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# Chapter 1

## Introduction

### 1.1 Interpreter and compiler

There are two approaches to implement a programming language: compilers and interpreters.

Interpreter is an online approach, i.e. the work done by the interpreter is part of running the program. The program we write and the data on which we wish to run the program are inputted into the interpreter, after which the output is produced by the interpreter.

Compiler is an offline approach, i.e. whatever the compiler does is the pre-processing of the program, and it does not take part in the actual execution of the program on the data. The program is translated into an executable by the compiler, and the data is passed to the executable, which then outputs the result.

### 1.2 History

In 1954, IBM developed the 704 machine. The customers found that the softwares cost more than the hardware, though the hardware already costs a lot. This inspired a lot of people to try to improve the productiveness of programming, among whom was John Backus. He developed “Speedcoding”, which from today’s the point of view is an interpreter. Speedcoding made it much faster to develop programs, but the programs developed with it run much slower and also occupies too much memory. Backus continued to develop the FORTRAN project, which is an abbr. for FORMula TRANslation. With FORTRAN I, he took a compiler approach: formulas written by programmers are translated into a form that could be understood by the machine. FORTRAN I is a successful project not only in the sense that it was soon adopted by most developers back in the 1950s, but also in the sense that its outline is still preserved by modern compilers. A compiler contains 5 phases:

**Lexical analysis** Syntactic.

**Parsing** Syntactic.

**Semantic analysis** Types, scopes, etc.

**Optimization**

**Code generation** Translation into another language.

## Chapter 2

# Lexical Analysis

An implementation of lexical analyzer must do two things:

1. Recognize substrings corresponding to tokens, i.e. the lexemes.
2. Identify the token class of each lexeme. A token is the  $\langle \text{token class}, \text{lexeme} \rangle$  pair.

The goal of lexical analysis is to partition the string. It is implemented by reading left-to-right, recognizing one token at a time. “Lookahead” might be required to decide where one token ends and the next token begins.

## 2.1 Tools: regular expression and finite automata

### 2.1.1 Lexical specification & regular expression

1. Write a regular expression for the lexemes of each token class.
  - Number =  $\text{digit}^+$
  - Keyword = ‘if’ + ‘else’ + ...
  - Identifier =  $\text{letter}(\text{letter} + \text{digit})^*$
  - Openpar = ‘(’
  - ...
2. Construct  $R$ , matching all lexemes of all token classes.
$$R = \text{Keyword} + \text{Identifier} + \text{Number} + \dots = R_1 + R_2 + \dots$$
3. Let input be  $x_1x_2 \dots x_n$ . For  $1 \leq i \leq n$ , check if  $x_1 \dots x_i \in L(R)$ .
4. If yes, then we know that  $x_1 \dots x_i \in L(R_j)$  for some  $j$ .
5. Remove  $x_1 \dots x_i$  from input and go to 3.

Problems & ambiguities:

1. How much input is used? What if we have

$$x_1 \dots x_i \in L(R)$$

$$x_1 \dots x_j \in L(R) (i \neq j)$$

at the same time?

The answer is to choose the **maximal match**: match as long as possible.

2. Which token should be used if more than one token is matched, i.e. what if  $x_1 \dots x_i$  simultaneously belongs to  $L(R_j)$  and  $L(R_k)$ ?

A priority rule is set up to prevent such ambiguity. Typically, the rule is to **choose the one listed first**. For example, if should not be recognized as identifier because it belongs to the language of keyword.

3. What if no rule matches, i.e. what if  $x_1 \dots x_i \notin L(R)$ ? This concerns the error handling of the compiler.

The solution is not to let this happen. We will define one more class, the error class, that matches all strings not in the lexical specification, and put it last in priority.

### 2.1.2 Finite automata

Regex is the specification language of lexical analysis, and finite automata is an implementation mechanism of regex.

A finite automaton consists of

- An input alphabet  $\Sigma$
- A set of states  $S$
- A start state  $n$
- A set of accepting states  $F \subseteq S$
- A set of transitions  $\text{state1} \xrightarrow{\text{input}} \text{state2}$

Transition  $s_1 \xrightarrow{a} s_2$  is read “in state  $s_1$  on input  $a$  go to state  $s_2$ ”. If the automaton is in accepting state at the end of the input, it will **accept** the string, meaning that the string is in the language of this machine. Otherwise it will **reject** the string. This is either because it terminates in state  $s \notin F$ , or because the machine gets stuck: there is no transition defined for the current state and input.

The language of a FA is equal to the set of its accepted strings.

It is possible that the machine changes its state without an input, when the transition is called an  $\varepsilon$ -move. Depending on whether  $\varepsilon$ -move is allowed, FA can be classified into two types. **Deterministic Finite Automata (DFA)**

make one transition per input and per state, which means for a certain state, an input can lead to at most one possible transition. No  $\varepsilon$ -move is allowed. **Nondeterministic Finite Automata** can have multiple transitions for one input at a given state, and can have  $\varepsilon$ -moves.

A DFA takes only one path through the state graph per input string, while an NFA can choose different paths. As long as some of the paths lead to accepting state, the NFA accept the input string.

DFAs and NFAs recognize the same set of languages, which is the regular languages. DFAs are faster to execute, while NFAs are in general much (exponentially) smaller.

## 2.2 Implementation

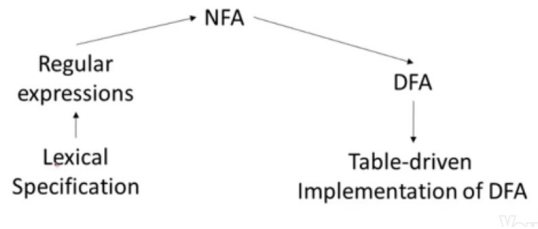


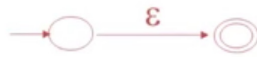
Figure 2.1: Pipeline of lexical analyser

We will follow the pipeline shown in Figure 2.1 to implement the lexical analyser step by step.

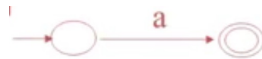
### 2.2.1 Regular expression into NFAs

Regex can be transformed into NFAs according to the following rules.

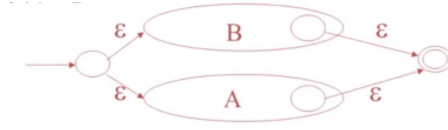
For the simplest  $\varepsilon$  regex:



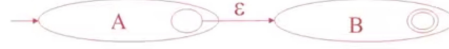
For regex with a single character  $a$ :



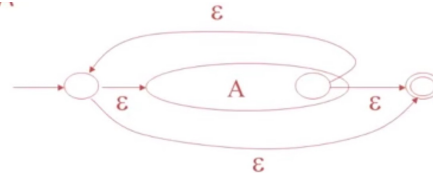
For union  $A + B$ :



For concatenation  $AB$ :



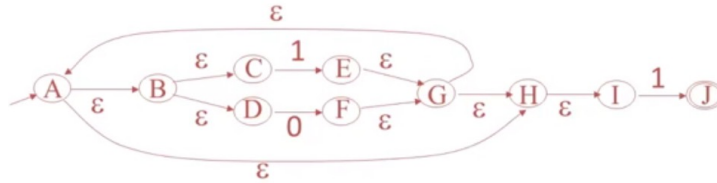
For iteration  $A^*$ :



By combining the rules above, we can transform any regex into NFAs.

