

BSc (Hons) Computer Science

University of Portsmouth

Second Year

Programming Applications and Programming Languages

M30235

Semester 1&2

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Part I

Teaching Block I

The first teaching block is 100% coursework, which makes up 50% of the overall grade. While there are lectures, they are informal, mostly teaching the basic concepts of Flutter, which is very practical, and so notes will not be made here.

Part II

Teaching Block II

Lecture - Intro to Programming Languages

14:00

22/01/24

Jiacheng Tan

Since there are many different types of application, there are also many types of programming language. The main programming domains are as follows

- Scientific (e.g. ForTran)
- Business (e.g. COBOL)
- AI (e.g. LISP)
- Systems Programming (e.g. C, C++)
- Web Software (e.g. HTML, JavaScript)

Language Categories

There are several ways to categorise programming languages, such as by uses, paradigms, abstraction level, etc

Machine Languages

- Machine languages directly run on the hardware, using the instruction set of the processor
- Machine code is usually written in hexadecimal as this is a more efficient way of displaying the binary which represent the instructions
- It is very hard for programmers to directly write machine code, as it is not easy to remember instructions and it lacks features such as jump targets, subroutines, etc

Assembly Languages

- A slight abstraction over machine languages
- Each instruction is replaced with an alphanumeric symbol which is easier for programmers to remember and understand
- They also include features such as subroutines, jump targets, etc which make it much easier to create complex programs

System Programming Languages

- More abstracted from machine languages, but you are still concerned with low-level functions such as memory management
- Used to create operating systems, and for embedded applications where low system requirements do not allow the use of high-level languages

High Level Languages

- Languages that are machine-independent (are not written directly in machine code, and are therefore portable between CPU architectures)
- Need to be compiled or otherwise translated from text to machine code before they can be run

Scripting Languages

- Used to create programs which perform a single, simple task
- These are used for system administration
- Usually interpreted languages
- More akin to pseudocode than other programming languages

Domain-Specific Languages

- Some languages are designed to perform a specific task much more efficiently
- The specific purpose could be just about anything, but are specific to that task and either cannot be used otherwise or are not well suited for it

Programming Paradigms

There are several different paradigms which are used in programming

- Procedural
 - Most programming languages are procedural
 - A program is made up of one or more routines which are run in a specific order
- Functional
 - Applies mathematical functions to inputs to get a result
 - Useful for data processing applications such as data analysis or big data
- Logical

There are also two major types of programming languages, which are designed for different purposes

- Imperative Languages
 - Programs are defined as a sequence of commands for the computer to perform
 - Like a recipe for exactly how to get the desired output
- Declarative Languages
 - Programs describe the desired results without actually specifying how the program should complete the task
 - Functional and logical programming languages are examples of this

Lecture - Implementation and Compilation

14:00

02/02/24

Jiacheng Tan

There are 3 main methods of implementing a language:

- Compilation - Programs are translated into machine language, either before (Compilation) or during (JIT) execution
- Pure Interpretation - Programs are interpreted by another program, known as an interpreter
- Hybrid Interpretation - A compromise between the two, code is compiled into an intermediary language, which is then interpreted with a Language Virtual Machine

Compilation

- High-level code is translated into machine code for a specific platform
- This results in slow translation, but much faster execution
- The compilation process has multiple stages
 - Lexical Analysis - Converts characters in the source into lexical units
 - Syntax Analysis - Transforms lexical units into parse trees which represent the syntactic structure of the program
 - Semantics Analysis - Generate intermediary code
 - Code Generation - Intermediary code is translated into platform-specific machine code
- The program which completes this process is known as the Compiler
- During this process, the compiler uses a "Symbol Table", which each stage interacts with

Lexical Analysis

The scanner reads the source code one character at a time and returns a sequence of tokens which are sent to the next phase. Tokens are symbolic names for elements of the source language. An example of a token in C++ is the keyword 'void', which is a type definition, another example is ';' which delimits the end of a statement. Each token is also stored in the symbol table, along with its attributes.

Symbol Table

The symbol table stores all of the identifiers of a source program, along with their attributes. These attributes include information such as the type of a variable, the size or length of a string or array, the arguments to be used with a function and the types of each argument, etc.

Syntax Analysis or Parsing

The parser analysis the structure of the source code. The parser takes the output of the lexical analyser as a sequence of tokens. It attempts to apply the syntactic rules (or grammar) of the language to the sequence of tokens. The parser uses the language's grammar to derive a parse tree for each statement. Parsers usually construct Abstract Syntax Trees (ASTs), which are slightly simpler and easier to represent with a computer, but which still represent the same syntax. If the syntax tree is invalid for the language's grammar, a syntax error is generated and the compilation process stops

Semantic Analysis

The semantic analyser catches any other issues that are still valid syntax. For example, if you attempt to add a string to a float, it could still be syntactically correct, but semantically makes no sense and is not possible to compute. It is also able to find issues with the variable types of function arguments, such as attempting to use a string in the place of an integer or float.

