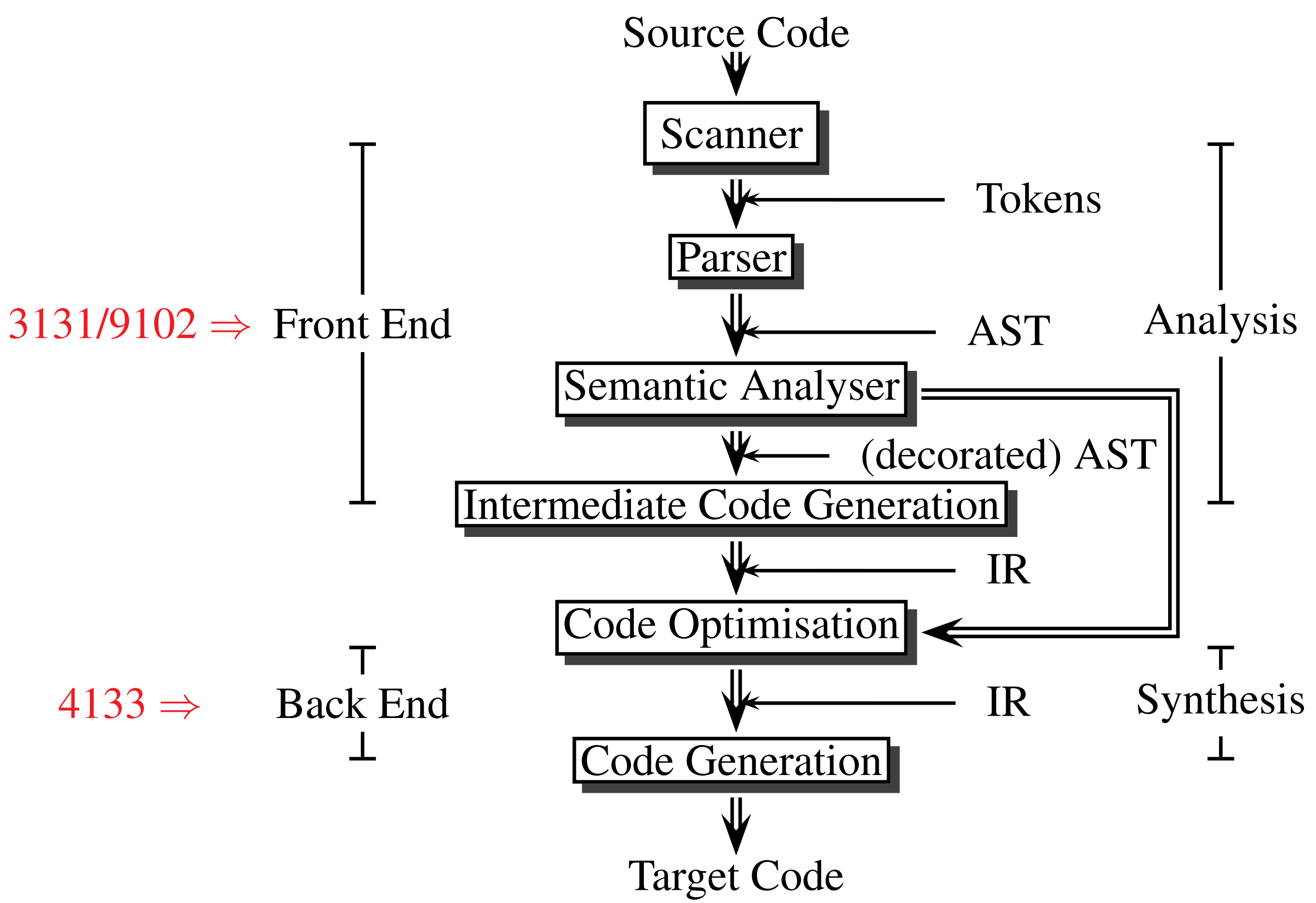
1. Administrivia $\surd$
2. Subject overview
3. Lexical analysis $\Longrightarrow$ Assignment 1