### 2.2.2 NFA to DFA

We introduce the idea of the  $\epsilon$ -closure of state. The  $\epsilon$ -closure of a state  $s$  is the set of the states that can be reached from  $s$  following only  $\epsilon$  moves. In the NFA



**Figure 2.2: Idea of  $\epsilon$ -closure**

shown in Figure 2.2, the  $\epsilon$ -closure of state  $B$  is  $\{B, C, D\}$ , while the  $\epsilon$ -closure of state  $G$  is  $\{A, B, C, D, G, H, I\}$ . We also introduce the denotation  $a(X)$ , which is defined as

$$a(X) = \{y \in S \mid \exists x \in X \text{ s.t. } x \xrightarrow{a} y\}.$$

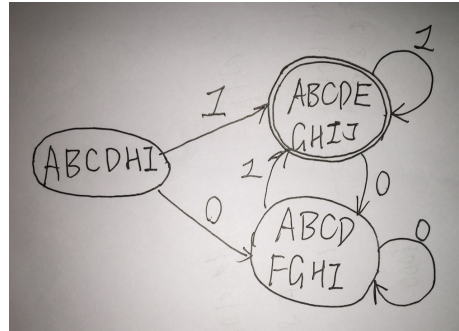
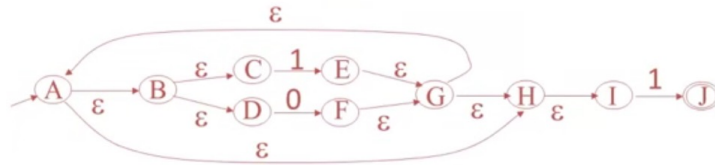
The NFA may be in many different states at any time. Suppose the NFA has  $N$  states, and it winds up in a subset of these states  $S$ . It is for sure that  $|S| \leq N$ . There exist totally  $2^N - 1$  subsets.  $2^N - 1$  is a big number, but still a finite one, which means that there exists a way to convert the NFA into a DFA. We set up a series of rules to convert an NFA to a DFA as shown in Table 2.1. The state of the DFA records the set of possible states that the NFA could



**Table 2.1: NFA to DFA**

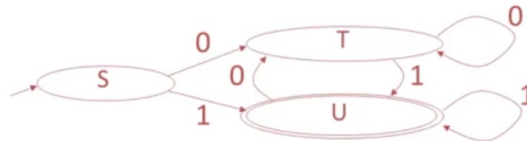
	NFA	DFA
states	$S$	$P(S) - \emptyset$ (subsets of $S$ except $\emptyset$ )
start	$s \in S$	$\varepsilon\text{-clos}(s)$
final	$F \subseteq S$	$\{X \in (P(S) - \emptyset) \mid X \cap F \neq \emptyset\}$
transition		$X \xrightarrow{a} Y$ if $Y = \varepsilon\text{-clos}(a(X))$

have gotten into with the same input. Below is an example demonstrating this conversion method.



### 2.2.3 Implementation of FA

A DFA can be implemented by a 2D **states-input symbol** table  $T$ . For every transition  $s_i \xrightarrow{a} s_k$ , there is  $T(i, a) = k$ . An example is shown below.



	0	1
S	T	U
T	T	U
U	T	U

Related C++ code to implement the state update:

```
1 int i = 0, state = 0;
2 while (i < len) {
3     state = T[state][input[i++]];
4 }
```

It is also possible to implement the NFA directly without converting it to a DFA, considering that the conversion could be expensive ( $N$  states NFA  $\rightarrow 2^N - 1$  states DFA). It is just a tradeoff between speed and space: DFA is faster but less compact, while NFA is slower but concise.

# Chapter 3

## Parsing

The lexer takes a string of characters as input and transforms it into a string of tokens. A parser takes the string of tokens as input, and produces a parse tree. Sometimes the parse tree is just implicit and is not actually built. Also, some compilers finish the two tasks in one phase.

### 3.1 Context free grammars

#### 3.1.1 Introduction

Not all strings of tokens are valid programs, which calls for a language for describing valid strings of tokens as well as a method to distinguish valid strings of tokens from invalid ones.

Programming languages have recursive structures: an **expression** is often made up of other expressions. **Context free grammars** are a natural notation for such structure.

A context free grammar consists of

- a set of terminals ( $T$ )
- a set of non-terminals ( $N$ )
- a start symbol ( $S \in N$ )
- a set of productions ( $P$ )

A production is a relation of symbols:

$$X \rightarrow Y_1 Y_2 \dots Y_n$$

in which  $X \in N$ , and  $Y_i \in T \cup N \cup \{\varepsilon\}$ .

As an example, the language  $\{(i)^i\}, i = 0, \dots, N$  can be expressed by the CFG with  $N = \{S\}, T = \{(\,,\,)\}$  and productions  $\{S \rightarrow (S), S \rightarrow \varepsilon\}$ .

Productions can be regarded as substitution rules. Terminals are so-called because there is no rule to replace them. Once generated, they are permanent. Terminals ought to be tokens of the programming language. Let  $G$  be a CFG with start symbol  $S$ . The language  $L(G)$  of  $G$  is

$$\{a_1 \dots a_n \mid \forall a_i \in T, S \xrightarrow{*} a_1 \dots a_n\}$$

in which  $S \xrightarrow{*} a_1 \dots a_n$  means that  $S$  can be rewritten into  $a_1 \dots a_n$  in a few steps with the substitution rules defined by the productions.

In the definition of production, no precedence between operators or associativity of operator is assumed. For example, the grammar

$$E \rightarrow E + E \mid E - E \mid E * E \mid E / E \mid (E) \mid int \quad (3.1)$$

defines the normal  $+$   $-$   $\times$   $\div$  operations of integers, but do not assume the precedence of  $\times \div$  over  $+-$ , or the normal left associativity of these operators.

### 3.1.2 Derivations

With the help of CFG, we are able to figure out whether a string of tokens belongs to a language. However, we would also like to know the structure of the string, i.e. the parse tree, which calls for the help of derivations.

A sequence of productions is called a derivation. It can be drawn as a tree. The start symbol is the tree's root, and for each production  $X \rightarrow Y_1 Y_2 \dots Y_n$ ,  $Y_1 \dots Y_n$  is added as children of  $X$ . Such a tree drawn to describe an expression is called the **parse tree** of the expression.

A parse tree has terminals at the leaves and non-terminals at the interior nodes. An in-order traversal of the leaves is the original input. The parse tree shows the association of operations, while the input string does not.

According to the order of the non-terminals being replaced, a derivation can be left-most or right-most, or of a random order, which is rarely used. Both the left-most and the right-most derivation have the same parse tree.

### 3.1.3 Ambiguity

A grammar is **ambiguous** if it has more than one parse tree for some string. Equivalently, there is more than one left-most (right-most) derivation for this string. Ambiguity is a problem we strive to avoid. There are two solutions to the problem: either we directly rewrite the grammar unambiguously, or we enforce precedences on operations (e.g.  $*$  over  $+$ ).

Here we give an example of rewriting grammar. The grammar

$$E \rightarrow E * E \mid E + E \mid (E) \mid id$$

is ambiguous.  $1 + 2 + 3$  can be generated by  $\{1 + 2\} + 3$  or  $1 + \{2 + 3\}$ . It can be written as

$$\begin{aligned} E &\rightarrow E' + E \\ E' &\rightarrow id * E' \mid id \mid (E) * E' \mid (E), \end{aligned}$$

which is no longer ambiguous. In the new grammar,  $E$  can generate  $\text{sum}(+)$ , while  $E'$  can generate  $\text{product}(*)$ .  $\{1 + 2\} + 3$  is no longer legal in the new grammar.

Consider the grammar

$$\begin{aligned} E &\rightarrow \text{if } E \text{ then } E \\ &\quad | \text{if } E \text{ then } E \text{ else } E \\ &\quad | \text{OTHER} \end{aligned}$$

that describes an “if then else” relation in which “else” is optional. It is ambiguous because the expression “if  $E_1$  then if  $E_2$  then  $E_3$  else  $E_4$ ” has two parse trees because the “else” could correspond to both “then”s. The parse tree of the previous expression could be either “if  $E_1$  then {if  $E_2$  then  $E_3$  else  $E_4$ }” or “if  $E_1$  then {if  $E_2$  then  $E_3$ } else  $E_4$ ”. We want to rewrite the grammar so that every “else” matches the closest “then”. The new grammar is

$$\begin{aligned} E &\rightarrow \text{MIF} \\ &\quad | \text{UIF} \\ \text{MIF} &\rightarrow \text{if } E \text{ then MIF else MIF} \\ &\quad | \text{OTHER} \\ \text{UIF} &\rightarrow \text{if } E \text{ then } E \\ &\quad | \text{if } E \text{ then MIF else UIF} \end{aligned}$$

in which MIF means all “then”s are matched, while UIF means some “then”s are unmatched. In this new grammar, the second parse tree is no longer legal.

