Main topics of the week:
- Intro to Programming Language Concepts
- Programming Language Paradigms
- Compilation versus Interpretation
- Formal Definition of Grammar
- BNF Notation
- Languages and Grammars
- Parse Trees
- Ambiguity in Grammars

Programming Paradigms
In this course, we will look at four basic paradigms for programming languages. These are not the only ways of looking at programming languages, but are a convenient way of roughly categorizing languages by their characteristics. Some languages share characteristics from several paradigms. The four paradigms are: imperative, object oriented, functional, and logic.

The main characteristic of an imperative language is that it is closest to the architecture of the machine, and is execution oriented and allows assignment. An imperative language basically specifies a sequence of state changing actions. Variables are used to refer to the abstract machine’s memory locations, and the contents (state) changes as the sequence of actions unfolds. The key operation in an imperative language is assignment. Examples are Fortran, Algol, and C.

In a functional language, there are no named memory locations—everything is a function call, and values are passed to functions and returned by functions. In particular, there is no assignment. The key operation in a functional language is function application, i.e., calling a function. Recursion figures prominently in the use of a functional language. Examples are ML and Scheme.

Logic languages use a formal logical specification of a problem. These specifications will indicate how to recognize a solution, but not how to find it. The solution will be arrived at through a reasoning process. The key operation is unification. Prolog is a logic programming language.

In object oriented languages, the focus is on the data abstraction rather than the execution. These data objects communicate with each other and the key operation is this message passing. Object oriented languages may be imperative or functional. Examples are C++, Java.

In addition to considering the different programming paradigms, we also consider the differences between interpreted languages and compiled languages. The compiler statically analyzes program “source” and produces code that is then run on the computer. The compiled program can be executed many times. An interpreted language is dynamically interpreted as it is read and executed by the interpreter. This is for a single execution, and the interpretation of the program source must be done again for all subsequent executions. The latter approach is usually not as efficient, but can more accurately understand the intent of the programmer, as well as allow the program to change dynamically during execution.
Before we look at specific examples of languages, we will first spend some time considering the general structure of languages – that is, how the syntax of a language is formally specified by a grammar.

Syntax and Parsing

A program consists of a string of characters. The compiler and interpreter’s jobs are to determine which of these strings constitute a legal program and arrange for the execution. The process will begin with a lexical analysis. Basically, the lexical analysis will break the string of characters into meaningful substrings. These substrings are technically called the \textit{lexemes} of the language and categories of them are called the \textit{tokens} of the language. They can be things like variable names, keywords, operator symbols, etc. Lexemes cannot be broken into smaller pieces, so they are the atomic units of the language. The job of the lexical analyzer is to convert the program into a sequence of lexemes. This is generally done with pattern matching, and in fact the lexical syntax of the language is a regular grammar. The program that does the lexical analysis is usually called a scanner, and is actually an instance of a deterministic finite automaton. The scanner typically ignores and discards white space and comments in the program source, using white space only to the extent it is necessary to distinguish lexemes.

The next phase in the process is syntactical analysis of the stream of tokens. The job here is to determine if the program is syntactically correct, that is, is it a legal program. This stage is not concerned with any meaning of the program, rather just the form of the program – is it using the legal words of the language, and are they arranged correctly (i.e., is the grammar correct). The result of doing a syntactical analysis is to produce an abstract syntax tree (or parse tree).

Once the \textit{abstract syntax tree} is built, it can be \textit{semantically} analyzed and annotated with the semantic actions associated with the language constructs. This gives meaning to the program and provides the information needed to generate code (for immediate interpretive execution or later static execution).

We won’t focus on lexical analysis – that is a pretty straightforward task done by tools like Unix \texttt{lex}. It typically involves regular expressions to specify what character sequences constitute tokens in the language. We are more concerned with how to specify the syntax of a language. Tools are also available for this parsing, notably Unix \texttt{yacc}. This tool gets tokens from lex and according to a grammar we specify and code we provide, builds an abstract syntax tree (or whatever else we want to do). We won’t go over the code provided (that would be part of a compiler course), but we do want to understand how to specify a grammar. A parser like yacc uses recursion and is basically a push down automaton.

