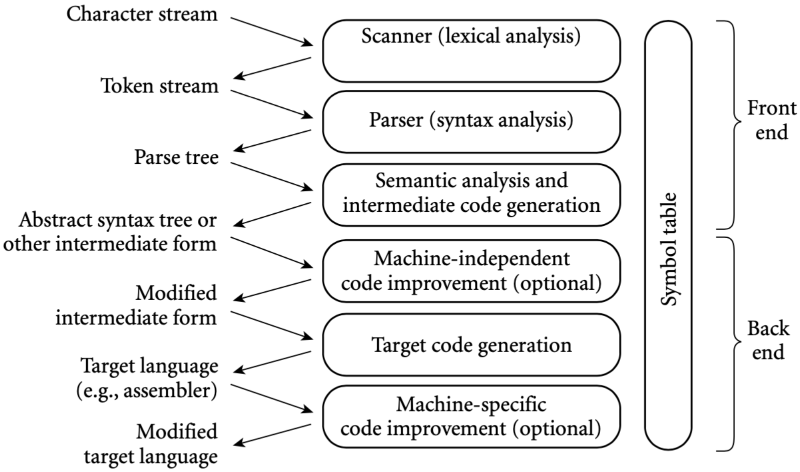
Programming Languages

Janyl Jumadinova

February 6-10, 2023

Most Important Steps in Compilation



Lexical Analysis

Lexical analysis produces a "token stream" in which the progam is reduced to a sequence of token types, each with its identifying number and the actual string (in the program) corresponding to it.

Lexical Analysis

For each token type, give a description:

- either a literal string
  - "$\leq$" or "while" to describe an operator or reserved word,

Lexical Analysis

For each token type, give a description:

- either a literal string
  – "$\leq$" or "while" to describe an operator or reserved word,
- or a $<$ *rule* $>$
  – a rule $<$ *unsigned int* $>$ example: "a sequence of one or more digits";
  – a rule $<$ *identifier* $>$ example: "a letter followed by a sequence of zero or more letters or digits."

Typical Tokens in Programming Languages

- *Operators and Punctuation*
  - `+ - * / ( )   [ ] ; :  ::  < <= == = != !  ...!`
- *Keywords*
  - `if while for goto return switch void ...`
- *Identifiers* (variables)
- *Integer constants*
  - Other constants (string, floating point, boolean, ...), etc.

Lexical Complications

- Most modern languages are free-form
  - Layout doesn't matter
  - White space separates tokens
- Alternatives
  - Haskell, Python - indentation and layout can imply grouping

Syntactic Analysis

- The syntax of a language is described by a **grammar** that specifies the legal combinations of tokens.

Syntactic Analysis

- The syntax of a language is described by a **grammar** that specifies the legal combinations of tokens.
- Grammars are often specified in BNF notation ("Backus Naur Form"):

Syntactic Analysis

- The syntax of a language is described by a **grammar** that specifies the legal combinations of tokens.
- Grammars are often specified in BNF notation ("Backus Naur Form"):

```
<item1> ::= valid replacements for <item1>
<item2> ::= valid replacements for <item2>
```

Alternative Notations

- There are several syntax notations for productions in common use; all mean the same thing. E.g.:
`ifStmt ::= if ( expr ) statement`
`ifStmt` $\rightarrow$ `if ( expr ) statement`
`<ifStmt> ::= if ( <expr> ) <statement>`

Example: Grammar for Pigese (or Pigish?)

- A formal grammar for a "pig language" could be:

```
PigTalk ::= oink PigTalk   (Rule 1)
          | oink!          (Rule 2)
```

Example: Grammar for Pigese (or Pigish?)

- A formal grammar for a "pig language" could be:
  `PigTalk ::= oink PigTalk` (Rule 1)
  `| oink!` (Rule 2)
- PigTalk can then generate, for example:
  1. `PigTalk ::= oink!` (Rule 2)

Example: Grammar for Pigese (or Pigish?)

- A formal grammar for a "pig language" could be:

```
PigTalk ::= oink PigTalk (Rule 1)
          | oink!   (Rule 2)
```

- PigTalk can then generate, for example:
  1. `PigTalk ::= oink!` (Rule 2)
  2. `PigTalk ::= oink PigTalk` (Rule 1)

     `::= oink oink!`

Example: Grammar for Pigese (or Pigish?)