Code Generation and Optimisation

The code optimiser attempts to improve the time and space efficiency of the program. It can do this in several ways, such as simplifying constants (e.g. replacing $10 * 10$ with 100), removing unreachable code, optimising the flow of code, etc.

The final task of the compiler is to generate the final output code. This could be in the form of platform-specific machine code, or intermediary code for use with a virtual machine. This stage also deals with scheduling and assigning registers for use during execution

Pure Interpretation

- High level code is directly executed by another program known as the interpreter
- There is no syntax or semantics analysis, and there is no optimisation
- Only really suitable for small, non-real-time applications
- It also often requires more space as it needs to store the symbol table during execution
- Very few modern languages use interpreters, other than Python, JavaScript and PHP

Hybrid Interpretation

- A compromise between compilers and pure interpreters
- High-level languages are translated or compiled into an intermediary language, using the same compilation steps as before
- The intermediary code is then run by a platform-specific virtual machine, which interprets the code into machine language

Just-in-Time

- Programs are initially translated into an intermediary language
- This is then loaded into memory and segments of the program are then translated into machine code just before execution
- The machine code is then kept in case the function is called again somewhere else in the program
- This drastically improves the execution speed as compared to pure interpretation, but is still slower and typically less space and memory efficient than a compiled program

Lecture - Regular Expressions

14:00

05/02/24

Jiacheng Tan

The full definition of a language includes definitions of its lexical structures, syntax and semantics. The lexical structures of a language are the form and structure of the individual symbols, such as keywords, identifiers, etc. The syntax determines the structure of the language, such as how a statement is defined, how to structure an expression, and so on. The semantics of a language determine how you can use each operator, what types they support, checking for type consistency in strongly typed languages, etc. The semantics of a language also define its “grammar”, which is how the compiler enforces the semantics.

Language Analysis

The implementations of a language must analyse the lexical and syntactic structure of the source code to determine if it is valid or not. This is usually implemented using two separate systems, the lexical analyser and syntax analyser. If the analyser is implemented using regex, it is a finite automaton, based on a regular grammar (that of the language)

Lexical Analysis

A lexical analyser reads the source code one character at a time and outputs a list of tokens to the next stage of the compiler. These tokens are made up of smaller substrings of source code, known as lexemes. Each lexeme matches a character pattern from the language’s grammar.

The lexical analyser can be implemented in several ways, but the most common are by using regular expressions (Regex), or a deterministic finite automata (DFA).

Definitions

- The Alphabet
 - Each language has its own alphabet, which is the set of all characters which could be used in a lexeme
 - An alphabet is usually represented using Σ
- String or Word
 - A string or word *over* an alphabet is a finite string of symbols from the alphabet
 - The length of a string is the number of symbols which make up the string
 - An empty or null string is denoted by ε , and so $|\varepsilon| = 0$
 - The set of all strings over Σ is denoted by Σ^* .
 - For a symbol or string x , x^n represents a string of that symbol, n times, e.g. $a^4 = aaaa$

Regular Expressions

Regular expressions specify patterns which can be used to match strings of symbols. A regular expression, r matches or is matched by a set of strings if the strings conform to r ’s pattern. The set of strings matched

by r is denoted by $L(r) \subseteq \Sigma^*$, i.e. all strings which are over the alphabet Σ . This is known as the language generated by r .

\emptyset is in and of itself a regular expression, but does not match any strings at all, and is only very rarely useful. ε is also a regular expression, which matches only the empty string ε .

Since ε is an empty string, it can be used as the identity element for concatenation, and as such, $\varepsilon + s = s + \varepsilon = s$.

For each symbol where $c \in \Sigma$, c is a regular expression over Σ . In this case, the expression only matches a single instance of the symbol.

If r and s are both regular expressions, then $r \mid s$ is also a regular expression. $a \mid b$ would match a single instance of either a or b . $a \mid \varepsilon$ would match a single instance of a or ε .

If r and s are both regular expressions, then rs is also a regular expression. This would match a single instance of the string rs , as the string would have to match both the regular expression r **and** s . As with arithmetic expressions, brackets can be used to make the meaning of a regular expression clearer. e.g. $(a \mid b)a$ matches the strings aa and ba .

If r is a regular expression, then r^* would match any number of rs in a row. Specifically, it means zero or more instances of r . r^+ would match one or more instances of r , which could also be written as rr^* .

As with arithmetic expressions, there is a specific order of operations which the symbols must follow. The order is as follows: $()$, $*$ or $^+$, concatenation, \mid . This is similar to arithmetic as anything inside parentheses must be processed before everything else.