# What Is a Compiler?




- recognise legal (and illegal) programs
- generate correct, hopefully efficient, code
- open-source compilers:
  - C/C++: GNU, LLVM, Open64
  - Java: Maxine, Jalapeno
  - Javascript: Google's Closure

# The Typical Structure of a Compiler

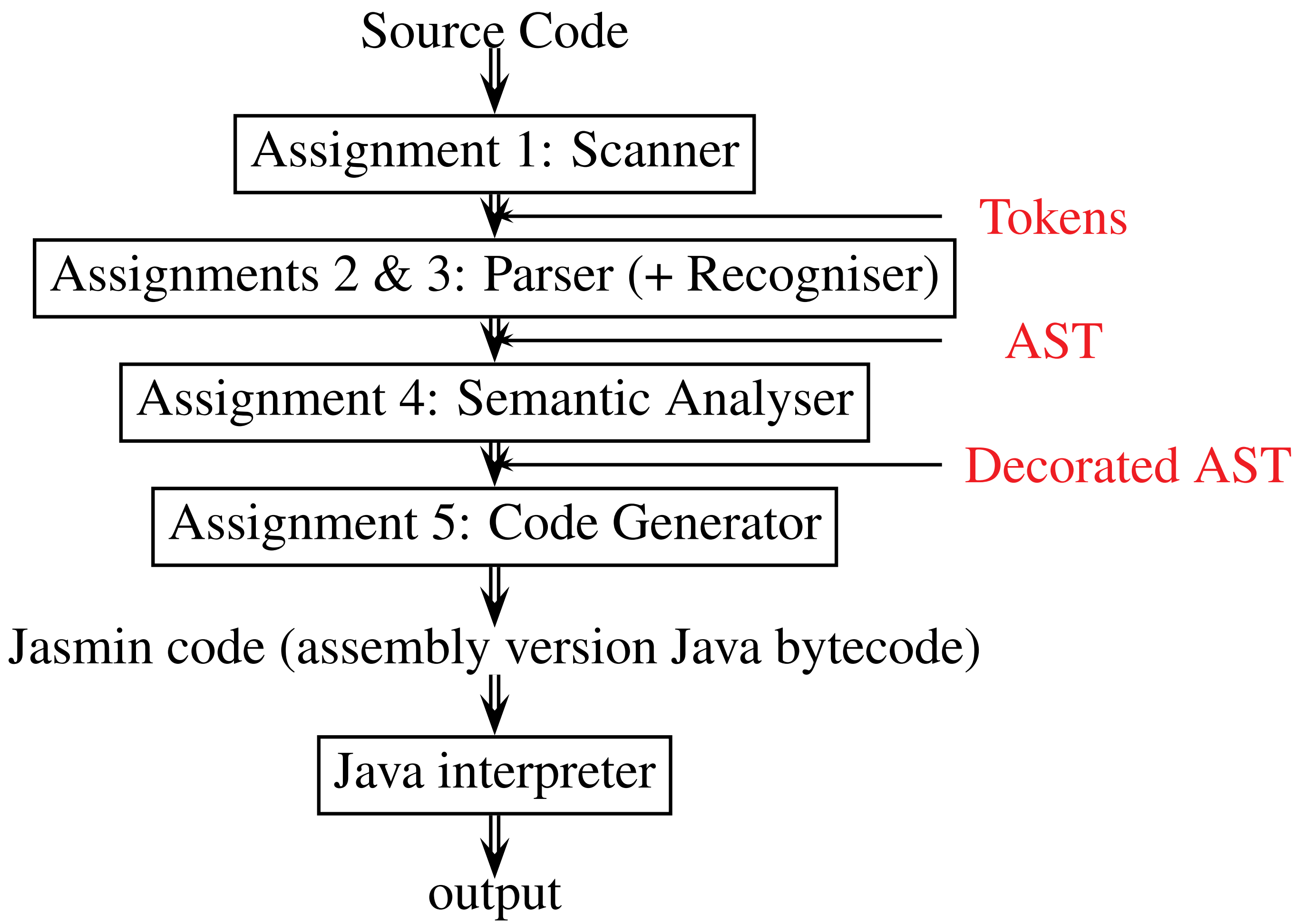



Informally, error handling and symbol table management also called "phases".

