

# Compilers and Formal Languages



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Slides & Progs: KEATS

1 Introduction, Languages	6 While-Language
2 Regular Expressions, Derivatives	7 Compilation, JVM
3 Automata, Regular Languages	8 Compiling Functional Languages
4 Lexing, Tokenising	9 Optimisations
5 Grammars, Parsing	10 LLVM

# Some Housekeeping

- SGT groups 4 + 6 for 10th November
- Ammonite FAQ

# Inject

Injecting (“Adding”) a character to a value

$inj\ (c)\ c\ (Empty)$	$\stackrel{\text{def}}{=} Char\ c$
$inj\ (r_1 + r_2)\ c\ (Left(v))$	$\stackrel{\text{def}}{=} Left(inj\ r_1\ c\ v)$
$inj\ (r_1 + r_2)\ c\ (Right(v))$	$\stackrel{\text{def}}{=} Right(inj\ r_2\ c\ v)$
$inj\ (r_1 \cdot r_2)\ c\ (Seq(v_1, v_2))$	$\stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2)$
$inj\ (r_1 \cdot r_2)\ c\ (Left(Seq(v_1, v_2)))$	$\stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2)$
$inj\ (r_1 \cdot r_2)\ c\ (Right(v))$	$\stackrel{\text{def}}{=} Seq(mkeps(r_1), inj\ r_2\ c\ v)$
$inj\ (r^*)\ c\ (Seq(v, Stars\ vs))$	$\stackrel{\text{def}}{=} Stars\ ((inj\ r\ c\ v) :: vs)$

*inj*: 1st arg  $\mapsto$  a rexp; 2nd arg  $\mapsto$  a character; 3rd arg  $\mapsto$  a value  
result  $\mapsto$  a value























# Parser



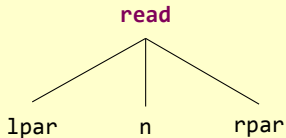
# Parser



parser input: a sequence of tokens

key(**read**) lpar id(n) rpar

parser output: an abstract syntax tree



# What Parsing is Not

Usually parsing does not check semantic correctness, e.g.

- whether a function is not used before it is defined
- whether a function has the correct number of arguments or are of correct type
- whether a variable can be declared twice in a scope



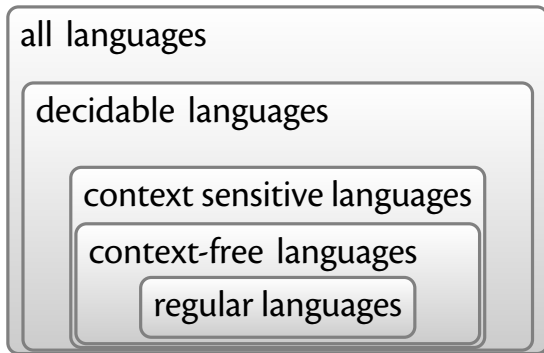
# Regular Languages

While regular expressions are very useful for lexing, there is no regular expression that can recognise the language  $a^n b^n$ .

$((((( ))) ) )$  vs.  $((((( ))) ( )))$

So we cannot find out with regular expressions whether parentheses are matched or unmatched. Also regular expressions are not recursive, e.g.  $(1 + 2) + 3$ .

# Hierarchy of Languages



Time flies like an arrow.  
Fruit flies like bananas.

# CFGs

A **context-free grammar**  $G$  consists of

- a finite set of nonterminal symbols (e.g.  $A$  upper case)
- a finite set terminal symbols or tokens (lower case)
- a start symbol (which must be a nonterminal)
- a set of rules

$$A ::= rhs$$

where  $rhs$  are sequences involving terminals and nonterminals, including the empty sequence  $\epsilon$ .

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where  $rhs$  are sequences involving terminals and nonterminals, including the empty sequence  $\epsilon$ .

We also allow rules

$$A ::= rhs_1 | rhs_2 | \dots$$

# Palindromes

A grammar for palindromes over the alphabet  $\{a, b\}$ :

$$S ::= a \cdot S \cdot a$$

$$S ::= b \cdot S \cdot b$$

$$S ::= a$$

$$S ::= b$$

$$S ::= \epsilon$$

# Palindromes

A grammar for palindromes over the alphabet  $\{a, b\}$ :

$$S ::= a \cdot S \cdot a \mid b \cdot S \cdot b \mid a \mid b \mid \epsilon$$

# Arithmetic Expressions

$$\begin{aligned} E ::= & 0 \mid 1 \mid 2 \mid \dots \mid 9 \\ & \mid E \cdot + \cdot E \\ & \mid E \cdot - \cdot E \\ & \mid E \cdot * \cdot E \\ & \mid ( \cdot E \cdot ) \end{aligned}$$



# Arithmetic Expressions

$$\begin{aligned} E ::= & 0 \mid 1 \mid 2 \mid \dots \mid 9 \\ & \mid E \cdot + \cdot E \\ & \mid E \cdot - \cdot E \\ & \mid E \cdot * \cdot E \\ & \mid ( \cdot E \cdot ) \end{aligned}$$

1 + 2 \* 3 + 4

# A CFG Derivation

1. Begin with a string containing only the start symbol, say  $S$
2. Replace any nonterminal  $X$  in the string by the right-hand side of some production  $X ::= rhs$
3. Repeat 2 until there are no nonterminals left

$$S \rightarrow \dots \rightarrow \dots \rightarrow \dots \rightarrow \dots$$

# Example Derivation

$$S ::= \epsilon \mid a \cdot S \cdot a \mid b \cdot S \cdot b$$

$$\begin{aligned} S &\rightarrow aSa \\ &\rightarrow abSba \\ &\rightarrow abaSaba \\ &\rightarrow abaaba \end{aligned}$$