Unfortunately, it is impossible to automatically convert an ambiguous grammar to an unambiguous one. The manual conversion job is tedious, and the unambiguous grammar is often too complex to comprehend quickly. On the contrary, grammar with ambiguity is almost always tidy and more natural. But we need some mechanism to tackle the problem of ambiguity, which is the approach taken by most parsing tools. The most frequently used disambiguation mechanisms are precedence declarations and associativity declarations.

Note that the rewritten grammar no longer generates the same set of expressions from the point of view of semantic meaning. It only ensures that the same set of strings is generated. The grammar (3.1) can be rewritten as

$$E \rightarrow E + \text{int} | E - \text{int} | E * \text{int} | E / \text{int} | (E) | \text{int}$$

to remove the ambiguity. However,  $3 * 5 + 2 - 6 / 2$  will be parsed as and only as  $\{\{\{3 * 5\} + 2\} - 6\} / 2$ , which is against normal precedence and associativity assumptions. In order to make the grammar work correctly in the intended way, simply rewriting the grammar is far from enough. It must be combined with other measures such as precedence and associativity definitions.

## 3.2 Error handling

Compiler has two major tasks to complete: translating valid programs and detecting invalid ones. Different kinds of errors can be detected by different components of the compiler: lexical errors by lexer, syntactic errors by parser and semantic errors by type checker. There are also errors that are not within the scope of the programming language, and thus remain to be found by the programmer through tests.

An error handler within the compiler is expected to

- report errors accurately and clearly;
- recover from an error quickly;
- not slow down the compilation of valid codes.

There are three different approaches to implement the error handler: panic mode, error productions and automatic local/global correction. The first two are used in current compilers.

### 3.2.1 Panic mode

Panic mode is the simplest and thus the most popular method. When an error is detected, it discards tokens until one with a clear role is found, and resumes the compilation there. The “clear” token it looks for is usually the terminator of a statement or a function. In Bison (a popular parser generator), a special terminal `error` is used to describe how much input to skip in case of an error. For example,

$$E \rightarrow E + E | (E) | \text{error int} | \text{error}$$

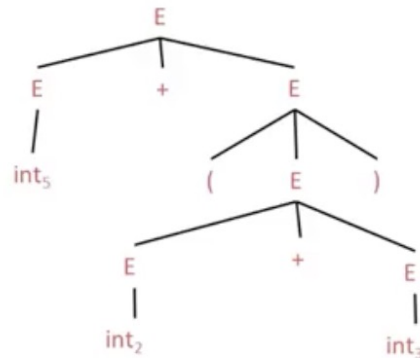
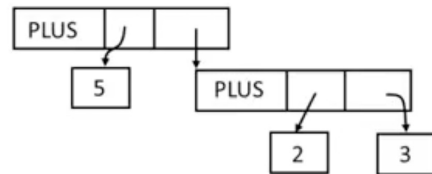
specifies that an integer is regarded as a token to resume the compilation when an error occurs.

### 3.2.2 Error productions

Common errors made by programmers can sometimes be predicted. For example, `5 * x` is often mistakenly written as `5 x`. We can add new productions covering such typos into the grammar so that the compilation can continue, and the programmer receives warnings concerning the errors. This approach has an obvious disadvantage that it complicates the grammar.

### 3.2.3 Automatic correction

In the early years of programming, compilation is a time-consuming process. Programmers had to spend hours or even a whole day waiting for the compilation result. So compilers were expected to automatically correct probable errors in the program so that the time would not be totally wasted due to small mistakes such as typos, and more errors could be found in a single compilation cycle.

Figure 3.1: Parse tree of  $5 + (2 + 3)$ Figure 3.2: AST of  $5 + (2 + 3)$ 

This requirement makes it hard to implement a satisfactory compiler, and it also slows down the compilation of correct codes. Nowadays compilation is much more faster, and programmers tend to recompile everytime they fix an error. Thus complex error recovery becomes less compelling than a few decades ago.

### 3.3 Top down parsing

#### 3.3.1 Abstract syntax tree

A parser traces the derivation of a sequence of tokens, but the rest of the compiler needs a structural representation of the program. **Abstract syntax tree**, or **AST** is the structure we use.

A parse tree traces operations of the parser and captures nesting structure of the token string being parsed. It contains a lot of verbose information, and the AST is an abstracted version that also captures the nesting structure, but is much more compact.

Consider the grammar  $E \rightarrow \text{int}|(E)|E + E$  and the string  $5 + (2 + 3)$ . The parse tree and the related AST are shown in Figure 3.1 and Figure 3.2.

### 3.3.2 Recursive descent algorithm

**Recursive descent parsing** is a top-down parsing method, with which the parse tree is built from the top and from left to right. When building a parse tree, we start with the top-level non-terminal  $E$ , and try the rules of  $E$  in order. When another non-terminal is met, this process is carried out recursively. If a mis-match is found, we need to do the back tracking to find the correct rule to match.

Some rules in the illustration of the recursive descent parsing algorithm: **TOKEN** will be the type of tokens, and its instances will be **INT** (for int), **OPEN** (for '('), **CLOSE** (for ')'), **TIMES** (for '\*'), etc; the global variable **next** will point to the next token in the input.

Some boolean functions need to be defined to check matches of token terminals and CFG rules. For a given token terminal **tok**, for the  $n$ th production of  $S$ , and for all productions of  $S$ , the functions are respectively

```

1 bool term(TOKEN tok) { return *next++ = tok; }
2 bool Sn() { ... }
3 bool S() { ... }

```

As an example, consider the grammar

$$\begin{aligned}
 E &\rightarrow T \mid T + E \\
 T &\rightarrow \text{int} \mid \text{int} * T \mid (E).
 \end{aligned}
 \tag{3.2}$$

We will have

```

1 bool E1() { return T(); }
2 bool E2() { return T() && term(PLUS) && E(); }
3 bool E() {
4     TOKEN *save = next;
5     return (next = save, E1()) || (next = save, E2());
6 }
7 bool T1 = { return term(INT); }
8 bool T2 = { return term(INT) && term(TIMES) && T(); }
9 bool T3 = { return term(OPEN) && E() && term(CLOSE); }
10 bool T() {
11     TOKEN *save = next;
12     return (next = save, T1()) ||
13         (next = save, T2()) ||
14         (next = save, T3());
15 }

```

To start the parser, **next** needs to be set to the first token, and **E()** should be invoked.

With the statement **\*save = next**, the current position is saved in **save**. If the matching for a production succeeds, the matching for the whole non-terminal ends; otherwise **next** is restored with **next = save**, and the string continues to be matched with the next production. The use of the C++ comma operator is interesting.



### Limitations

The recursive descent parsing algorithm just presented is easy to be implemented by hand, but it is not general. Specifically for this example, consider the matching process for the string `int * int`. We will go from  $E()$  to  $T()$  then to  $T_1()$ , which returns true and leaves us with the `* int` segment. This segment cannot be matched, forcing us to wrongly reject the whole string.

The problem is that with this algorithm, we have no way of back tracking and trying other productions once one production has been successfully matched. There exist a more general and yet more complex implementation that solves the problem by allowing “full back tracking”, which will be covered later.

### Left recursion

If a grammar has the form  $S \rightarrow^+ S\alpha$  for some  $\alpha$ , then it has a left recursion problem because the recursive descent matching process will end up in an infinite loop.