- A formal grammar for a "pig language" could be:

```
PigTalk ::= oink PigTalk (Rule 1)
          | oink!        (Rule 2)
```

- PigTalk can then generate, for example:

1. `PigTalk ::= oink!` (Rule 2)
2. `PigTalk ::= oink PigTalk` (Rule 1)
   `::= oink oink!`
3. `PigTalk ::= oink PigTalk` (Rule 1)
   `::= oink oink PigTalk` (Rule 1)
   `::= oink oink oink!` (Rule 2)

Grammars (Context-free Gramars)

- Collection of VARIABLES (things that can be replaced by other things), also called NON-TERMINALS.

Grammars (Context-free Gramars)

- Collection of VARIABLES (things that can be replaced by other things), also called NON-TERMINALS.
- Collection of TERMINALS ("constants", strings that can't be replaced)

Grammars (Context-free Gramars)

- Collection of VARIABLES (things that can be replaced by other things), also called NON-TERMINALS.
- Collection of TERMINALS ("constants", strings that can't be replaced)
- One special variable called the START SYMBOL.

Grammars (Context-free Gramars)

- Collection of VARIABLES (things that can be replaced by other things), also called NON-TERMINALS.
- Collection of TERMINALS ("constants", strings that can't be replaced)
- One special variable called the START SYMBOL.
- Collection of RULES, also called PRODUCTIONS.

Grammars (Context-free Gramars)

- Collection of VARIABLES (things that can be replaced by other things), also called NON-TERMINALS.
- Collection of TERMINALS ("constants", strings that can't be replaced)
- One special variable called the START SYMBOL.
- Collection of RULES, also called PRODUCTIONS.

`variable` $\rightarrow$ `rule1 | rule2 | rule3 | ...`

You can also write each rule on a separate line

Grammars (Context-free Grammars): EXAMPLE

Grammar

A, B, and C are non-terminals.
0, 1, and 2 are terminals.
The start symbol is A.
The rules are:

- $A \rightarrow 0A|1C|2B|0$
- $B \rightarrow 0B|1A|2C|1$
- $C \rightarrow 0C|1B|2A|2$

Grammars (Context-free Grammars): EXAMPLE

Grammar

A, B, and C are non-terminals.
0, 1, and 2 are terminals.
The start symbol is A.
The rules are:

- $A \rightarrow 0A|1C|2B|0$
- $B \rightarrow 0B|1A|2C|1$
- $C \rightarrow 0C|1B|2A|2$

Can 2011020 be parsed?

Grammars (Context-free Gramars): ACTIVITY

Grammar

A, B, and C are non-terminals.

0, 1, and 2 are terminals.

The start symbol is A, the rules are:

- $A \rightarrow 0A|1C|2B|0$
- $B \rightarrow 0B|1A|2C|1$
- $C \rightarrow 0C|1B|2A|2$

https://itempool.com/jjumadinova/live

Grammars (Context-free Gramars): ACTIVITY

Grammar

A, B, and C are non-terminals.
0, 1, and 2 are terminals.
The start symbol is A, the rules are:

- $A \rightarrow 0A|1C|2B|0$
- $B \rightarrow 0B|1A|2C|1$
- $C \rightarrow 0C|1B|2A|2$

https://itempool.com/jjumadinova/live

Can 1112202 be parsed?
Can 00102 be parsed?
Can 2121 be parsed?

Ambiguity

A context-free grammar is said to be ambiguous if there is more than one derivation for a particular string.

Ambiguity

A context-free grammar is said to be ambiguous if there is more than one derivation for a particular string.