A regular definition is a named regular expression, which can be used to make up more complex regular expressions, without re-writing the same expression several times. For example, you might define number as $\text{number} = 0 \mid \dots \mid 9$

Regular Expressions for Lexical Analysis

Regular expressions provide a method to describe the patterns which make up the lexical structure of a language, as well as restricting the alphabet which can be used to write source code. In most cases, languages use a standard alphabet, such as ASCII or UTF-8. An example of a regular expression used in a typical language could be if for the token of IF, $;$ for a semicolon, $(0 \mid \dots \mid 9)^+$ for a number, etc.

Languages are sets of strings chosen from some alphabet Σ . More formally, a language L over an alphabet Σ , $L \subseteq \Sigma^*$.

Given a language L over some alphabet Σ , it is necessary to be able to write an algorithm which takes any input string $w \in \Sigma^*$, and outputs True if $w \in L$ and False if $w \notin L$. This algorithm is known as a decision procedure for L . A decision procedure can be written using either a Deterministic Finite Automaton (DFA) or a Non-deterministic Finite Automaton (NFA). Any language which can be denoted by a regular expression is known as a regular language.

Lecture - Deterministic Finite Automata

14:00

09/02/24

Jiacheng Tan

Rather than regular expressions, you can use state transition diagrams to describe patterns, or the process of matching said patterns. State transition diagrams (or state diagrams) are directed graphs which represent Finite State Automata (FSA) or Finite Automata (FA)

FSA

An FSA has

- A set of states
- A unique start state
- A set of one or more final/accepting states
- An input alphabet, including a unique symbol to represent the end of the input string
- A state transition function, represented by the edges of a directed graph from one state to another, labelled by one or more symbols of the alphabet

Mathematically speaking, an FSA M consists of

- A finite set, Q , of states
- A finite alphabet, Σ of input symbols
- A unique start state, $q_1 \in Q$
- A set of one or more final/accepting states, $F \in Q$
- A transition function $\delta : Q \times \Sigma \rightarrow Q$ which selects a new state for M based on the current state, $s \in Q$ and the current input symbol $a \in \Sigma$

DFAs and NFAs

A finite automata can be either deterministic (DFA) or non-deterministic (NFA). For a FA to be deterministic, it must perform the exact same state transition in a given situation (it's current state and input). If the FA is non-deterministic, it can perform any state transition in a given situation

DFAs for Lexical Analysis

In the context of lexical analysis, a DFA is a string processing machine, using the following process, being in one of a finite set of states at any given step

- Read a string from left to right, one symbol at a time
- On reading a symbol, move to a new state determined by the current state and the symbol which was read
- Upon reading the final symbol, if the current state is an accepting state, then the string is valid. If not, the string is invalid

Transition Diagrams

A DFA is usually represented using a transition diagram. This is a directed graph in which each node represents a possible state, and each edge a transition between states. The label for each edge determines what input character is required for the transition to take place. The DFA begins in the initial state, represented by the small arrow pointing into state 1. Each edge is labelled with the character required to make that transition, such as requiring an 'a' to transition from state 1 to 2. Transitions can move to another state, or return to themselves. The accepting state, 4, is represented by a double circle.

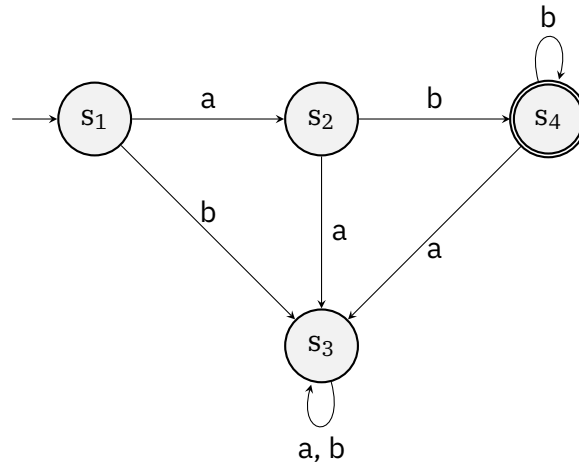


Figure 4.1: A simple DFA, M , which uses the alphabet $\Sigma = \{a, b\}$

For this DFA, the equivalent regular expression could be either $r = abb^*$ or $r = ab^+$. In the case of the transition diagram above, the DFA would be defined as

- $Q = \{s_1, s_2, s_3, s_4\}$ is the set of states
- $\Sigma = \{a, b\}$ is the DFA's input alphabet
- $q_1 = s_1, \in Q$ is the initial state
- $F = \{s_4\}$ is the set of accepting states
- The transition function can be represented as the following set of triples:
 $\{(s_1, a, s_2), (s_1, b, s_3), (s_2, a, s_3), (s_2, b, s_4), (s_3, \{a, b\}, s_3), (s_4, a, s_3), (s_4, b, s_4)\}$

Languages

The set of all strings which a DFA accepts is known as its recognised language. For a DFA, M , the language, $L(M)$ is defined as the set of all strings $w \in \Sigma^*$ such that, when the DFA starts processing w from its initial state, it ends up in an accepting state. For example, the language, $L(M)$ of the DFA above could be defined as $L(M) = \{ab^n \mid n \geq 1\}$, and therefore is the same as the regular expression $r = ab^+$. For any regular expression, r , there is a DFA or NFA, M , such that $L(r) = L(M)$. This makes DFAs and transition diagrams very useful for creating regular expressions, and testing that they work as intended.