Left recursion problem can be solved by writing the algorithm. The grammar  $S \rightarrow S\alpha | \beta$  that generates the language  $\beta\alpha^*$  can be rewritten as  $S \rightarrow \beta S'$ ,  $S' \rightarrow \alpha S' | \epsilon$ . More generally, the grammar  $S \rightarrow S\alpha_1 | \dots | S\alpha_n | \beta_1 | \dots | \beta_m$  that generates the language  $(\beta_1 | \dots | \beta_m)(\alpha_1 | \dots | \alpha_n)^*$  can be rewritten as  $S \rightarrow \beta_1 S' | \dots | \beta_m S'$ ,  $S' \rightarrow \alpha_1 S' | \dots | \alpha_n S' | \epsilon$ . The general rule is to recognize the terminal rather than the non-terminal first when matching a combination of the two.

There are algorithms that carries out the elimination of left recursion automatically (in the Dragon book).

### 3.3.3 Predictive parsing

Predictive parsing is another top-down parsing method. It is able to “predict” which production to use by looking at the next few tokens (lookahead) and no backtracking is needed. Predictive parser accepts so-called **LL(k)** grammars which means **left-to-right left-most-derivation** grammars requiring **k** lookahead tokens. Here we will focus only on the case with  $k=1$ . Recall that in recursive descent, many choices of productions could be used at each step, and we use backtracking to undo the bad choices. But with LL(1) grammar, at most one production is available at each step.

Consider the grammar (3.2). It is hard to predict the best production to use because for  $T$ , there are two productions that start with an `int`, and for  $E$ , both productions start with  $T$  so that it is not clear how to make the predication. The grammar needs to be **left-factored** in order to apply predicative parsing.

The new grammar is

$$\begin{aligned} E &\rightarrow TX \\ X &\rightarrow +E \mid \epsilon \\ T &\rightarrow \text{int } Y \mid (E) \\ Y &\rightarrow * T \mid \epsilon \end{aligned} \tag{3.3}$$

A **LL(1) parsing table** can be generated according to this grammar as shown in Table 3.1. The method to generate it will be covered later. \$ is the end

**Table 3.1: Parsing table of grammar (3.3)**

	int	*	+	(	)	\$
E	TX			TX		
X			+E		$\epsilon$	$\epsilon$
T	int Y			(E)		
Y		* T	$\epsilon$		$\epsilon$	$\epsilon$

of the input. Rows of the table represent the current leftmost non-terminal, while columns of the table represent the next input token. The entry is the rhs of the production to be used according to the combination of the leftmost non-terminal and the next input token. As an example, we have  $[E, \text{int}] = \text{TX}$ , which means that when the current non-terminal is E and the next input token is int, we should use the production  $E \rightarrow \text{TX}$ . Also,  $[Y, +] = \epsilon$  means that when the current non-terminal is Y and the next input token is +, the production  $Y \rightarrow \epsilon$  should be used, i.e. Y should be got rid of. Finally, empty entry means that there is an error.

In order to carry out predictive parsing, we need to construct a stack that records the frontier of the parse tree. It contains non-terminals to be expanded as well as terminals to be matched. The top of the stack is always the leftmost pending terminal or non-terminal. The algorithm can be illustrated by Algorithm (3.1). If the stack is empty when we reach the end of the input,

---

**Algorithm 3.1** Predictive parsing algorithm

---

```

Initialize stack = <S,$> and next
repeat
  switch stack
    case <X,rest>:
      if  $T[X, *next++] == Y_1 \dots Y_n$  then
         $stack \leftarrow \langle Y_1 \dots Y_n \text{ rest} \rangle$ 
      else error()
    case <t,rest>:
      if  $t == *next++$  then
         $stack \leftarrow \langle \text{rest} \rangle$ 
      else error()
until stack == < >

```

---

the string is accepted. If any error state is reached, the string is rejected. A step-by-step predictive parsing process of the string `int * int` with the grammar (3.3) is shown in Table 3.2.

Now let's discuss the construction of LL1 parsing tables. For non-terminal A, production  $A \rightarrow \alpha$  and terminal t, we will have  $T[A, t] = \alpha$  in and only in two

**Table 3.2: Predictive parsing of  $\text{int} * \text{int}$** 

Stack	Input	Action
E\$	int * int\$	TX
TX\$	int * int\$	int Y
intYX\$	int * int\$	terminal
YX\$	* int\$	* T
*TX\$	* int\$	terminal
TX\$	int\$	int Y
intYX\$	int\$	terminal
YX\$	\$	$\epsilon$
X\$	\$	$\epsilon$
\$	\$	accept

cases:

1. When  $\alpha \xrightarrow{*} t\beta$ , i.e.  $\alpha$  can derive a  $t$  at the beginning. We say  $t \in \text{First}(\alpha)$ .
2. Otherwise when  $\alpha \xrightarrow{*} \epsilon$  and  $S \xrightarrow{*} \beta A t \delta$ . We say  $t \in \text{Follow}(\alpha)$ .

### First set

The formal definition of  $\text{First}(X)$  is

$$\text{First}(X) = \{t | X \xrightarrow{*} t\alpha\} \cup \{\epsilon | X \xrightarrow{*} \epsilon\}.$$

The algorithm to calculate  $\text{First}(X)$  is

1. For all terminal  $t$ ,  $\text{First}(t) = \{t\}$ .
2.  $\epsilon \in \text{First}(X)$  if  $X \xrightarrow{*} \epsilon$ , or if  $X \xrightarrow{*} A_1 \dots A_n$  and  $\epsilon \in \bigcap_j \text{First}(A_j)$ .
3.  $\text{First}(\alpha) \subseteq \text{First}(X)$  if  $X \xrightarrow{*} A_1 \dots A_n \alpha$  and  $\epsilon \in \bigcap_j \text{First}(A_j)$ .

For grammar (3.3), we have

- For terminals,  $\text{First}(t) = t$ ,  $t = +, *, (, ), \text{int}$ .
- $\text{First}(T) = \{\text{int}, (\}$
- $\text{First}(E) = \{\text{int}, (\}$
- $\text{First}(X) = \{+, \epsilon\}$
- $\text{First}(Y) = \{*, \epsilon\}$

**Follow set**

The formal definition of  $\text{Follow}(X)$  is

$$\text{Follow}(X) = \{t \mid S \xrightarrow{*} \beta X t \delta\}.$$

The algorithm to calculate  $\text{Follow}(X)$  is

1.  $\$ \in \text{Follow}(S)$
2. For production  $A \rightarrow \alpha X \beta$ ,  $\text{First}(\beta) - \{\epsilon\} \subseteq \text{Follow}(X)$ .
3. For production  $A \rightarrow \alpha X \beta$  in which  $\epsilon \in \text{First}(\beta)$ ,  $\text{Follow}(A) \subseteq \text{Follow}(X)$ .

For grammar (3.3), we have

- $\text{Follow}(E) = \{\$, \})$
- $\text{Follow}(X) = \{\$, \})$
- $\text{Follow}(T) = \{+, \$, \})$
- $\text{Follow}(Y) = \{+, \$, \})$
- $\text{Follow}('(') = \{\text{int}, (\}$
- $\text{Follow}(')') = \{+, \$, \})$
- $\text{Follow}(\text{int}) = \{*, +, \$, \})$
- $\text{Follow}(+) = \{\text{int}, (\}$
- $\text{Follow}(*) = \{\text{int}, (\}$

**Parsing table**

To build a parsing table, for each production  $A \rightarrow \alpha$ , we need to do:

1. For each terminal  $t \in \text{First}(\alpha)$ ,  $T[A, t] = \alpha$ .
2. If  $\epsilon \in \text{First}(\alpha)$ , for each terminal  $t \in \text{Follow}(A)$ ,  $T[A, t] = \alpha$ .
3. If  $\epsilon \in \text{First}(\alpha)$  and  $\$ \in \text{Follow}(A)$ ,  $T[A, \$] = \alpha$ .

If any entry of the parsing table is multiple defined, then the grammar is not LL(1). In particular, if the grammar is

- not left factored
- left recursive
- ambiguous
- ...

then it is not LL(1). Actually most programming language CFGs are not LL(1). LL(1) grammar is too weak to describe all the features required in these languages.