(1) Analysis: breaks up the program into pieces and creates an intermediate representation (IR), and

(2) Synthesis: constructs the target program from the IR

# The VC Compiler – Marked Only for Correctness




Correspond to the first four components in Slide 24

# The Example for JVM (from Our VC Compiler)

`position = initial + rate * 60` (all of float type)

$\Downarrow$

Scanner

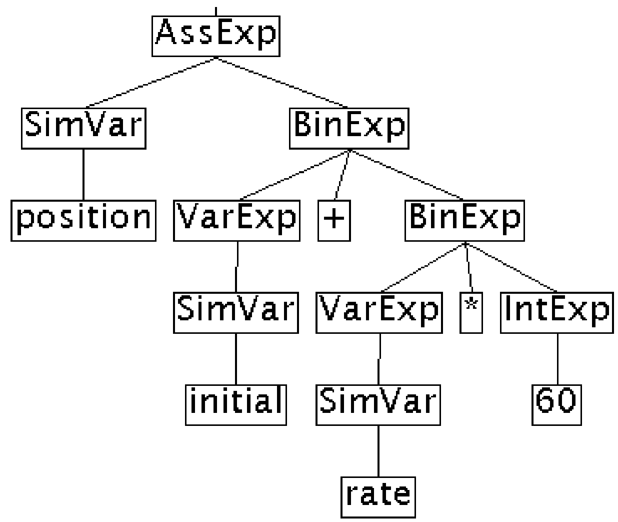
$\Downarrow$

$\textbf{id}_1 = \textbf{id}_2 + \textbf{id}_3 * \textbf{intliteral}$

$\Downarrow$

Parser (+ Recogniser)

$\Downarrow$

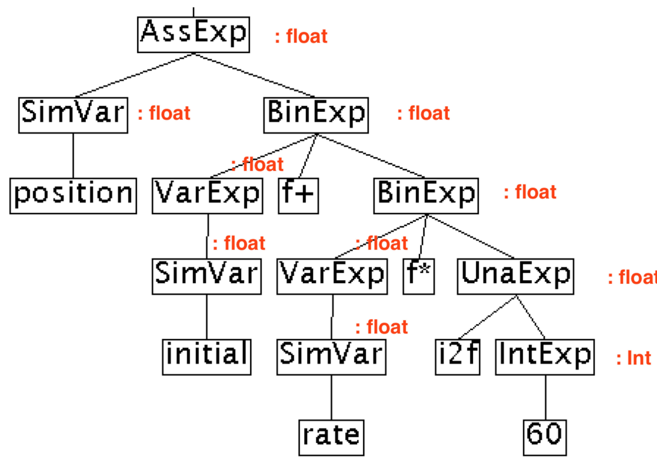



$\Downarrow$

Static Semantic

$\Downarrow$

# The Example for JVM (Cont'd)




⇓

Code Generator

⇓

```
fload_3          index   variable   value
fload 4          ------------------------
bipush 60          ...
i2f              ------------------------
fmul               2     position
fadd               3     initial
fstore_2           4     rate
```

# Lexical Analysis

## Scanner

- groups characters into tokens – the basic unit of syntax

```
position = initial + rate * 60
```

  becomes

```
1. The identifier position
2. The assignment operator =
3. The identifier initial
4. The plus sign
5. The identifier rate
6. The multiplication sign
7. The integer constant 60.
```

- character string forming a token is a lexeme
- eliminates white space (blanks, tabs and returns)

# Syntax Analysis

## Parser

- groups tokens into grammatical phrases
- represents the grammatical phases as an AST
- produces meaningful error messages
- attempts error detection and recovery

The syntax of a language is typically specified by a CFG (Context-Free Grammar).