Simplifying Transition Diagrams

Since most regular expressions, and therefore FAs, work with real languages such as English, each transition may have many characters for which it is valid. For example, a letter match would require 52 characters, one for each lower-case and capital letter. For this reason, as with regular expressions, you can define a set of symbols which are then used to label each transition, without rewriting the entire set of characters each time.

Building a Lexical Analyser

Lexical analysers tend to be built using one of three methods

- Write the formal description, e.g. a regular expression, of the token patterns, then use this as an input to a program such as **Lex**, which automatically generates a lexical analyser based upon the input
- Design DFAs which describe the patterns, then write a program to implement the DFAs
- Design DFAs which describe the patterns, then write a table-driven implementation of the DFAs

There are also algorithms which can be used to automatically construct a lexical analyser from the DFAs

Lex

Lex was originally written in the 70s, but since then several variants have been created, such as Quex which is a much faster implementation of the same algorithms, written in C and C++. The program takes an input file, called a lex file, which contains regular expressions for various tokens, and automatically generates the C source code for a lexical analyser.

In its most basic form, a Lex file consists of a series of lines in the form `pattern action`, where `pattern` is a regular expression which should be matched, and `action` is a piece of C code.

Lecture - Describing Language Syntax

14:00

16/02/24

Jiacheng Tan

Context-Free Grammars

There are four classes of grammars for describing natural languages: regular, context-free, context-sensitive, and recursively enumerable. Of these, regular and context-free grammars have been found to be useful for describing programming languages. Context-Free Grammars are by far the most widely used in describing programming languages.

A context-free grammar is usually defined as a tuple, $G = (T, N, S, P)$, where

- T - A finite, non-empty set of terminal symbols, which consist of strings referring to parts of sentences in the language
- N - A finite, non-empty set of non-terminal symbols, which refer to syntactic structures defined by other structures and rules
- $S \in N$ - The start symbol
- P - A set of (context-free) productions of the form $A \rightarrow \alpha$ (A produces α) where $A \in N$ and $\alpha \in (T \cup N)^*$

For example, $G_1 = (T, N, S, P)$ where

- $T = \{a, b\}$
- $N = \{S\}$
- $P = \{S \rightarrow ab, S \rightarrow aSb\}$

or $G_2 = (T, N, S, P)$ where

- $T = \{a, b\}$
- $N = \{S, C\}$
- $P = \{S \rightarrow \epsilon, S \rightarrow C, S \rightarrow aSa, S \rightarrow bSb, C \rightarrow a, C \rightarrow b\}$

As you can see, G_2 uses a recursive production to allow for more complex productions to be simplified.

Shorthand

Rules for each non-terminal can be written in an alternative shorthand notation, using $|$. For example, G_1 could also be written as $G_1 \mid ab \mid aSb$.

Backus-Naur Form (BNF)

Another alternative notation for CFG definitions is the Backus-Naur Form (BNF). In BNF, non-terminal symbols are given a descriptive name, enclosed within $\langle \rangle$. For example, you could define $\langle \text{digit} \rangle$ to represent $0, 1, \dots, 9$. This is typically the for which programming languages are actually defined in.

As an example, you could use $\langle \text{exp} \rangle$, $\langle \text{number} \rangle$ and $\langle \text{digit} \rangle$ as non-terminals, and $+, -, *, /, 0, 1, \dots, 9$ as terminal symbols. Using these symbols, the syntactic structure for an arithmetic expression could be defined by the following productions:

```

<exp> -> <exp> + <exp> | <exp> - <exp> | <exp> * <exp>
        | <exp> / <exp> | (<exp>) | <number>
<number> -> <digit> | <digit> <number>
<digit> -> 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

```

Derivations

You can use a context-free grammar to derive strings of terminal symbols. Starting with the start symbol S , you repeatedly apply the production rules until you are left with a string containing only terminal symbols, which is known as a sentence. This process is known as a derivation. Every string of symbols in a derivation is a sentential form.