Grammars

We need to have some way of precisely describing a language so that we can tell if a given program is a legal program in the language. English descriptions could be used to define the language, but are easily subject to misinterpretation. A \textbf{context free grammar} (from now on, just grammar) is a formalism for specifying this structure of a language precisely. It specifies how the tokens can be combined to produce legal programs and generally reveals something about the structure of programs in the language. A grammar consists of
1) A set T of terminal symbols
2) A set N of non-terminal symbols (sometimes called variables)
3) A set P of production rules
4) A special start symbol S

Although this is a precise definition of a grammar, it is not to be construed as a programmer’s guide to the language. The grammar is the “legal” definition of the syntax of the language but is not likely to be the place you would look if you were trying to learn the language. However, if you were writing a compiler for the language, you would certainly be interested in seeing this specification of the grammar.

**Backus-Naur Form** (BNF) is a notation used to write down a grammar. The terminals are usually just written as themselves (or sometimes in quotes to emphasize they are literal). Non-terminals are often written between angle brackets and may have suggestive names like <expr> or <statement>. The production rules consist of a non-terminal on the left, the symbol ::= and the right hand side as a sequence of terminals and non-terminals. Single production rules for the same non-terminal may be combined into a single rule by joining the right hand sides of the rules into a single right hand side with the “or” operation denoted by ‘|’. Unless otherwise specified, the non-terminal on the left of the first rule is the start symbol. Another style is to use upper case letters for the non-terminals and lower case letters for the terminals.

A grammar gives the rules for producing all legal programs. The way the rules work is this: beginning with the start symbol, we replace it using any of the rules for the start symbol. In the resulting string, any non-terminals are replaced according to a rule for them. In this way, we keep eliminating non-terminals until we have a string consisting of just terminals. This result is called a **production** of the grammar, and is a legal program according to the grammar. The sequence of substitutions using the rules of the grammar is called a **derivation**.

Here are some examples of production rules that you might expect to find in a language parser:

```plaintext
<stmt> ::= <var> = <expr> ;
<var> ::= A | B | C
<expr> ::= <var> + <var> | <var> - <var> | <var>
```

This is just a simple production with start symbol <stmt> that would generate assignment statements consisting of an identifier name (A, B, or C), the assignment operator ‘=’, the variable name B, a plus sign, the variable C, and a terminating semicolon. From this little grammar, we could generate ‘A = B + C;’, that is, this statement would be in the language of the grammar. We can see that this statement is in the grammar by the derivation:

```
<stmt> → <var>=<expr>; → A=<expr> ; → A=<var>+<var>;
        → A=B+<var> ; → A=B+C;
```

The derivation can also be represented by a **parse tree**:
where we read the resulting generated string in the language along the bottom. Notice
that in a parse tree, the start variable is at the top, and its children are a production rule.
All leaves in the parse tree must be terminals and internal nodes are the non-terminals.

Grammars do not have to be unique. The above grammar could add the rules:
\[
<\text{sum}> ::= <\text{var}> + <\text{var}>
\]
\[
<\text{diff}> ::= <\text{var}> - <\text{var}>
\]
and change the rule:
\[
<\text{expr}> ::= <\text{sum}> | <\text{diff}> | <\text{var}>
\]
This clearly generates the same language, but the parse trees would be different since
there would be more internal nodes in the example given.

A good grammar captures the logical structure of the language, and like “good”
programs, uses meaningful names, and is easy to read and as unambiguous as possible.

Here’s a fragment of the top level of a programming language:

\[
\text{program}::= \text{declarations}_\text{and}_\text{process}_\text{list}
\]
\[
\text{declarations}_\text{and}_\text{process}_\text{list}::= \text{declarations}
| \text{process}
| \text{declarations}_\text{and}_\text{process}_\text{list} \\text{declarations}
| \text{declarations}_\text{and}_\text{process}_\text{list} \\text{process}
\]
\[
\text{process}::= \text{SESSION} \\text{ID} \\text{body}
| \text{SESSION} \\text{ID} \text{LPAREN} \text{arg}_\text{list} \text{RPAREN} \\text{body}
| \text{SUBSESSION} \text{dtype} \\text{ID} \text{LPAREN} \text{param}_\text{list} \text{RPAREN} \\text{body}
\]
\[
\text{statement}_\text{list}::= \text{statement}
| \text{declarations}
| \text{statement}_\text{list} \\text{statement}
| \text{statement}_\text{list} \\text{declarations}
\]
\[
\text{body}::= \text{LBRACE} \text{statement}_\text{list} \text{RBRACE}
\]
\[
\text{statement}::= \text{expr} \text{SEMI}
| \text{SEMI}
| \text{compound}_\text{statement}
| \text{PRINT} \text{expr} \text{SEMI}
| \text{IF} \text{LPAREN} \text{expr} \text{RPAREN} \text{statement}
| \text{IF} \text{LPAREN} \text{expr} \text{RPAREN} \text{statement} \text{ELSE} \text{statement}
| \text{SWITCH} \text{LPAREN} \text{expr} \text{RPAREN} \text{LBRACE} \text{case}_\text{list} \text{RBRACE}
| \text{FOR} \text{LPAREN} \text{expr} \text{SEMI} \text{expr} \text{SEMI} \text{expr} \text{RPAREN} \text{statement}
\]
| WHILE LPAREN expr RPAREN statement |
| CONTINUE SEMI |
| BREAK SEMI |
| EXIT SEMI |
| EXIT LPAREN RPAREN SEMI |
| EXIT expr SEMI |
| REGION ID cstatement |
| SESSION_RETURN expr SEMI |
| SESSION_RETURN SEMI |
| TRY cstatement catch_list FINALLY cstatement |
| TRY cstatement catch_list |
| THROW ID SEMI |
| THROW ID LPAREN RPAREN SEMI |
| THROW ID LPAREN expr RPAREN SEMI |

Grammar Ambiguity

Consider the following small grammar for assignment statements:

\[
\text{<assign>} ::= \text{<id>} = \text{<expr>}
\]

\[
\text{<id>} ::= \text{A} | \text{B} | \text{C}
\]

\[
\text{<expr>} ::= \text{<expr>} + \text{<expr>} | \text{<expr>} * \text{<expr>} | ( \text{<expr>} ) | \text{id}
\]

The sentence \(A = B + C * A\) has two different parse trees:

```
<assign>  
  <id>    <expr>  
   A      <expr>  
    <expr> <expr>  
     <id> <id>    
      B   C  *  A
```

```
<assign>  
  <id>    <expr>  
   A      <expr>  
    <expr> <expr>  
     <id> <id>    
      B   C  *  A
```

This happens since the grammar allows \text{<expr>} to grow on the left or the right. This ambiguity can be a problem for semantic analysis if the semantic analysis is based on the parse tree, which it often is. This particular example is a case where we want the grammar to reflect operator precedence. That is, multiplication should bind more tightly than addition to follow the usual rules in algebra. We can cause this to happen in the grammar by introducing more symbols:

\[
\text{<assign>} ::= \text{<id>} = \text{<expr>}
\]

\[
\text{<id>} ::= \text{A} | \text{B} | \text{C}
\]

\[
\text{<expr>} ::= \text{<expr>} + \text{<term>} | \text{<term>}
\]

\[
\text{<term>} ::= \text{<term>} * \text{<factor> } | \text{<factor>}
\]
<factor> ::= ( <expr> ) | <id>

Then we will have a unique parse tree for A = B + C * A, and the parse tree reflects the higher precedence of multiplication. Inserting parentheses alters this precedence as expected, because our grammar has parentheses enclosing just an <expr>, bringing us back to an expression subtree. This grammar also gives us left associativity of the operators since the parse trees expand to the left for + or *. Generally, when a production rule has its LHS also appearing at the beginning of the RHS, the rule is called left recursive, and this captures the idea of left associativity. If the LHS appears at the end of the RHS, then we have a right recursive rule, which implements right associativity.