The typical arithmetic expressions are defined:

$$
\begin{array}{lcl}
\langle \text{expr} \rangle & \rightarrow & \langle \text{expr} \rangle + \langle \text{term} \rangle \mid \langle \text{expr} \rangle - \langle \text{term} \rangle \mid \langle \text{term} \rangle \\
\langle \text{term} \rangle & \rightarrow & \langle \text{term} \rangle * \langle \text{factor} \rangle \mid \langle \text{term} \rangle \,/\, \langle \text{factor} \rangle \mid \langle \text{factor} \rangle \\
\langle \text{factor} \rangle & \rightarrow & (\ \langle \text{expr} \rangle\ ) \mid \textbf{ID} \mid \textbf{INTLITERAL}
\end{array}
$$

# Semantic Analysis

## Semantic Analyser

- Checks the program for semantic errors
  - variables used before defined
  - operands called with compatible types
  - procedures called with the right number and types of arguments
- An important task: type checking
  - reals cannot be used to index an array
  - type conversions when some operand coercions are permitted
- The symbol table will be consulted

| Name | Type | |
|---|---|---|
| initial | float | $\cdots$ |
| position | float | $\cdots$ |
| rate | float | $\cdots$ |

## (Intermediate) Code Generation

(Intermediate) Code Generator generates an explicit IR

- Important IR properties:
  - ease of generation
  - ease of translation into machine instructions
- Subtle decisions in the IR design have major effects on the speed and effectiveness of the compiler.
- Popular IRs:
  - Abstract Syntax trees (ASTs)
  - Directed acyclic graphs (DAGs)
  - Postfix notation
  - Three address code

# Topic, Theory and Tools

| Topic | Theory | Tools |
|---|---|---|
| lexical analysis | REs, NFA, DFA | scanner generator (lex, JFlex) |
| syntactic analysis | CFGs, LL(k) and LR(k) | parser generator (yacc, JavaCC, CUP) |
| semantic analysis | attribute grammars, type checking | formal semantics |
| code optimisation | loop optimisations, ... | data-flow engines |
| code generation | syntax-directed translation | automatic code generators (tree tilings) |

## Error Detection, Reporting and Recovery

- Detection:
  - Lexical errors: e.g., ”123 $\Longrightarrow$ unterminated string
  - Syntax Errors: e.g., forgetting a closing parenthesis
  - Semantic Errors: e.g., incompatible operands for an operator
- Report as accurately as possible the locations where errors occur.
- After detecting an error, can recover and proceed, allowing further errors in the source program to be detected.

You can optionally implement error recovery in your parser.

# VC

- comments: Java-like // and /* */
- Types:
  - primitive: void, int, float and boolean
  - array: int[], float[], boolean[]
- variables: global and local
- Literals: integers, reals, boolean, strings
- Expressions: conditional, relational, arithmetic and call
- Statements: if, for, while, assignment, break, continue, return
- Functions: the parameters are passed by value

Read the VC specification to become familiar with the language

# Syllabus

1. Lexical analysis
   - crafting a scanner by hand
   - regular expressions, NFA and DFA
   - scanner generator (e.g.,, lex and JLex)
2. Context-free grammars
3. Syntactic analysis
   - abstract syntax trees (ASTs)
   - recursive-descent parsing and LL(k)
   - bottom-up parsing and LR(k) – not covered
   - Parser generators (e.g., yacc, JavaCC and JavaCUP)
4. Semantic analysis
   - symbol table
   - identification (i.e., binding)
   - type checking
5. Code generation
   - syntax-directed translation
   - Jasmin assembly language
   - Java Virtual Machines (JVMs)