For example, if we used the grammar G_2 , we can derive the string $abbba$ as follows

- Start at the symbol S
- Apply the rule $S \rightarrow aSa$, and replace S with aSa to obtain the string aSa
- Apply the rule $S \rightarrow bSb$, and replace the S in aSa with bSb to get the string $abSba$
- Apply the rule $S \rightarrow C$, and replace the S in $abSba$ with C to get the string $abCba$
- Apply the rule $C \rightarrow b$, and replace the C in $abCba$ with b to get the final string, $abbba$ which consists only of terminal symbols

If we can get from α to β using a single production, you can say that α immediately derives β , which is written as $\alpha \Rightarrow \beta$. Therefore you can write the full derivation of $abbba$ from S as

$$\begin{aligned}
 S &\Rightarrow aSa \\
 &\Rightarrow abSba \\
 &\Rightarrow abCba \\
 &\Rightarrow abbba
 \end{aligned}$$

With this definition of a derivation, we can define a language as “A grammar is made up of exactly those sentences which can be derived from it”

Left- and Right-Most Derivations

A derivation can be either left- or right-Most, depending upon the order in which non-terminal symbols are resolved. If you start from the left and work rightwards, that is the left-most derivation of the sentence. If you were to instead start from the right and work leftwards, that would be a right-most derivation of the sentence. You can also have a neither left- nor right-most derivation, in which you start in the middle and work outwards.

For some grammars, the left- and right-most derivations of a given sentence could be different, i.e. have a different parse tree.

Parse Trees

You can also represent the structure of an expression given by a derivation as a parse tree. I will not give an example, but the internal nodes represent non-terminal symbols which are used in the derivation, and leaf nodes represent the terminal symbols.

Lecture - Syntax Analysis and Parsing

14:00

19/02/24

Jiacheng Tan

Ambiguity

Some grammars are ambiguous, such that there are multiple valid derivations of any given sentence. This means that the parse trees would be different, and therefore could produce different results. For example, using the same grammar as the previous lecture, a left-most derivation of the sentence $x + y * z$ could be either

```
<exp> => <exp> + <exp>
      => x + <exp>
      => x + <exp> * <exp>
      => x + y * <exp>
      => x + y * z
```

which would give you a parse tree equivalent to $x + (y * z)$, or it could be

```
<exp> => <exp> * <exp>
      => <exp> + <exp> * <exp>
      => x + <exp> * <exp>
      => x + y * <exp>
      => x + y * z
```

which would give you a parse tree equivalent to $(x + y) * z$, which gives you a completely different value.

For almost any language, it is possible to completely remove the ambiguity by introducing new or extra non-terminals and rules. For example, if you were to add a new rule that forces the $+$ operation to appear higher in parse trees than $*$. E.g.

```
<exp> -> <exp> + <term> | <term>
<term> -> <term> * <factor> | <factor>
<factor> -> x | y | z
```

where `term` and `factor` are new non-terminals which have been added to remove the ambiguity.

The Limits of Context-Free Grammars

Some programming languages cannot be fully described using only CFGs. For example, if a variable must be defined before it is referenced, the context is required to determine whether the reference or declaration comes first. These are known as Context-sensitive properties, and must be resolved by the semantic analyser rather than the syntax analyser.

Syntax Analysis

Given some input source code, the goal of syntax analysis is to: find all syntax errors and produce a descriptive error for the user; and produce the parse tree for the program to be used in code generation. This process is completed by a syntax analyser, sometimes known as the parser. There are several algorithms which can be used for parsing, which fall into two categories - top-down and bottom-up parsers.

Top-Down Parsers

Starting at the root (the start symbol of the grammar), each node of the parse tree is visited before its branches. The branches are visited from left-to-right, giving a left-most derivation. When manually performing the derivation, you start by replacing the start symbol with the right-hand-side of its production. Then you replace the left-most non-terminal symbol with the right-hand-side of (one of) its production(s). You repeat this process until the string consists only of terminal symbols.

With the grammar

```
S -> AB
A -> aA | Epsilon
B -> b | bB
```

and the string aaab

```
S
AB
aAB
aaAB
aaaAB
aaa{Epsilon}B
aaaB
aaab
```

More on Top-Down Parsers

Different top-down parsers may use different information or rules to determine which production should be selected to replace a non-terminal symbol. Most compare the next input token with the first symbol of each production, these parsers are known as predictive parsers. These work using only the next input symbol and the current non-terminal.

Recursive-Descent Parsers (RDP)

A recursive descent parser is an implementation of a parser based upon the BNF of a grammar. An RDP consists of a collection of functions (or sub-programs), many of which are recursive. Each non-terminal symbol corresponds to a single function, which handles parsing that particular non-terminal symbol in the grammar. For example, if you wanted to implement the following grammar

```
<exp> -> <exp> + <term> | <exp> - <term> | <term>
<term> -> <term> * <factor> | <term> / <factor> | <factor>
<factor> -> integer | (<exp>)
```

with an RDP, you would need to implement 3 functions - `exp()`, `term()` and `factor()`. Assuming that there is another function, `lex()` which updates the variable `nextToken` to be the next token in the sentence, each function will need to

- Check if the symbol is terminal, in which case make a call to `lex()`
- Check if the symbol is non-terminal within the current production, in which case make a call to the corresponding function
- If it is neither, then there is a syntax error and it should be raised with a helpful message for the user

Rules With Multiple Productions

When parsing a rule with more than one production, it is necessary to select which of the productions should be parsed. This can be done in several ways, but in the case of a predictive parser, the production should be selected based upon the next input token. The next input token is compared with the first token of each production until either a match is found, or all options are expended. If the token does not match any of the productions, there is a syntax error and an error should be raised with a helpful message for the user.