# Example Derivation

$$\begin{aligned} E ::= & 0 \mid 1 \mid 2 \mid \dots \mid 9 \\ & \mid E \cdot + \cdot E \\ & \mid E \cdot - \cdot E \\ & \mid E \cdot * \cdot E \\ & \mid ( \cdot E \cdot ) \end{aligned}$$

$$\begin{aligned} E &\rightarrow E * E \\ &\rightarrow E + E * E \\ &\rightarrow E + E * E + E \\ &\rightarrow^+ 1 + 2 * 3 + 4 \end{aligned}$$

# Example Derivation

$E ::= 0 \mid 1 \mid 2 \mid \dots \mid 9$

$\mid E \cdot + \cdot E$

$\mid E \cdot - \cdot E$

$\mid E \cdot * \cdot E$

$\mid (\cdot E \cdot)$

$E \rightarrow E * E$

$\rightarrow E + E * E$

$\rightarrow E + E * E + E$

$\rightarrow^+ 1 + 2 * 3 + 4$

$E \rightarrow E + E$

$\rightarrow E + E + E$

$\rightarrow E + E * E + E$

$\rightarrow^+ 1 + 2 * 3 + 4$

# Language of a CFG

Let  $G$  be a context-free grammar with start symbol  $S$ .  
Then the language  $L(G)$  is:

$$\{c_1 \dots c_n \mid \forall i. c_i \in T \wedge S \rightarrow^* c_1 \dots c_n\}$$

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- Terminals, because there are no rules for replacing them.
- Once generated, terminals are “permanent”.
- Terminals ought to be tokens of the language (but can also be strings).

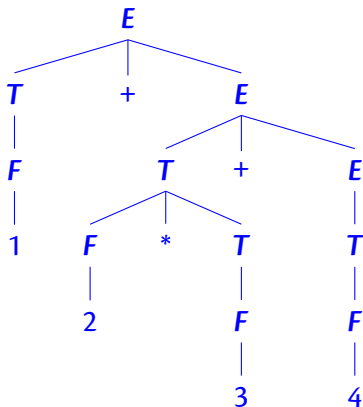
# Parse Trees

$E ::= T \mid T \cdot + \cdot E \mid T \cdot - \cdot E$

$T ::= F \mid F \cdot * \cdot T$

$F ::= 0 \dots 9 \mid (\cdot E \cdot)$

1 + 2 \* 3 + 4





# Arithmetic Expressions

$E ::= 0..9$

|  $E \cdot + \cdot E$

|  $E \cdot - \cdot E$

|  $E \cdot * \cdot E$

|  $(\cdot E \cdot)$

# Arithmetic Expressions

$$\begin{aligned} E &::= 0..9 \\ &| E \cdot + \cdot E \\ &| E \cdot - \cdot E \\ &| E \cdot * \cdot E \\ &| (\cdot E \cdot) \end{aligned}$$

A CFG is **left-recursive** if it has a nonterminal  $E$  such that  $E \rightarrow^+ E \cdot \dots$

# Ambiguous Grammars

A grammar is **ambiguous** if there is a string that has at least two different parse trees.

$E ::= 0...9$

|  $E \cdot + \cdot E$

|  $E \cdot - \cdot E$

|  $E \cdot * \cdot E$

|  $(\cdot E \cdot)$

$1 + 2 * 3 + 4$

# 'Dangling' Else

Another ambiguous grammar:

$$\begin{array}{l} E \rightarrow \text{if } E \text{ then } E \\ \quad | \text{if } E \text{ then } E \text{ else } E \\ \quad | \dots \end{array}$$

if a then if x then y else c

# CYK Algorithm

Suppose the grammar:

$S ::= N \cdot P$

$P ::= V \cdot N$

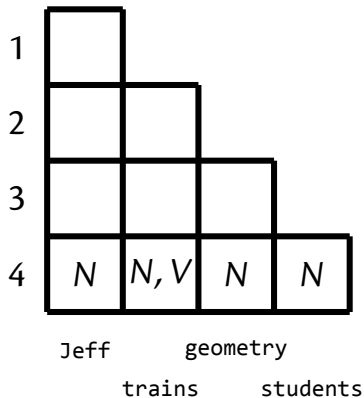
$N ::= N \cdot N$

$N ::= \text{students} \mid \text{Jeff} \mid \text{geometry} \mid \text{trains}$

$V ::= \text{trains}$

Jeff trains geometry students

# CYK Algorithm



$S ::= N \cdot P$   
 $P ::= V \cdot N$   
 $N ::= N \cdot N$   
 $N ::= \text{students} \mid \text{Jeff}$   
 $\quad \quad \mid \text{geometry} \mid \text{trains}$   
 $V ::= \text{trains}$

# Chomsky Normal Form

A grammar for palindromes over the alphabet  $\{a, b\}$ :

$$S ::= a \cdot S \cdot a \mid b \cdot S \cdot b \mid a \cdot a \mid b \cdot b \mid a \mid b$$

# CYK Algorithm

- fastest possible algorithm for recognition problem
- runtime is  $O(n^3)$
- grammars need to be transformed into CNF



*"The C++ grammar is ambiguous, context-dependent and potentially requires infinite lookahead to resolve some ambiguities."*

from the [PhD thesis](#) by Willink (2001)

```
int(x), y, *const z;  
int(x), y, new int;
```

# Context Sensitive Grammars

It is much harder to find out whether a string is parsed by a context sensitive grammar:

$$S ::= bSAA \mid \epsilon$$

$$A ::= a$$

$$bA ::= Ab$$

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$$S \rightarrow \dots \rightarrow^? ababaa$$