# Lectures (Tentative)

1. Week 1: Intro, lexical analysis, DFAs and NFAs
2. Week 2: CFGs + parsing
3. Week 3: Parsing + Abstract syntax trees (ASTs)
4. Week 4: Attribute grammars
5. Week 5: Static semantics
6. Week 6: Lecture-free
7. Week 7: JVM + Jasmin
8. Week 8: Code generation
9. Week 9: DFAs + NFAs + Parsing
10. Week 10: Revision

# What Are Lectures for?

- Introduce new material mostly on the theoretical aspect of compiling
  - REs and parsing $\Longrightarrow$ automatic scanner and parser generators
  - Usually assessed in the final exam
- Guide you for implementing your VC compiler.
  - Introduce important design issues
  - Explain how to use the supplied classes – but the on-line description of each assignment should mostly suffice

## COMP3131/9102 Is Challenging and Fun

- Project is challenging
- One of the few opportunities for writing a large, complex software
- But
  - you learn how languages and compilers work, and
  - you will improve your programming and software engineering skills

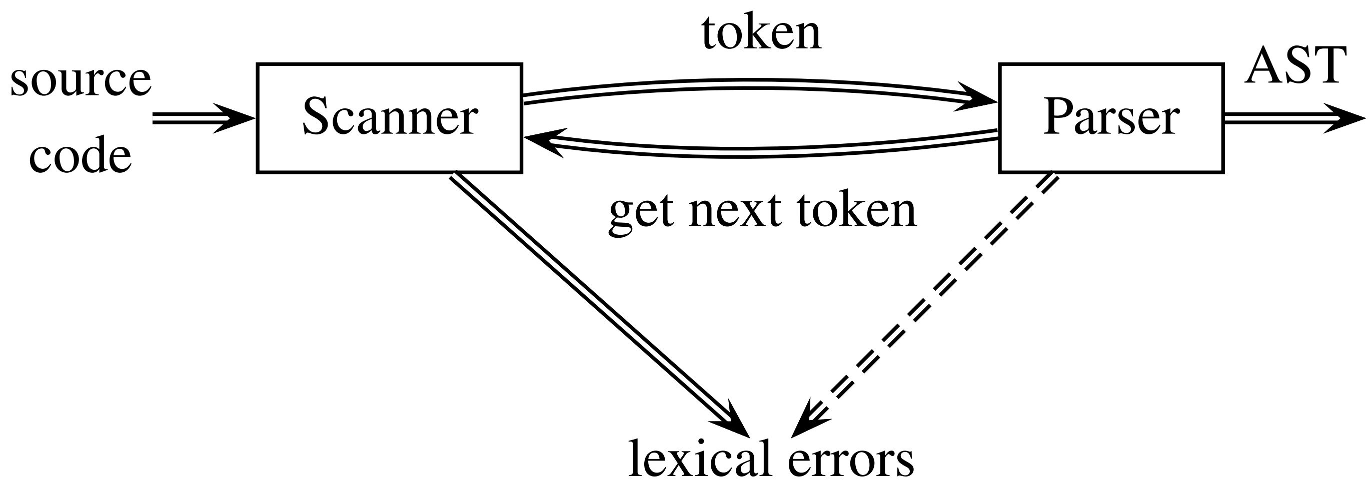
# Outline

1. Administrivia $\surd$
2. Subject overview $\surd$
3. Lexical analysis $\Longrightarrow$ Assignment 1

## Lexical Analysis

1. The role of a scanner
2. Import concepts
   - Tokens
   - Lexemes (i.e., spellings)
   - Patterns
3. Design issues in crafting a scanner by hand $\Longrightarrow$ Assignment 1

# The Role of the Scanner




- The tokens to programming languages are what the words to natural languages.
- The scanner operates as a subroutine called by the parser when it needs a new token in the input stream.
- In comparison with Section 2.7 of Dragon Book, a symbol table will only be used in Assignment 3.