Rules with Left Recursion

If a grammar has left recursion, it cannot be directly used by a recursive-decent parser. This is because it leads to an indefinite or non-terminating recursion loop. A left-recursive grammar cannot be transformed into one which is not left- recursive. Instead, the grammar must be modified to remove any direct left recursion. For each non-terminal, A , group the A rules as $A \rightarrow A\alpha_1 \mid A\alpha_2 \mid \dots \mid B_1 \mid B_2 \mid \dots \mid B_n$ where $A\alpha_m$ represents any rules with left-recursion, and B_n represents any rules without. To get rid of the direct recursion, you have to add a new non-terminal, such as A' and replace the original rules with $A \rightarrow B_1A' \mid B_2A' \mid \dots \mid B_nA'$ and $A' \rightarrow \alpha_1A' \mid \alpha_2A' \mid \dots \mid \alpha_mA' \mid \epsilon$

Lecture - LL(k) Parsers

14:00

23/02/24

Jiacheng Tan

An LL(k) parser is a top-down, predictive parser. It's name means that it parses from (L)eft-to-right, (L)eft-most derivation, with (k) tokens of look-ahead. They are also known as a table-driven predictive parser, since they use a stack and a parsing table.

An LL(1) parser parses the input left-to-right, and always using a left-most derivation. In this case, it uses one token of lookahead to predict which production should be used. It also uses a stack to store the symbols of the right-hand-side of productions, in right-to-left order, as that way the left-most symbol is always at the top of the stack. A parsing table is also used to store the rules which the parser should use based upon the input token and which value is at the top of the stack.

Parse Tables

With the grammar

$E \rightarrow TE'$
 $E' \rightarrow +TE' \mid \text{Epsilon}$
 $T \rightarrow FT'$
 $T' \rightarrow *FT' \mid \text{Epsilon}$
 $F \rightarrow (E) \mid \text{int}$

the parse table might look as below

Top of Stack Input	int	+	*	()	\$
E	$E \rightarrow TE'$			$E \rightarrow TE'$		
E'		$E' \rightarrow +TE'$			$E' \rightarrow \epsilon$	$E' \rightarrow \epsilon$
T	$T \rightarrow FT'$			$T \rightarrow FT'$		
T'		$T' \rightarrow \epsilon$	$T' \rightarrow *FT'$		$T' \rightarrow \epsilon$	$T' \rightarrow \epsilon$
F	$F \rightarrow \text{int}$			$F \rightarrow (E)$		

With this parse table, it is quite easy to parse a sentence, as it is a matter of simply picking the rule from the table, according to the current non-terminal (on the top of the stack) and the current input symbol and pushing the right-hand side of the production back onto the stack. \$ is selected if the end of the input is reached. The parsing process begins with the start symbol (E) and it's right-hand side (TE') is pushed onto the stack, and so T is the top of the stack. If the next token is int, we would pick the rule $T \rightarrow FT'$, and so FT' is pushed onto the stack. As such, the top of the stack is now F.

This process is more generally written as

- If X and w are both the end symbol, \$, stop and accept the input
- if X is a terminal, if $X = w$, pop X off the stack and get the next token, otherwise halt and give a descriptive error to the user
- If X is a non-terminal, if there is a production at position $[X, w]$, push the right-hand side onto the stack, otherwise halt and give a descriptive error to the user

Parse Table Construction

It is easy to perform an LL(1) parse if the parse table is already available. To construct the table, you must compute the first and follow sets of the non-terminals from the grammar. These are sets of terminal symbols. If these sets are available, the construction of the table is a simple procedure which can be performed automatically.

First Sets

For the grammar

- $E \rightarrow TE'$
- $E' \rightarrow +TE' \mid \epsilon$
- $T \rightarrow FT'$
- $T' \rightarrow *FT' \mid \epsilon$
- $F \rightarrow (E) \mid \text{int}$

The first sets of its non-terminals are

- $\text{First}(E) = \text{First}(T) = \text{First}(F)$ (Rules 1&3) = $\{ (, \text{int}) \}$ (Rule 5)
- $\text{First}(T') = \{ *, \epsilon \}$ (Rule 4)
- $\text{First}(E') = \{ +, \epsilon \}$ (Rule 2)

The first set of a non-terminal symbol, A, is the set of terminals which start the sequences of symbols which can be derived from A. (Written as $\text{First}(A)$). To calculate $\text{First}(A)$ where A is in the form $A \rightarrow X_1, X_2, \dots, x_n$, you must follow the process below

- If X_1 is a terminal, add X_1 to $\text{First}(A)$, and that's it.
- Otherwise, add $\text{First}(X_1)$ to $\text{First}(A)$, as any symbol which starts X_1 also starts A
- If X_1 can go to ϵ , e.g. it is nullable, add $\text{First}(X_2)$ to $\text{First}(A)$. Repeat this for X_2 until you find the first non-nullable symbol.
- If all of these are nullable, add ϵ to the first set.