### 3.4 Bottom-up parsing

Bottom-up parsing is more general than deterministic top-down parsing. Actually it is as efficient, and builds on all the ideas we have discussed in top-down parsing. Bottom-up parsing is the preferable method in reality. Bottom-up parsing does not require left-factored grammar, thus we can revert to the natural grammar (3.2) in the following discussion. Nonetheless, bottom-up parsers do not deal with ambiguous grammars, thus we still have to enforce precedence and associativity rules.

Bottom-up parsing reduces a string to the start symbol by inverting productions. As an example, consider the string  $\text{int} * \text{int} + \text{int}$ . It can be reduced to the start symbol  $E$  via the following path:

$\text{int} * \text{int} + \text{int}$	$T \rightarrow \text{int}$
$\text{int} * T + \text{int}$	$T \rightarrow \text{int} * T$
$T + \text{int}$	$T \rightarrow \text{int}$
$T + T$	$E \rightarrow T$
$T + E$	$E \rightarrow T + E$
$E$	

Obviously, the left column is the rightmost derivation of the string written in reverse. This is actually always true for bottom up parsers. **Bottom-up parser traces a rightmost derivation in reverse.** It builds the parse tree from its leaves up towards the root, by combining smaller parse trees into larger ones.

#### 3.4.1 Shift reduce parsing

Suppose  $\alpha\beta\omega$  is a step of a bottom-up parse, and the next reduction to apply is  $X \rightarrow \beta$ . Since  $\alpha X\omega \rightarrow \alpha\beta\omega$  is a step in a rightmost derivation, we can be sure that  $\omega$  is a string of terminals. This inspires us of the idea of shift-reduce parsing. The string is split into two substrings, the right one unexamined by the parser, and the left one containing terminals and non-terminals. The dividing point is marked by a  $|$  sign. Two actions are needed to carry out bottom-up parsing: **Shift** and **Reduce**. Shift means moving  $|$  one place to the right, i.e. shifting one terminal to the left substring. Reduce means applying an inverse production at the right end of the left substring.

The left substring in shift-reduce string can be implemented by a stack, with the top of the stack being the  $|$  sign. Each shift action pushes a terminal on the stack. Each reduce action pops symbols (rhs of the production rule, terminals and nonterminals) out of the stack, and pushes a nonterminal on the stack.

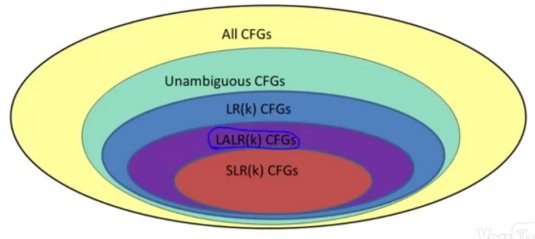
In a given state, more than one action might lead to a valid parse. If it is legal to shift or reduce, there is a **shift/reduce** conflict. If there are two legal reduces, then there is a **reduce/reduce** conflict. Reduce/reduce conflicts are always bad, indicating some serious problem of the grammar. Shift/reduce conflicts can usually be removed by precedence definitions.

### 3.4.2 Handle & viable prefixes

Reducing whenever we meet a rhs of production will probably cause incorrect results. For example, we cannot reduce  $\text{int} * \text{int}$  to  $T * \text{int}$  after the first shift according to the grammar (3.2). We should only reduce when its result can still be reduced to the start symbol. A **handle** is a reduction that also allows further reductions back to the start symbol. For a rightmost derivation  $S \xrightarrow{*} \alpha X \omega \rightarrow \alpha \beta \omega$ , we say  $\alpha \beta$  is a handle of  $\alpha \beta \omega$ . **In shift-reduce parsing, handles appear only at the top of the stack (never inside).** Handles are never to the left of the rightmost non-terminal. Thus shift-reduce moves are sufficient, and the  $|$  sign never has to move left. Bottom-up parsing algorithms are based on recognizing handles.

#### Recognizing handles

Unfortunately there exists no known efficient algorithm to recognize handles. Nonetheless, there are good heuristics for guessing handles, and for some fairly large classes of CFGs, these heuristics always identify the handles correctly. Figure 3.3 illustrates the relationship of different kinds of CFGs. Most of the



**Figure 3.3: Relationship of different CFGs**

time we will talk about SLR(k) CFGs.

It is not obvious how to detect handles. We should always keep in mind that at each step, the parser sees only the stack and not the entire input, which is the starting point of the whole discussion. First we define a **viable prefix**.  $\alpha$  is a viable prefix if there is an  $\omega$  such that  $\alpha|\omega$  is a state of a shift-reduce parser. Here,  $\alpha$  is the visible stack, while  $\omega$  is the rest of the input. A viable prefix is a string that does not extend past the right end of the handle. It is called “viable” because it is a prefix of the handle. As long as the parser has viable prefixes on the stack, it means that no parsing error has been detected.

**For any grammar, the set of viable prefixes is a regular language.** As a result, the set of viable prefixes can be recognized by a finite automaton. We will show how to compute the automata that accept viable prefixes.

First we introduce the idea of an **item**. An item is a production with a  $\cdot$ <sup>1</sup> somewhere in the rhs. For example, the production  $T \rightarrow (E)$  produces 4 items:

<sup>1</sup>In the lectures  $\cdot$  is used. I use  $\cdot(\text{\LaTeX}\backslash\text{cdot})$  to avoid confusion with period.

$T \rightarrow \cdot(E)$ ,  $T \rightarrow (\cdot E)$ ,  $T \rightarrow (E \cdot)$  and  $T \rightarrow (E) \cdot$ . For  $\epsilon$ -productions, the only item for  $X \rightarrow \epsilon$  is  $X \rightarrow \cdot$ . Items are usually called the LR(0) items. They provide a description of intermediate steps of shift-reduce parsing. Consider the input (int) for grammar (3.2).  $(E|)$  is a state of a shift-reduce parse for it.  $(E$  is a prefix of the rhs of the production  $T \rightarrow (E)$ , and it is to be reduced if a  $)$  is recognized after the next shift. Item  $T \rightarrow (E \cdot)$  describes such situation: we have seen  $(E$  and hope to see  $)$ .

The stack contains actually many prefixes of rhses of productions:

$$\text{Prefix}_1 \text{Prefix}_2 \dots \text{Prefix}_{n-1} \text{Prefix}_n$$

Let  $\text{Prefix}_i$  be a prefix of rhs of  $X_i \rightarrow \alpha_i$ .  $\text{Prefix}_i$  will eventually reduce to  $X_i$ . In order that the parsing can continue, the missing part of  $\alpha_{i-1}$  must start with  $X_i$ , i.e. there must exist a production  $X_{i-1} \rightarrow \text{Prefix}_{i-1} X_i \beta$  for some  $\beta$ . Recursively  $\text{Prefix}_{k+1} \dots \text{Prefix}_n$  eventually reduces to the missing part of  $\alpha_k$ .

Consider  $(\text{int} * \text{int})$  for grammar (3.2).  $(\text{int} * | \text{int})$  is a state of a shift-reduce parse. We have the stack of items:

$$\begin{aligned} T &\rightarrow (\cdot E) \\ E &\rightarrow \cdot T \\ T &\rightarrow \text{int} * \cdot T \end{aligned}$$

### Recognizing viable prefixes

As concluded previously, to recognize viable prefixes, we must recognize a sequence of partial rhses of productions, where each partial rhs can eventually reduce to part of the missing suffix of its predecessor. We will build an NFA that takes the stack as an input and decides whether to accept or reject it.

1. Add a dummy production  $S' \rightarrow S$  to the grammar  $G$ .
2. The NFA states are items of  $G$ , including the dummy production just added.
3. For item  $E \rightarrow \alpha \cdot X \beta$ , add transition

$$E \rightarrow \alpha \cdot X \beta \xrightarrow{X} E \rightarrow \alpha X \cdot \beta$$

Here  $X$  is either a terminal or a non-terminal. This rule extends a prefix or an rhs.

4. For item  $E \rightarrow \alpha \cdot X \beta$  and production  $X \rightarrow \gamma$ , add transition

$$E \rightarrow \alpha \cdot X \beta \xrightarrow{\epsilon} X \rightarrow \cdot \gamma$$

Here  $X$  can only be non-terminals. This rule ends the current prefix and starts a new one.