Consider:

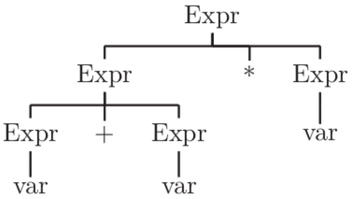
1. $S \rightarrow AS \mid \epsilon$
2. $A \rightarrow A1 \mid 0A1 \mid 01$

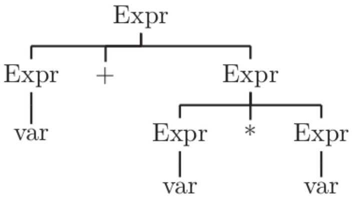
Ambiguity

Consider:

1. Expr $\rightarrow$ Expr + Expr
2. Expr $\rightarrow$ Expr * Expr
3. Expr $\rightarrow$ (Expr)
4. Expr $\rightarrow$ var
5. Expr $\rightarrow$ const

There are two different derivation trees for the string var+var*var





Ambiguity

- We need unambiguous grammars for parsing
  - The derivation determines the shape of the parse tree/ abstract syntax tree, which in turn determines meaning.

Ambiguity

- We need unambiguous grammars for parsing
  - The derivation determines the shape of the parse tree/ abstract syntax tree, which in turn determines meaning.
- If a grammar can be made unambiguous at all, it is usually made unambiguous through **layering**.

Ambiguity

- We need unambiguous grammars for parsing
  - The derivation determines the shape of the parse tree/ abstract syntax tree, which in turn determines meaning.
- If a grammar can be made unambiguous at all, it is usually made unambiguous through **layering**.
  – Have exactly one way to build each piece of the string.
  – Have exactly one way of combining those pieces back together.

Resolving Ambiguity

- *With grammar*: If you can re-design the language, can avoid the problem entirely, e.g., create an `end` to match closest `if`

Resolving Ambiguity

- *With grammar*: If you can re-design the language, can avoid the problem entirely, e.g., create an `end` to match closest `if`
- *With tools*: Most parser tools can cope with ambiguous grammars.
  - Typically one can specify operator precedence and associativity.
  - Allows simpler, ambiguous grammar with fewer non-terminals as basis for generated parser, without creating problems.

Activity 7: Grammar Ambiguity

Determine if the grammar is ambiguous

Regular Expressions used for Scanning

- Defined over some alphabet $\sum$.
  - For programming languages, alphabet is usually ASCII or Unicode.
- If `re` is a regular expression, `L(re)` is the language (set of strings) generated by `re`.

Fundamentals of Regular Expressions (REs)

- These are the basic building blocks that other REs are built from.

re	*L*(*re*)	Notes
a	{ a }	Singleton set, for each symbol a in the alphabet Σ
ε	{ ε }	Empty string
$\varnothing$	{ }	Empty language

Operations on REs

re	*L(re)*	Notes
rs	L(r)L(s)	Concatenation – r followed by s
r|s	L(r) ∪ L(s)	Combination (union) – r or s
r*	L(r)*	0 or more occurrences of r (Kleene closure)

Operations on REs

re	*L(re)*	Notes
rs	L(r)L(s)	Concatenation – r followed by s
r|s	L(r) $\cup$ L(s)	Combination (union) – r or s
r*	L(r)*	0 or more occurrences of r (Kleene closure)

- Precedence: (R), R*, R_1R_2, $R_1|R_2$ (lowest).
- Parenthesis can be used to group REs as needed.

Examples

re	Meaning
+	single + character
!	single ! character
!=	2 character sequence "!="
xyzzy	5 character sequence "xyzzy"
(1|0)*	Zero or more binary digits
(1|0)(1|0)*	Binary constant (possible leading 0s)
0|1(1|0)*	Binary constant without extra leading 0s, i.e, 0 or starts with 1 (| has lowest precedence)

Abbreviations on REs

- There are common abbreviations used for convenience.

Abbr.	Meaning	Notes
r+	(rr*)	1 or more occurrences
r?	(r | ε)	0 or 1 occurrence
[a-z]	(a|b|...|z)	1 character in given range
[abxyz]	(a|b|x|y|z)	1 of the given characters

Example

- Possible syntax for numeric constants

```
digit ::= [0-9]
digits ::= digit +
number ::= digits ( .  digits )?
([eE] (+ | -)?  digits )?
```

- Notice that this allows (unnecessary) leading 0s, e.g., 00045.6. (0, or 0.14 would be necessary 0s).

Example

- **Possible syntax for numeric constants**

```
digit ::= [0-9]
nonzero_digit ::= [1-9]
digits ::= digit +
number ::= (0 | nonzero_digit digits?)
( .  digits )?
([eE] (+ | -)?  digits )?
```

RE Practice:

`https://regexone.com/`