Follow Sets

Lecture - Bottom-Up Parsing

14:00

01/03/24

Jiacheng Tan

Bottom-up parsing works (shockingly enough) in the opposite direction as top-down parsing. A bottom-up parser starts with the string of terminals and works backwards to the start symbol, applying the productions in reverse as it goes.

With the grammar

- $S \rightarrow AB$
- $A \rightarrow aA \mid \varepsilon$
- $B \rightarrow b \mid bB$

A bottom-up parse of the string `aaab` would look like

- Starting with the right-most symbol, we can apply the production $B \rightarrow b \mid bB$ in reverse, to end up with the string `aaaB`
- Since neither `a` nor `aB` are the right-hand-side of a production, insert ε to give the string `aaa ε B`.
- Replace ε with A to get `aaaAB`
- Replace `aA` with A to get `aaAB`
- Replace `aA` with A to get `aAB`
- Replace `aA` with A to get `AB`
- Replace `AB` with S to get the start symbol, and therefore a valid sentence

vs Top-Down

Bottom-up parsers are typically more powerful than top-down parsers. There are excellent generator tools, such as `yacc` that can build a parser from an input specification, as `lex` does for scanners.

Shift-Reduce Parsing

A shift-reduce parser takes a stream of tokens as an input and creates the list of productions used to build a parse tree. It uses a stack to track the position in the parsing process and a parse table to determine the correct production to use. Shift-reduce parsing is typically the most common and most powerful method of bottom-up parsing.

One type of shift-reduce parser is an LR parser (Scans input from left-to-right, using a reversed right-most derivation)

The Shift-Reduce Process

When parsing a string of tokens, v , the input is initialised to v and the stack is empty. At each step, the parser can take one of four actions at each step - shift, reduce, accept or error. The first step of the process is always to shift the first token to the top of the stack.

For this example, the grammar will be as follows

- $S \rightarrow E$
- $E \rightarrow T \mid E + T$
- $T \rightarrow \text{id} \mid (E)$

Shift

The token at the start of the input string is *shifted* onto the top of the stack.

Reduce

Suppose that the contents of the stack are qw where w is a string of terminal and non-terminal symbols, and q may be an empty string. If there is a production such that $A \rightarrow w$, the stack can be *reduced* to qA . This means that the production for A is applied backwards, such that we replace the right-hand-side (w) with the left-hand-side non-terminal (A). In this case, w is known as a handle.

Accept

If the entire contents of the stack has been reduced to the start symbol (S), and there are no remaining input tokens, the input is a valid sentence in the parsers grammar. This means that the parser has ended in an acceptance state.

Error

If it is not possible to Shift, Reduce or Accept, then the parser must Error. In this case, the sequence on the stack cannot be reduced to the left-hand-side of any production, and any further shifting would be pointless as the input cannot form a valid sentence in the parsers grammar.

Lecture - Scopes and Memory Allocation

14:00

11/03/24

Jiacheng Tan

Variables

A variable is a place-holder for a run-time value. Each variable has multiple run-time attributes. These attributes include:

- Name - The name which is used in code to refer to the variable
- Address - The memory address which stores the value of the variable
- Value - The contents of the memory which corresponds to the variable
- Type - The range of values the variable can store, and the operations which can be performed upon it
- Lifetime - The time for which the variable is bound to the specific memory location
- Scope - The area in code which the variable is accessible

Implicit vs Explicit Declaration

A variable is introduced into the scope using a declaration. This can be done implicitly or explicitly. An explicit declaration is a statement in the source code which defines the type and name of a new variable, e.g.

C - `int i;`
Pascal - `i : integer`

An implicit declaration is a mechanism by which variables are automatically assigned a type based upon conventions of the language, rather than declaring it manually. For example, in Fortran the type of a variable is defined by the first character of the variable name. If the first character is I, J, K, L, M, or N then it is an integer, otherwise it is real.

Another form of implicit declaration is type inference. For example, if you define a `late` variable in Dart, it infers the type of the variable from the first value which is assigned to it, e.g.

```
late final variable;  
  
variable = "This is a string";
```

In this case, the variable would be assigned the `String` type.