5. Every state is an accepting state.

6. Start state is  $S' \rightarrow S$ .

Consider grammar (3.2). After adding the dummy production, it becomes

$$\begin{aligned} S' &\rightarrow E \\ E &\rightarrow T \mid T + E \\ T &\rightarrow \text{int} \mid \text{int} * T \mid (E). \end{aligned}$$

By applying the algorithm above, we wind up with the NFA shown in Figure 3.4.

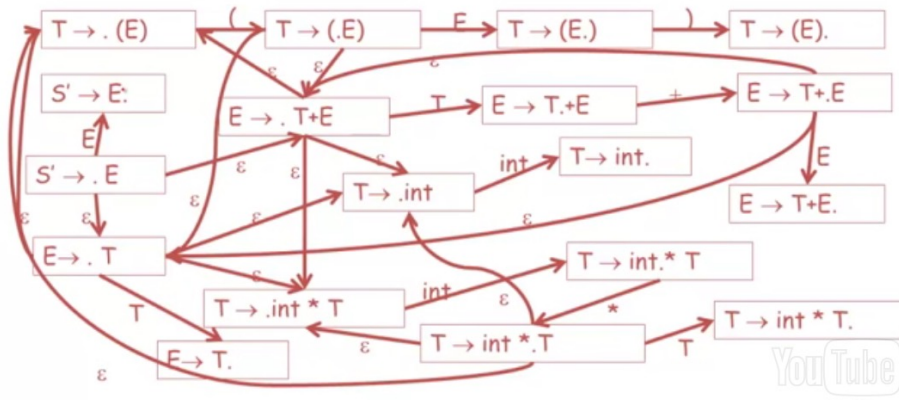


Figure 3.4: NFA of grammar (3.2)

The NFA gained using the algorithm above can be converted into a DFA. The states of the DFA are sets of items. The state of the DFA are called “canonical collections of items (or LR(0) items)”<sup>2</sup>.

The item  $X \rightarrow \beta \cdot \gamma$  is said to be **valid** for a viable prefix  $\alpha\beta$  if

$$S' \xrightarrow{*} \alpha X \omega \rightarrow \alpha \beta \gamma \omega$$

by right-most derivation. After parsing  $\alpha\beta$ , the valid items are possible tops of the stack of items. An equivalent explanation is that for a given viable prefix  $\alpha$ , the valid items are exactly the items in the final state of the DFA after it reads that prefix.

### 3.4.3 SLR parsing

In this section we will present the **SLR parsing** algorithm. SLR means “simple left-to-right rightmost”.

First we will introduce a weak bottom-up parsing algorithm called LR(0) parsing. Suppose that the stack contains  $\alpha$  and the next input is token  $t$ . The DFA on input  $\alpha$  terminates in state  $s$ . Then the rules for shift-reduce actions are:

<sup>2</sup>Dragon book provides another way to define LR(0) items.



- Reduce by  $X \rightarrow \beta$  if  $X \rightarrow \beta \cdot \in s$
- Shift if  $X \rightarrow \beta \cdot t\omega \in s$ . This is equivalent to the fact that  $s$  has a transition labeled  $t$ .

LR(0) parsing has a reduce/reduce conflict if any state has two reduce items  $X_1 \rightarrow \beta_1 \cdot$  and  $X_2 \rightarrow \beta_2 \cdot$ . It has a shift/reduce conflict if any state has a reduce item  $X_1 \rightarrow \beta_1 \cdot$  and a shift item  $X_2 \rightarrow \beta_2 \cdot t\delta$ .

SLR improves on LR(0) shift/reduce heuristics. As a result, fewer shift/reduce conflicts will happen. The only adjustment is on the reduce rule, which is changed to

- Reduce by  $X \rightarrow \beta$  if  $X \rightarrow \beta \cdot \in s$  and  $t \in \text{Follow}(X)$

If any conflict still exists, then the grammar is not an SLR grammar. The handles of SLR grammars can be exactly detected by the heuristics. A lot of grammars are not SLR grammars. We can define rules to resolve some conflicts for such grammars, which sometimes have the effect of precedence declaration.

Now we present the complete SLR parsing algorithm.

---

**Algorithm 3.2** SLR parsing algorithm

---

Let  $M$  be the DFA for viable prefixes of  $G$ . and let  $|x_1 \dots x_n \$$  be the initial configuration.

**repeat**

Let  $\alpha|\omega$  be the current configuration and run  $M$  on the current stack  $\alpha$ .

**if**  $M$  rejects  $\alpha$  **then**

report parsing error

**else**

$M$  accepts  $\alpha$  with items  $I$ , let  $a$  be the next input

**if**  $X \rightarrow \beta \cdot a\gamma \in I$  **then** shift

**else if**  $X \rightarrow \beta \cdot \in I$  **and**  $a \in \text{Follow}(X)$  **then** reduce

**else** report parsing error

**until** configuration is  $S| \$$

---

See video 8-6 for an exhaustive example of applying the algorithm.

Algorithm (3.2) can be improved because rerunning the viable prefixes automaton is wasteful: reduce or shift will only change a few symbols on the top of the stack, while the rest of the stack stays the same, and the work on them is just a repeat. If the repeat can be avoided, the algorithm can run much more quickly.

The state of the automaton on each prefix can be remembered. It will be more convenient to make the stack store  $\langle \text{Symbol}, \text{DFA state} \rangle$  pairs rather than just symbols. We will have a stack

$$\langle \text{sym}_1, \text{state}_1 \rangle \cdots \langle \text{sym}_n, \text{state}_n \rangle,$$

in which  $\text{state}_n$  is the final state of the DFA on  $\text{sym}_1 \dots \text{sym}_n$ . The bottom of the stack is now  $\langle \text{any}, \text{start} \rangle$ , in which any is any dummy state, while start is the start state of the DFA. The algorithm has 4 possible moves:

- Shift  $x$ .  $\langle a, x \rangle$  will be pushed on the stack, in which  $a$  is the current input, while  $x$  is a DFA state.
- Reduce  $X \rightarrow \alpha$ . As before, pop the rhs elements off the stack and push the lhs on.
- Accept.
- Error.

We will define two parsing tables.

- Define  $\text{goto}[i, A] = j$  if  $\text{state}_i \xrightarrow{A} \text{state}_j$ .  $\text{goto}$  is just the transition function of the DFA.
- Define  $\text{action}[i, a]$  for each DFA state  $s_i$  and the next input terminal  $a$ .
  - If  $s_i$  contains item  $X \rightarrow \alpha \cdot a\beta$  and  $\text{goto}[i, a] = j$  then  $\text{action}[i, a] = \text{shift } j$ .
  - If  $s_i$  contains item  $X \rightarrow \alpha \cdot$  and  $a \in \text{Follow}(X)$  and  $X \neq S'$  then  $\text{action}[i, a] = \text{reduce } X \rightarrow \alpha \cdot$ .
  - If  $s_i$  contains item  $S' \rightarrow S$ , then  $\text{action}[i, \$] = \text{accept}$ .
  - Otherwise  $\text{action}[i, a] = \text{error}$ .

The improved algorithm is shown in Algorithm (3.3).

In practice, SLR parsing is too simple and sometimes naive. LR(1), or LALR(1), which is based on LR(1) and includes some optimisations, parsing is much more widely used. The main difference between LR(1) and SLR is that LR(1) builds lookahead into the items. An LR(1) item looks like  $[T \rightarrow \cdot \text{int} * T, \$]$ , which means “after seeing  $\text{int} * T$ , reduce if lookahead is  $\$$ ”. This mechanism is more accurate than using just the follow set to decide whether to reduce.