Ambiguity can cause problems for statements as well, and the classic example is the dangling else. Suppose we have the grammar:

<if-stmt> ::= if <expr> <stmt>| if <expr> <stmt> else <stmt>
<stmt> ::= <if-stmt> | S1 | S2

For the sentence “if <expr> if <expr> S1 else S2” we would get two distinct trees:

and this clearly poses a problem for semantic analysis: who does the else belong to? To fix this, we would need additional non-terminals to distinguish between else-less if’s and if-else’s or change the language to include delimiters. For example, some languages use delimiters as in the following grammar:

<if-stmt> ::= if <expr> then <stmt> fi | if <expr> then <stmt> else <stmt> fi
<stmt> ::= <if-stmt> | S1 | S2

Alternatively, we could use more non-terminals to “catch” the dangling else:

<matched> ::= if <expr> <matched> else <matched>
<unmatched> ::= if <expr> <stmt> | if <expr> <matched> else <unmatched>
<stmt> ::= <matched>| <unmatched> | S1 | S2

Here when there is an else, the if statement must be a matched type (i.e., have its own else).
It is not always possible to remove an ambiguity by restructuring the grammar. A language for which there is no unambiguous grammar is said to be inherently ambiguous. However, there is no algorithm that can tell if a given context free grammar is ambiguous – this is an undecidable problem.

Top-down and bottom-up Parsing

A grammar is a language generator, but a programming language compiler or interpreter needs to have a parser – a parser recognizes the language. It can be shown that for any CFG, we can create a parser that runs in $O(n^3)$ time (where $n$ is the length of the input program), but this amount of time is much too slow for large programs. Fortunately, there are large classes of grammars for which it is possible to build linear time parsers.

The most important of these classes are called LL (left-to-right scanning, left-most derivation) and LR (left-to-right scanning, right-most derivation).

LL parsers are top-down (or predictive) parsers. They build the parse tree from the root down by predicting at each step which production will be used to expand the current node after looking at the next token of input. LR parsers are bottom-up parsers, and build the parse tree from the leaves up, recognizing when a set of leaves can be combined as the children of a single parent. Let’s look at these parsers for a simple example:

```plaintext
<csv> ::= val <csv_tail>
<csv_tail> ::= , val <csv_tail> | ;
```

This grammar describes a list of comma separated values terminated by a semi-colon. Here val is a terminal token that could be, say A, B, or C. Let’s examine how the different parsers would build the parse tree for the string: A,B,C;

The LL parser starts with the root <csv>, predicting it will be replaced by val <csv_tail> (the only rule), and looks to the input for a val token, which it finds (the A). It then predicts (by looking at the input and seeing a comma) that the <csv_tail> will be replaced by , val <csv_tail>. It then looks for a val token, and finds B. Again, it predicts, by peeking at the comma, that csv_tail will be replaced by the same rule again, and proceeds in this manner until all input is exhausted, and the tree is built.

The LR parser gets the first token, and sees that it is a val (A), so forms a leaf. The next token is a comma, so is another leaf. It continues in this way until it sees a complete right hand side. This happens when it sees the semi-colon, at which point it can form a <csv_tail> node, into which it reduces the last leaf. It continues working back through the leaves in this way, reducing and building the parse tree from the bottom up.

Although this example grammar could be parsed top-down or bottom-up, we can see that in the bottom-up case all the input has to be read before the tree can be constructed. In a very large program, this would require too much memory, so this example grammar is not very conducive to bottom-up parsing. By shifting the focus to the front of the list, we can get around this problem, e.g.,

```plaintext
<csv> ::= <csv_prefix> ;
```
\[<\text{csv\_prefix}> ::= <\text{csv\_prefix}> , \text{val} | \text{val}\]

However, this grammar can no longer be parsed top-down since we can’t tell the difference between a \(<\text{csv\_prefix}>\) and a val when we peek ahead, so we don’t know which rule to use. The rule for \(<\text{csv\_prefix}>\) is called left recursive since the symbol of the rule also appears as the left most symbol in the rule itself. This property is exactly what makes the grammar desirable for bottom up parsers since it allows for incremental reduction.

Yacc is an LALR (Look Ahead LR) parser generator. It allows disambiguating rules to resolve ambiguities. Thus, you can specify a BNF like grammar to yacc with ambiguities, but use its rules to specify left or right associativity for particular tokens, thus avoiding the need to express that directly in the grammar. A bottom-up parser works by maintaining a stack of the tokens that have been seen. When these tokens constitute a right hand side of a rule, it can reduce them to the left hand side of the rule. When the parsing is finished, the stack will have one object on it – the root of the tree.

Although parsers for simple languages can be hand crafted, most implementations will use a parser generator that is table driven. Issues of error recovery in parsers can become complex. However, in general, the area of parsers is well known and techniques and tools exist to implement parsers.