Programming Language Syntax

In this set of notes you will learn about:

- Tokens and regular expressions
- Syntax and context-free grammars
- Grammar derivations
- Parse trees
- Top-down and bottom-up parsing
- Recursive descent parsing
- Putting theory into practice:
    - Writing a Recursive Descent Parser for Simple Expressions

Note: These slides cover Chapter 2 of the textbook upto and including Section 2.2.3

Tokens and Regular Expressions

- Tokens are the basic building blocks of a programming language: keywords, identifiers, numbers, punctuation
- The first compiler phase (scanning) splits up the character stream into tokens
- *Free-format* language: program is a sequence of tokens and position of tokens on page is unimportant
- *Fixed-format* language: indentation and/or position of tokens on page is significant (early Basic, Fortran, Haskell)
- *Case-sensitive* language: upper- and lowercase are distinct (C, C++, Java)
- *Case-insensitive* language: upper- and lowercase are identical (Ada, Fortran, Pascal)
- Tokens are described by *regular expressions*

Describing Tokens by Regular Expressions

A regular expression is one of

- a character
- *empty* (denoted e)
- *concatenation*: sequence of regular expressions
- *alternation*: regular expressions separated by a bar |
- *repetition*: a regular expression followed by a star `*`

Example regular expressions

```
digit -> 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

unsigned_integer -> digit digit*

signed_integer -> (+ | - | e) unsigned_integer
```

Note: Java provides a class `StreamTokenizer` with which you can write scanners in Java to convert character streams into token streams

Context-Free Grammars: BNF

- Regular expressions cannot describe nested constructs, but *context-free grammars* can
- Backus-Naur Form (BNF) grammar *productions* are of the form
  ```
  <nonterminal> -> sequence of (non)terminals
  ```
- A `terminal` of a grammar is a token e.g. specific programming language keyword, e.g. **`return`**
- A <*nonterminal*> denotes a syntactic category
- The symbol `|` denotes *alternative* forms in a production, e.g. different program statements are catagorized
  For example:
  ```
  <stmt> -> return | break | <id> := <expression>
  ```
- The special symbol e denotes *empty*, e.g. used in optional constructs
  For example:
  ```
  <optional_static> -> static | e
  ```

Extended BNF

- *Extended* BNF includes an explicit form for *optional* constructs with [and]
  For example:
```
<stmt> -> for <id> := <expr> to <expr> [ step <expr> ]
do <stmt>
```
- *Extended* BNF includes a *repetition* construct *
  For example:
```
<decl> -> int <id> (, <id>)*
```

Example Grammar for Expressions

Context-free grammar for a simple expression syntax with identifiers, integers, unary minus, parenthesis, and +, -, *, /

Example expression grammar productions

```
<expression> -> identifier
              | unsigned_integer
              | - <expression>
              | ( <expression> )
              | <expression> <operator> <expression>

<operator> -> + | - | * | /
```

Note that `identifier` and `signed_integer` are tokens defined by a regular expression, not by the grammar. They are provided as tokens by the scanner in a compiler.

Derivations

- From a grammar we can derive *strings* (= sequences of tokens/terminals)
- In each *derivation step* a nonterminal is replaced by a right-hand side (part after `->`) of a production for that nonterminal
- Each representation after each step is called a *sentential form*
- When the nonterminal on the far right (left) in a sentential form is replaced in each derivation step the derivation is called *right-most (left-most)*
- The final form consists of terminals only and is called the *yield* of the derivation
- A context-free grammar is a *generator* of a *context-free language*: the language defined by the grammar is the set of all strings that can be derived

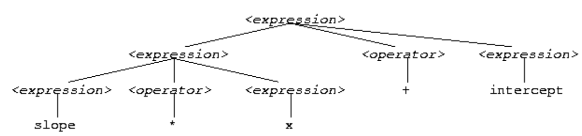
Example derivation (right-most)

```
<expression>
  => <expression> <operator> <expression>
  => <expression> <operator> identifier
  => <expression> + identifier
  => <expression> <operator> <expression> + identifier
  => <expression> <operator> identifier + identifier
  => <expression> * identifier + identifier
  => identifier * identifier + identifier
```

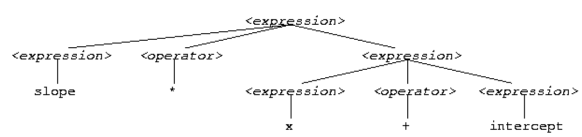
Parsing and Parse Trees

- A *parse tree* depicts a derivation as a tree
- The *nodes* are the nonterminals
- The *children* of a node are the symbols (terminals and nonterminals) on a right-hand side of a production
- The *leaves* are the terminals

- For example, given string `slope*x+intercept` a *parser* constructs a parse tree:



- An alternative parse tree for this string is:



Note: An interactive parser demo demonstrates the parsing of a Pascal example program into a parse tree (see also textbook pp. 20-21)

Ambiguous Grammars

- When more than one distinct derivation of a string exists resulting in distinct parse trees, the grammar is *ambiguous* (as is the case above)
- A programming language construct should have only one parse tree to avoid misinterpretation by a compiler
- For expression grammars, *associativity* and *precedence* of operators need to be included somehow

An unambigous grammar for simple expressions

```
<expression> -> <term>
              | <expression> <add_op> <term>

<term> -> <factor>
        | <term> <mult_op> <factor>

<factor> -> identifier | unsigned_integer
          | - <factor> | ( <expression> )

<add_op> -> + | -

<mult_op> -> * | /
```

Exercise: construct *all* possible left-most derivations of the string `a-b+1` from the ambiguous simple expression grammar and from the unambiguous grammar. Also construct the parse trees. Answer:

Ambiguous If-Then-Else

- A classical example of an ambiguous grammar are the grammar productions for `if-then-else` in C, C++, and Pascal
- It is possible to write an unambiguous grammar, but the fact that it is not easy indicates a problem in the programming language design

An ambigous grammar for `if-then-else`

```
<stmt> -> if <expr> then <stmt>
        | if <expr> then <stmt> else <stmt>
```

- Ada uses `if then [ else ] end if` as a solution

Exercise: given the above grammar, find two derivations for the program fragment

```
if C1 then if C2 then S1 else S2
```

(where `C1` and `C2` are some expressions, `S1` and `S2` are some statements)
Answer:

Top-Down and Bottom-Up Parsing

- A parser is a *recognizer* of a context-free language
  - a string can be parsed into a parse tree only if the string is in the language
- For any arbitrary context-free grammar parsing can be done in $O(n^3)$ time, where n is the size of the input
- There are large classes of grammars for which we can construct parsers that run in linear time:
  - Top-down parsers for LL (Left-to-right scanning of input, Left-most derivation) grammars
  - Bottom-up parsers for LR (Left-to-right scanning of input, Right-most derivation) grammars

LL Grammars and Top-Down Parsing

- Top-down parser is a parser for LL class of grammars (which is a subset of the larger LR class of grammars)
- Also called *predictive* parser
- Top-down parser constructs parse tree from the root down
- Easy to implement a predictive parser for an LL grammar by hand
- LL grammars cannot exhibit *left-recursive productions* (but LR can)

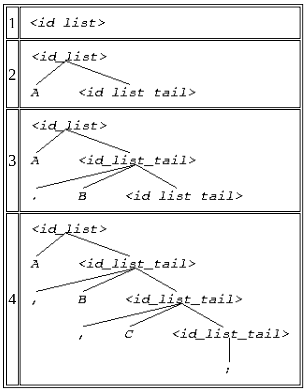
Example LL grammar for list of identifiers

```
<id_list> -> identifier <id_list_tail>

<id_list_tail> -> , identifier <id_list_tail>
                | ;
```

Top-Down Parsing Example

Top-down parsing of `A,B,C;`

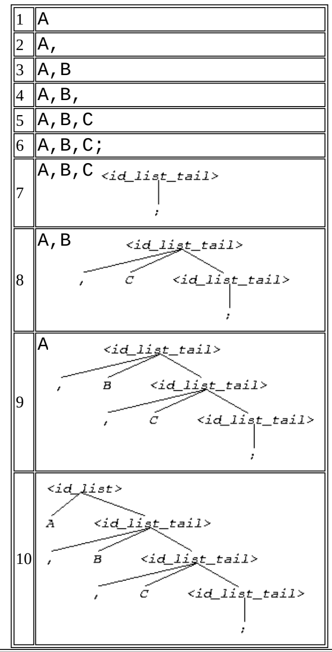


- Top-down parsing is called *predictive* parsing because it predicts what it is going to see:
  - As root `<id_list>` is predicted
  - After reading `A` the parser predicts that `<id_list_tail>` must follow
  - After reading , and `B` the parser predicts that `<id_list_tail>` must follow
  - After reading , and `C` the parser predicts that `<id_list_tail>` must follow
  - After reading `;` the parser stops

LR Grammars and Bottom-Up Parsing

- Bottom-up parser is a parser for LR class of grammars
- Difficult to implement by hand
- Tools (e.g. bison) exist that generate bottom-up parsers for LR grammars
- Parsing is based on shifting tokens on a stack until it recognizes a right-hand side of a production which it then reduces to a left-hand side (nonterminal) with a partial parse tree

Bottom-up parsing of `A,B,C;`



Recursive Descent Parsing

- Predictive parsing method for LL(1) grammar (LL with one token lookahead)
- Based on recursive subroutines
  - Each nonterminal has a subroutine that implements the production(s) for that nonterminal so that calling the subroutine will parse a part of a string described by the nonterminal
  - When more than one alternative production exists for a nonterminal, lookahead token from scanner should decide which production is to be applied

LL(1) for a simple calculator language

```
<expr> -> <term> <term_tail>

<term_tail> -> <add_op> <term> <term_tail> | e

<term> -> <factor> <factor_tail>

<factor_tail> -> <mult_op> <factor> <factor_tail> | e

<factor> -> ( <expr> ) | - <factor>
          | identifier | unsigned_integer

<add_op> -> + | -

<mult_op> -> * | /
```

A Recursive Descent Parser

Pseudo-code outline of recursive descent parser for the calculator grammar

```
procedure expr()
  term(); term_tail();
procedure term_tail()
  case (input_token())
  of '+'or '-': add_op(); term(); term_tail();
  otherwise: /* skip */
procedure term()
  factor(); factor_tail();
procedure factor_tail()
  case (input_token())
  of '*' or '/': mult_op(); factor(); factor_tail();
  otherwise: /* skip */
procedure factor()
  case (input_token())
  of '(': match('('); expr(); match(')');
  of '-': factor();
  of identifier: match(identifier);
  of number: match(number);
  otherwise: error;
procedure add_op()
  case (input_token())
  of '+': match('+');
  of '-': match('-');
  otherwise: error;
procedure mult_op()
  case (input_token())
  of '*': match('*');
  of '/': match('/');
  otherwise: error;
```

Exercise: Write a recursive descent parser in Java for this grammar. Answer:

Example Recursive Descent Parsing

- The *dynamic call graph* of a recursive descent parser corresponds exactly to the parse tree of input
- Call graph of input string `1+2*3`