---

**Algorithm 3.3** Improved SLR parsing algorithm

---

```
Let  $I = w\$$  be the initial input
Let  $j = 0$ .
Let DFA state 1 have item  $S' \rightarrow S$ .
Let  $\text{stack} = \langle \text{dummy}, 1 \rangle$ 
repeat
  switch  $\text{action}[\text{top\_state}(\text{stack}), I[j]]$ 
    case Shift  $k$ :
      Push  $\langle I[j++], k \rangle$  on stack
    case reduce  $X \rightarrow A$ :
      Pop  $|A|$  pairs
      Push  $\langle X, \text{goto}[\text{top\_state}(\text{stack}), X] \rangle$  on stack
    case accept:
      Halt normally
    case error:
      Halt with an error
until configuration is  $S|\$$ 
```

---

## Chapter 4

# Semantic Analysis

The lexer detects illegal tokens inside the input, while the parser detects ill-formed parse trees inside the input. Semantic analysis is the last “front end” phase of the compiler to catch errors. It is necessary because there are errors that cannot be caught by the parser and lexer, and some language constructs are not context free.

As a typical statically type checked object oriented language, Cool language requires its semantic analyser doing the following checks:

- All identifiers are declared
- Type checking (major function)
- Inheritance relationships
- Classes are defined only once
- Methods in a class are defined only once
- Reserved identifiers are not misused

This is not an exhaustive list.

### 4.1 Scope

There can be more than one definition of an identifier before it is used. In order to match the correct declaration of an identifier with its uses, we need to understand the conception of scope.

The **scope** of an identifier is the portion of a program in which that identifier is accessible. The same identifier may refer to different things in different parts of the same program. In such case, different scopes of the same identifier should not overlap. Programming languages can have either **static scope** or **dynamic scope**. Today most languages, including Cool, have static scope, which means

scopes of identifiers depend only on the program text, not the runtime behaviors. There are languages that are dynamically scoped, like SNOBOL and ancient Lisp, for which scopes depend on the execution process of the program. Generally speaking, static scoped language follows **the most closely nested rule**, meaning that the variable binds to the definition that is the most closely enclosing it. Dynamically scoped language follows **the most recent binding rule**, meaning that the variable binds to the most recent definition during the execution.

In Cool, identifier bindings are introduced by a lot of mechanisms:

- class definitions (class names)
- method definitions (method names)
- let expressions (object ids)
- formal parameters (object ids)
- attribute definitions (object ids)
- case expressions(object ids)

Not all identifiers in Cool follow the most closely nested rule. For example, class definitions in Cool cannot be nested, and they are globally visible throughout the program, which means that a class can be used before it is defined. Also, attribute names are globally visible within the class in which they are defined. What's more, method names have some complex rules, such as they can be defined in a parent class, and they can be overridden.

## 4.2 Symbol tables

Much of semantic analysis can be expressed as a recursive descent of an AST. In each step we do the following 3 things:

- Before: Begin processing an AST node  $n$  (preprocessing)
- Recurse: Process the children of  $n$
- After: Finish processing node  $n$  (postprocessing)

When performing semantic analysis on a portion of the AST, we need to know which identifiers are defined. If we divide the processing of the expression  $\text{let } x:T \leftarrow e_0 \text{ in } e_1$  into the 3 phases listed above, the preprocessing phase will add definition of  $x$  to the current definitions and override any previous definition of  $x$ , while the postprocessing phase will remove definition of  $x$  and restore the old definition of  $x$ . A **symbol table** is the data structure used to track the current bindings of identifiers.

To implement a simple symbol table, we can use just a stack. It contains three operations:

- `add_symbol(x)`: push symbol `x` and its associated info on the stack.
- `find_symbol(x)`: search the stack from the top. Returns the first `x` found or `NULL`.
- `remove_symbol()`: pop the stack.

This simple implementation works for `let` expression because in `let` expressions, declarations are perfectly nested, and symbols are added to the symbol table one at a time. In other cases, the functionality of this implementation is not sufficient, e.g. in the definition of a method in which more than one symbols can be introduced each time. We need an implementation that covers the following operations:

- `enter_scope()`: start a new nested scope
- `find_symbol(x)`: find current `x` (or `NULL`)
- `add_symbol(x)`: add a symbol `x` to the table
- `check_scope(x)`: true if `x` is defined in the current scope
- `exit_scope()`: exit current scope

Class names should be specially considered here because classes can be used before they are defined. Thus they cannot be checked using a symbol table, neither in one single pass. The solution is to complete two passes: gather all class names in the first one, and do the checking in the second one. In general, semantic analysis requires multiple passes. In the implementation of semantic analysis, a few simple passes is superior to one complex pass.

## 4.3 Type checking

### 4.3.1 Types

“What is a type” is a question worthy of asking because type is a notion varying from language to language. The consensus is that a type is a set of values and a set of operations on these values. In OO languages, classes are one instantiation of the modern notion of type, but types do not need to be associated with classes.

**The goal of type checking is to ensure that operations are used only with the correct types.** It is nonsensical to add a function pointer to an integer in C, but at assembly language level they share the same implementation. Type checking is intended to avoid such errors.

There are 3 kinds of languages:

**Statically typed** Almost or all type checking is done as part of compilation.  
e.g. C, java, cool.

**Dynamically typed** Almost all type checking is done at run time. e.g. Python, Lisp, Perl.

**Untyped** No type checking. e.g. machine code.

There have always been debates on the merits of static typing v.s. dynamic typing. Static typing proponents assert that static checking catches many errors at compile time, and it avoids overhead of runtime type checks. Dynamic typing proponents argue that static type systems are too restrictive, and it causes difficulty when it comes to rapid prototyping. In the end, we end up with compromises on both sides: static typed languages often provide an “escape” mechanism, e.g. casting in C-like languages; dynamic typed languages are often retrofitted for optimisation and debugging with static typing.

Types in Cool include class names and SELF.TYPE. User is supposed to declare types for identifiers, and the compiler will do the rest of the job: a type will be inferred for every expression.

### 4.3.2 Logical inference rules

We have seen two formal notations as the specification of parts of a compiler: regular expressions and context free grammars. Logical inference rules are the appropriate formalism for type checking.

Inference rules have the form

If Hypothesis is true, the Conclusion is true.

In the specific case of type checking rules, they often have the form

If  $E_1$  and  $E_2$  have certain types, then  $E_3$  has a certain type.

In order to simplify the notation, we use  $\wedge$  to denote “and”,  $\Rightarrow$  to denote “if-then”, and  $x:T$  to denote “ $x$  has type  $T$ ”. Thus, the rule “if  $e_1$  has type  $\text{Int}$ ,  $e_2$  has type  $\text{Int}$ , then  $e_1 + e_2$  has type  $\text{Int}$ ” is denoted as

$$(e_1 : \text{Int} \wedge e_2 : \text{Int}) \Rightarrow e_1 + e_2 : \text{Int}$$

By convention, inference rules are written in the form

$$\frac{\vdash \text{Hypothesis}_1 \cdots \vdash \text{Hypothesis}_n}{\vdash \text{Conclusion}}$$

in which  $\vdash$  is read “it is provable that”. Here we give some rules as examples.

$$\begin{array}{c}
\frac{}{\vdash i \text{ is an integer literal}} \\
\vdash i : \text{Int} \\
\frac{}{\vdash e_1 : \text{Int} \vdash e_2 : \text{Int}} \\
\vdash e_1 + e_2 : \text{Int} \\
\frac{\frac{}{\vdash 1 : \text{Int}} \quad \frac{}{\vdash 2 : \text{Int}}}{\vdash 1 + 2 : \text{Int}} \\
\vdash \text{false} : \text{Bool} \\
\frac{}{\vdash \text{new } T : T} \\
\vdash e : \text{Bool} \\
\vdash !e : \text{Bool} \\
\vdash e_1 : \text{Bool} \vdash e_2 : T \\
\hline
\vdash \text{while } e_1 \text{ loop } e_2 \text{ pool} : \text{Object}
\end{array}$$

A type system is sound if whenever  $\vdash e : T$ ,  $e$  evaluates to a value of type  $T$ . We only want sound rules, but some sound rules are better than others. For example,  $\frac{\vdash i : \text{Int}}{\vdash i : \text{Object}}$  is sound but not helpful at all.