Binding

A binding is an association between an entity and attribute, such as between a variable and its type, or a symbol and the operation it corresponds to. Binding can take place at many different times, but is always referred to as the *binding time*. An example of this are the following C statements

```
1. int x;  
2. x = 1;  
3. x = x + 1;
```

In this case,

- The type of `x` is bound at compile time, as C is a statically typed language
- The range of values which `x` can take is bound when the compiler is designed, as this is when they pick the number of bits, and therefore maximum value that an integer can be
- The operation of the `+` operator is bound at compile time, as this is when the types of its operands are known
- The value of `x` is bound at run-time, since that is when the statement is executed

Binding can also take place at load time (when the variable is bound to a memory location) or link time (the variable in one module is bound to another module)

Static vs Dynamic Type Binding

A type binding can be either static or dynamic. It is static if it occurs before run-time, e.g. at compile time, and remains unchanged throughout the execution of a program. Declarations always have type information, and so binding is done at compile time. Languages with static type declaration are known as statically typed as, once set, the type cannot change. This gives the advantage of type errors being detected at compile time, and using less memory for each variable, but it is not very flexible and can lead to issues when user input is involved.

A dynamic type binding occurs when the type is bound during execution, or if it is able to change at run-time. This is the case in languages such as Python, JavaScript and PHP. These languages are known as dynamically typed, since the type of any given variable is unknown until run-time and can change at any point. This has the advantage of being more flexible (useful when user input is necessary) and allowing the developer to not need to know the type of a variable when the program is written, but has a much higher overhead due to dynamic type checking, and makes compile-time type error detection impossible.

Strongly and Weakly Typed Languages

A language is known as strongly typed if **all** type errors can be detected by the compiler. In this case, a language is also type safe, as it is impossible for the program to crash due to an invalid type. Some examples are Java, Haskell and Ada. Some languages may seem to be strongly typed languages, such as Fortran or C, but actually aren't. A strongly typed language can be either statically or dynamically typed.

A weakly typed language is any language which is not strongly typed, such as JavaScript. Once again, a weakly typed language can be either statically or dynamically typed.

Scopes

A block is a section of code, which defines the local environment for any given statement. Blocks are usually denoted by a start and end marker, such as in C, which uses `{` and `}`, but can also be denoted by indentation, if you are a masochist and/ or sadist (cough cough Python). A block can contain variables local to said block, and has its own reference environment (the names and identifiers which are accessible to statements in the block).

Most languages allow blocks to be nested within each other, but some may restrict the type of blocks which can nest. In C and Java, methods can be nested within classes and other blocks, but not within other methods. In Python and Pascal, it is possible to nest a method within a method.

Since blocks contain variable definitions, the local reference environment for each statement must be determined, which also allows you to determine the **scope** of identifiers. The scope determines where each identifier can be used, and if an error should be thrown if there are multiple identifiers with the same

name. In most languages, the scope of an identifier is the block in which it is declared and, by extension, any nested blocks. There is also a scope known as the global scope, which allows identifiers within it to be accessed anywhere within the program. These are known as global identifiers, and are typically only used when they are absolutely necessary, to reduce the chance of overlapping identifiers.

Duplicated Identifiers

Most languages have a rule or set thereof to determine which declaration of an identifier takes precedence. In languages such as Pascal, the local variable *hides* any variables with a larger scope. In this case, it is said that there is a hole in the scope of the hidden variable, as its scope is everywhere aside from any blocks in which it is hidden.

Some languages just flat out refuse to allow any duplicated identifiers, as this reduces the confusion since it will cause an error at compile time, rather than a mysterious run-time error.

Static and Dynamic Scoping

In the previous example, the scope of variables is determined by their visibility, and therefore the scope depends upon the lexical structure of the program, and the compiler can therefore determine the scope of all variables. This is known as static or lexical scoping. On the other hand, with dynamic scoping, the reference environment depends upon the sequence of sub-programs, rather than the layout of the nested blocks. This means that the scope of any given identifier can only be determined at run-time.

Dynamic scoping is typically less used than static scoping, as it is less reliable due to the unknown order of execution and results in poor code readability. It is however, easier to implement using stacks and resolving a variable does not require tracing the structure of the entire program.

Lifetimes

The lifetime of a variable is the period of time for which the variable exists, and has a value that is only known at the time of execution. The lifetime of a local variable is the execution of the method. Each recursive execution of a method has its own copy of any local variables. The lifetime of a global variable is the execution of the entire program.

This is related to the way that memory is allocated and deallocated. There are several basic mechanisms which a programming language may use to allocate memory

- Static allocation is when a fixed memory address is retained throughout the variables lifetime
- Stack-based allocation is done on a last-in first-out basis, and is used for function calls, as the lifetime of the variable is that of the function
- Heap-based allocation is used for variables that are dynamically allocated. They often have no identifier, and are therefore known as anonymous variables, and can only be referenced by pointers