## java.util.StringTokenizer

```
import java.util.*;

public class JavaStringTokenizer {

  public static void main(String argv[]) {
    StringTokenizer s =
    new StringTokenizer("(02) 9385 4889", "() ", false);
    // "() ": token delimiters
    // false: () not part of tokens

    while (s.hasMoreTokens())
      System.out.println(s.nextToken());
  }
}
```

# Tokens

- The tokens in VC are classified as follows:
  - identifiers (e.g., sum, i, j)
  - keywords (e.g., int, if or while)
  - operators (e.g., “+” or “$*$”, “$<=$”)
  - separators (e.g., “{”, ‘}”, “;”)
  - literals (integer, real, boolean and string constants)
- The exact token set depends on the programming language in question (and the grammar used).

  The assignment operator token is “:=” in Pascal and “=” in C.
- Analogously, in natural languages, “types” of tokens (i.e., words): verb, noun, article, adjective, etc. The exact word set depends on the natural language in question.

## Lexemes (i.e., Spellings of Tokens)

- The lexeme of a token: the character sequence (i.e., the actual text of) forming the token.
- Examples:

| Token | Token Type | Lexeme |
|---|---|---|
| rate_1 | ID | rate_1 |
| i | ID | i |
| + | + | + |
| <= | <= | <= |
| while | while | while |
| 100 | INTLITERAL | 100 |
| 1.1e2 | FLOATLITERAL | 1.1e2 |
| true | BOOLEANLITERAL | true |

## (Token) Patterns

- Pattern: a rule describing the set of lexemes that can represent a particular token.
- The pattern is said to match each string in the set.

| Token Type | Pattern | Lexeme (i.e., spelling) |
|---|---|---|
| **INTLITERAL** | a string of decimal digits | 127, 0 |
| **FLOATLITERAL** | fill a verbal spec here for C! | 127.1, .1, 1.1e2 |
| **ID** | a string of letters, digits and underscores beginning with a letter or underscore | sum, line_num |
| + | the character '+' | + |
| **while** | the letters 'w', 'h', 'i', 'l', 'e' | while |

- Need a formal notation for tokens $\Longrightarrow$ REs, NFA, DFA (Week 1 (Thursday))
- But today's lecture sufficient for doing Assignment 1

## Regular Expressions for Integer and Real Numbers in C

- Integers:

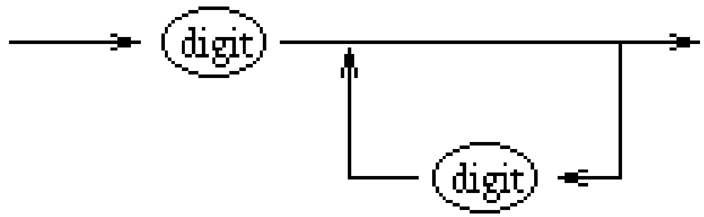
```
intLiteral: digit (digit)*
     digit: 0|1|2|...|9
```

- Reals:

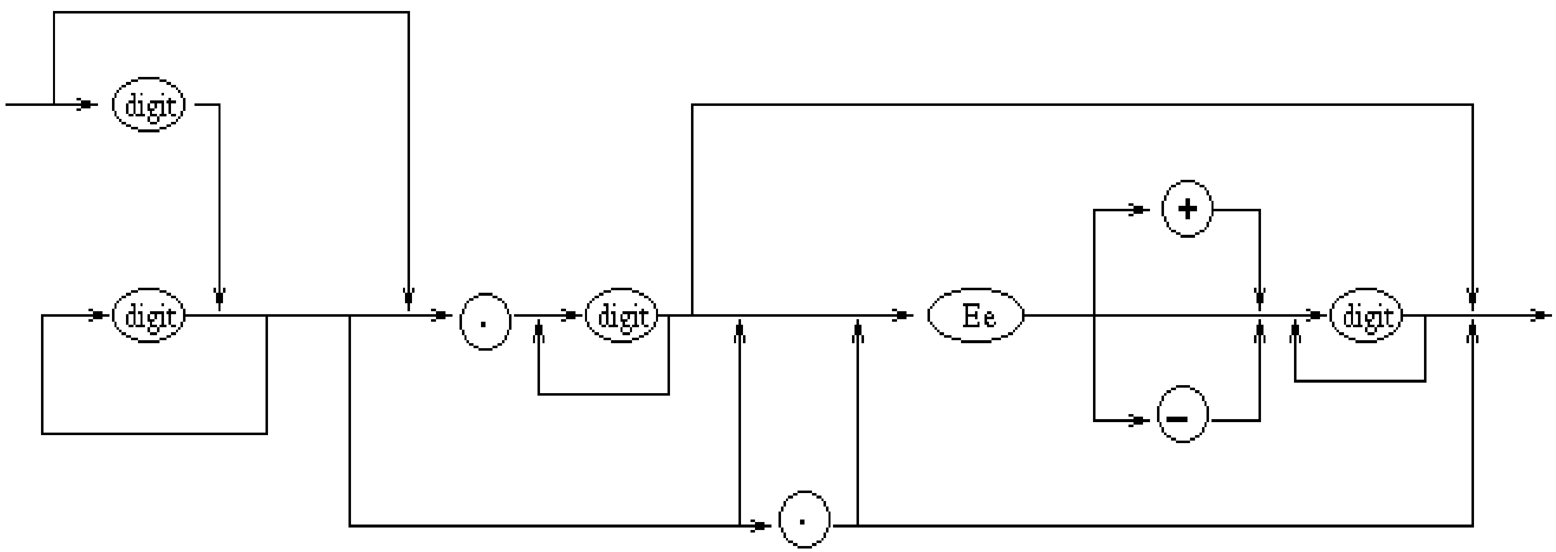
```
floatLiteral: digit* fraction exponent?
            | digit+.
            | digit+.?exponent
       digit: 0|1|2|...|9
    fraction: .digit+
    exponent: (E|e)(+|-)?digit+
```

# Finite State Machines for Integers and Reals

- Integers (DFA):




- Reals (NFA):



# Assignment 1: Scanner

```
Scanner.java: a skeleton of the scanner program
              (to be completed)

Token.java:   The class for representing all the tokens
              and for distinguishing between identifiers
              and keywords

SourceFile.java: The class for handling the source file

SourcePosition.java: The class for defining the position
              of a token in the source file

vc.java:      a driver program for testing your scanner
```

# Design Issues in Hand-Crafting a Scanner (for VC)

1. What are the tokens of the language? – see Token.java
2. Are keywords reserved? – yes in VC, as in C and Java
3. How to distinguish identifiers and keywords? – see Token.java
4. How to handle the end of file? – return a special Token
5. How to represent the tokens? – see Token.java
6. How to handle whitespace and comments? – throw them away
7. What is the structure of a scanner? – see Scanner.java
8. How to detect and recover from lexical errors?
9. How many characters of lookahead are needed to recognise a token?

## PL/1 Has No Reserved Words

- A legal but bizarre PL/1 statement:

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

  Keywords such as **IF** and **THEN** can be used as identifiers.

- Another legal PL/1 snippet:

```
real    integer;
integer real;
```

- Two approaches to distinguishing identifiers from reserved words:
  - The scanner interacts with the parser
  - Regard the identifiers and keyword as having the same token type, leaving the task of distinguishing them to the parser

## How to Represent a Token?

```
Token                          Representation
------------------------------------------------------------
sum    new Token(Token.ID, "sum", sourcePosition);
123    new Token(Token.INTLITERAL, "123", sourcePosition);
1.1    new Token(Token.FLOATLITERAL, "1.1", sourcePosition);
+      new Token(Token.PLUS, "+", sourcePosition);
,      new Token(Token.COMMA, ",", sourcePosition);
```

sourcePosition is an instance of the Class SourcePosition:

- charStart: the beginning column position of the token
- charFinish: the ending column position of the token
- lineStart=lineFinish: the number of the line where the token is found.