Type check proves facts in the form of  $e : T$ . The proof is on the structure of the AST. It actually has the shape of the AST, because one type rule is used for each AST node. In the rule used for an AST node  $e$ , Hypotheses are the proofs of the types of  $e$ 's subexpressions, while the conclusion is the type of  $e$ . Types are computed in a bottom-up pass over the AST.

### 4.3.3 Type environment

For a variable, the local structural rule does not carry enough information to give it a type.

$$\frac{x \text{ is a variable}}{\vdash x : ?}$$

More information should be put into the rules in such case. A **type environment** gives types to **free** variables. A variable is free if it is not defined within the expression. A type environment is a function from object identifiers to types. It is implemented by the symbol table.

Let  $O$  be a function from ObjectIdentifiers to Types, the sentence  $O \vdash e : T$  is read: under the assumption that free variables in expression  $e$  have the type given by  $O$ , it is provable that  $e$  has type  $T$ . The type environment should be added to the earlier rules. For example now we have

$$\begin{array}{c}
\frac{}{\vdash i \text{ is an integer literal}} \\
O \vdash i : \text{Int} \\
O \vdash e_1 : \text{Int} \quad O \vdash e_2 : \text{Int} \\
\hline
O \vdash e_1 + e_2 : \text{Int}
\end{array}$$



And we can now write some new rules:

$$\frac{O(x) = T}{O \vdash x : T}$$

We use  $O[T/x]$  to denote the function that returns  $T$  for  $x$ , and  $O(y)$  for whatever  $y \neq x$ . We can now define the rule for let expression:

$$\frac{O \vdash e_0 : T \quad O[T/x] \vdash e_1 : T_1}{O \vdash \text{let } x : T \leftarrow e_0 \text{ in } e_1 : T_1} \quad (4.1)$$

The type environment is passed down the AST from the root to the leaves, while types are computed up the AST from the leaves to the root.

#### 4.3.4 Subtyping

The rule (4.1) is not satisfactory in practice because It is not necessary that  $x:T$ .  $x$  can actually be of any subtype of  $T$ . In order to allow the use of subtypes, we introduce the  $\leq$  relationship between classes. Its formal definition is

- $X \leq X$
- $X \leq Y$  if  $X$  inherits from  $Y$
- $X \leq Z$  if  $X \leq Y$  and  $Y \leq Z$

With  $\leq$  relationship added, rule (4.1) can be written as

$$\frac{O \vdash e_0 : T_0 \quad O[T/x] \vdash e_1 : T_1 \quad T_0 \leq T}{O \vdash \text{let } x : T \leftarrow e_0 \text{ in } e_1 : T_1}$$

Similarly, the rule of assignment can be written as

$$\frac{O(x) = T_0 \quad O \vdash e_1 : T_1 \quad T_1 \leq T_0}{O \vdash x \leftarrow e_1 : T_1}$$

Attribute initialization inside a class also uses subtyping.  $O_C(x) = T$  means for all attributes  $x$  of class  $C$  we have  $x : T$ .

$$\frac{O_C(x) = T_0 \quad O_C \vdash e_1 : T_1 \quad T_1 \leq T_0}{O_C \vdash x : T_0 \leftarrow e_1 : T_0}$$

Consider the case of the if expression. The type of `if  $e_0$  then  $e_1$  else  $e_2$  fi` can be either the type of  $e_1$  or that of  $e_2$ , depending on whether the else clause or the then clause is executed at runtime. In this case, the best we can do is to use the smallest super type larger than both the types of  $e_1$  and  $e_2$ , i.e. **their least upper bound**, which is denoted by  $Z = \text{lub}(X, Y)$ . Its formal definition is

- $X \leq Z \wedge Y \leq Z$
- if  $X \leq Z' \wedge Y \leq Z', Z \leq Z'$

In Cool, the least upper bound of two types is their least common ancestor in the inheritance tree. Equipped with the definition of  $\text{lub}(X, Y)$ , we can write the rule of the if expression:

$$\frac{\begin{array}{c} O \vdash e_0 : \text{Bool} \\ O \vdash e_1 : T_1 \\ O \vdash e_2 : T_2 \end{array}}{O \vdash \text{if } e_0 \text{ then } e_1 \text{ else } e_2 \text{ fi} : \text{lub}(T_1, T_2)}$$

The rule of case expression takes a similar but more complex form:

$$\frac{\begin{array}{c} O \vdash e_0 : T_0 \\ O[T_1/x_1] \vdash e_1 : T'_1 \\ \dots \\ O[T_n/x_n] \vdash e_n : T'_n \end{array}}{O \vdash \text{case } e_0 \text{ of } x_1 : T_1 \rightarrow e_1; \dots; x_n : T_n \rightarrow e_n : \text{lub}(T'_1, \dots, T'_n)}$$

### 4.3.5 Typing methods

In order to check the type of a method call, we need a mechanism similar to type environment  $O$  for variables. In Cool, method type rules are put in namespace  $M$  different from  $O$ , which means that a method and an object can share the same name. A rule

$$M(C, f) = (T_1, \dots, T_n, T_{n+1})$$

means that in class  $C$ , there is a method  $f$  with signature  $f(x_1 : T_1, \dots, x_n : T_n) : T_{n+1}$ . Now we can write the rule of normal dispatch:

$$\frac{\begin{array}{c} O, M \vdash e_0 : T_0 \\ O, M \vdash e_1 : T_1 \\ \dots \\ O, M \vdash e_n : T_n \\ M(T_0, f) = (T'_1, \dots, T'_n, T_{n+1}) \\ T_i \leq T'_i \text{ for } 1 \leq i \leq n \end{array}}{O, M \vdash e_0.f(e_1, \dots, e_n) : T_{n+1}}$$

Similarly, the rule of static dispatch is

$$\begin{array}{c}
 O, M \vdash e_0 : T_0 \\
 O, M \vdash e_1 : T_1 \\
 \dots \\
 O, M \vdash e_n : T_n \\
 M(T, f) = (T'_1, \dots, T'_n, T_{n+1}) \\
 T_0 \leq T \\
 \frac{T_i \leq T'_i \quad \text{for } 1 \leq i \leq n}{O, M \vdash e_0 @ T.f(e_1, \dots, e_n) : T_{n+1}}
 \end{array}$$

For some cases involving `SELF_TYPE`, we need to know the class in which an expression appears. Thus the full type environment of Cool contains 3 parts:

- A mapping  $O$  giving types to object identifiers.
- A mapping  $M$  giving types to methods.
- The current class  $C$ .

The whole environment must be added to all rules, although in most cases  $M$  and  $C$  are passed down but not actually used. For example, the rule for add of int is now

$$\frac{O, M, C \vdash e_1 : \text{Int} \quad O, M, C \vdash e_2 : \text{Int}}{O, M, C \vdash e_1 + e_2 : \text{Int}} \quad (4.2)$$

### 4.3.6 Implementation

Cool type checking can be implemented in a single traversal over the AST. The type environment is passed down the tree from parent to child, while types are passed up the tree from child to parent.

The implementation of a rule is somewhat self-explaining. The addition rule for int (4.2) could be implemented with the following pseudo-code.

```

1 TypeCheck(Environment, e1 + e2) {
2   T1 = TypeCheck(Environment, e1);
3   T2 = TypeCheck(Environment, e2);
4   Check T1 == T2 == Int; // report error if false
5   return Int;
6 }

```

The rule of let expression

$$\frac{
 \begin{array}{c}
 O, M, C \vdash e_0 : T_0 \\
 O[T/x], M, C \vdash e_1 : T_1 \\
 T_0 \leq T
 \end{array}
 }{O, M, C \vdash \text{let } x : T \leftarrow e_0 \text{ in } e_1 : T_1}$$

can be implemented as

```
1 TypeCheck(Environment, let x:T ← e0 in e1) {  
2   TypeCheck(Environment, e0) = T0;  
3   TypeCheck(Environment, e1) = T1;  
4   Check subtype(T0, T); // report error if false  
5   return T1;  
6 }
```