# Blanks Aren't Token Delimiters in FORTRAN

- In the statement

  **DO 10 I = 1,100**

  **DO** is a keyword. However, in the statement

  **DO 10 I = 1.100**

  **DO10I** is an identifier.

  The scanner must look ahead many characters to distinguish the two cases.

- These Fortran Programs are the syntactically identical:

| | |
|---|---|
| DO 10 STEP=1, 10<br>10 WRITE(*,*) 'HELLO!'<br>END | DO10STEP=1, 10<br>10 WRITE(*,*) 'HELLO!'<br>END |
| DO 10 S T    E P=1, 10<br>10 WRITE(*,*) 'HELLO!'<br>END | DO 10 STEP=1, 10<br>10 W    RITE(*,*) 'HELLO!'<br>E      N      D |

## The Structure of a Hand-Written Scanner

```
public final class Scanner {

  getToken() {

  // 1. skip whitespace and comments
  // 2. form the next token
  switch (currentChar) {
  case '(':
    accept();
    return  the token representation for '('

  case '<':
    accept();
    if (currentChar == '=') {
      accept(); // get the next char
      return the token representation for '<='
     } else
```

```
      return the token representation for '<'

  case '.':
    attempting to recognise a float

  ...

  default:
    return an error token
  }
 ...
 return new Token(kind, spelling, sourcePosition);
}
```

You need to think about how to recognise efficiently ids, keywords, integers, etc.

## My accept() Method in the Scanner Class

```
private void accept() {
  currentChar = sourceFile.getNextChar();

  inc my counter for the current line number, if necessary

  inc my counter for the current char column number

  perhaps, you can also accumulate the current lexeme here

}
```

Make sure you count tabs in terms of the number of blank spaces correctly.

## Maintaining Two Scanner Invariants

Every time when the scanner is called to return the next token:

1. currentChar is pointing to either the beginning of
   - some whitespace or
   - some comment or
   - a token
2. Scanner always returns the longest possible match in the remaining input

| Input | Tokens |
|---|---|
| >= | ">=" not ">" and "=" |
| // | end-of-line comments not "/" and "/" |

# Lookahead

```
1.2e+ 3  --->  "1.2"  "e"  "+"  "3" (four tokens)
  ^^^^
  ||||
  |  \
  |  |
  |  +---- three chars of lookahead required:
  |                                 "e","+" and " "
 current char
```

```
The output from your scanner:
Kind = 35 [<float-literal>], spelling = ‘‘1.2’’, position = 1(1)..1(3)
Kind = 33 [<id>], spelling = ‘‘e’’, position = 1(4)..1(4)
Kind = 11 [+], spelling = ‘‘+’’, position = 1(5)..1(5)
Kind = 34 [<int-literal>], spelling = ‘‘3’’, position = 1(7)..1(7)
Kind = 39 [$], spelling = "$", position = 2(1)..2(1)
```

// the following function provided in the supporting code

```
private char inspectChar(int nthChar) {
    return sourceFile.inspectChar(nthChar);
}
```

## Maximal Munch (in C++)

- Each token formed is the longest possible
- Consequences:
  - Syntactically legal:

```
i+++1 ===> i++ + 1;
```

  - Syntactically legal only if some spaces are in between:

```
template <typename T, typename CON=deque<T> >
class stack { ... }
```

  - But the following is ok now in C++11:

```
template <typename T, typename CON=deque<T>>
```

# Lexical Errors

Lexical errors (see the Assignment 1 spec):

```
(1) /*  -> prints an error message (unterminated comment)


(2) |, ^, %, etc.   -> returns an error token and
                       continues lexical analysis
```

## Reading

- Textbook: Chapter 1 and Sections 3.1 – 3.2
- Read the "Course Outline" on the course home page:
- Assignment 1 spec is available on the subject home page

Next Class: Regular Expressions, NFA and DFA