

CS 301

Lecture 09 – Context-free grammars

Context-free grammars (CFGs)

Method of generating (or describing) languages by giving rules to derive strings

Rules contain

Terminals symbols from an alphabet (written in typewriter font)

Variables which expand to sequences of terminals and variables (typically upper case letters)

Rules have a variable on the left, an arrow (\rightarrow), and a sequence of terminals and variables on the right

Example:

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Example:

$$S \rightarrow AB$$

$$A \rightarrow aA$$

$$A \rightarrow \varepsilon$$

$$B \rightarrow bB$$

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Example:

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$$B \rightarrow \varepsilon$$

We often combine multiple rules with the same left-hand side using $|$

$$S \rightarrow AB$$

$$A \rightarrow aA \mid \varepsilon$$

$$B \rightarrow bB \mid \varepsilon$$

Deriving strings

A CFG **derives** a string by starting with the start variable (usually the variable on the left in the first rule) and applying rules until no variables remain

The CFG

$$S \rightarrow AB$$

$$A \rightarrow aA \mid \varepsilon$$

$$B \rightarrow bB \mid \varepsilon$$

derives the following strings

$$S \Rightarrow AB \Rightarrow \varepsilon B \Rightarrow \varepsilon\varepsilon = \varepsilon$$

$$S \Rightarrow AB \Rightarrow aAB \Rightarrow a\varepsilon B \Rightarrow a\varepsilon\varepsilon = a$$

$$S \Rightarrow AB \Rightarrow aAB \Rightarrow aaAB \Rightarrow aa\varepsilon B \Rightarrow aabB \Rightarrow aab\varepsilon = aab$$

⋮

Derivations

The order in which we replace a variable in a derivation with the RHS of a production rule doesn't matter¹

In a **left-most derivation**, we replace the left-most variable in each step

In a **right-most derivation**, we replace the right-most variable in each step

¹except in one case we'll get to

Left-most/right-most derivation example

$$S \rightarrow ST \mid aTa$$

$$T \rightarrow S \mid aTa \mid b$$

Left-most derivation of aabaaaba:

$$S \Rightarrow$$

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Left-most/right-most derivation example

$$S \rightarrow ST \mid aTa$$

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Left-most derivation of aabaaaba:

$$\begin{aligned} S &\Rightarrow ST \\ &\Rightarrow aTaT \\ &\Rightarrow aaTaaT \\ &\Rightarrow aabaaT \\ &\Rightarrow aabaaTa \\ &\Rightarrow aabaaaba \end{aligned}$$

Right-most derivation of aabaaaba:

$$\begin{aligned} S &\Rightarrow ST \\ &\Rightarrow SaTa \\ &\Rightarrow Saba \\ &\Rightarrow aTaaba \\ &\Rightarrow aaTaaba \\ &\Rightarrow aabaaaba \end{aligned}$$

Another example

The CFG

$$S \rightarrow aSb \mid \varepsilon$$

derives

$$S \Rightarrow \varepsilon$$

$$S \Rightarrow aSb \Rightarrow ab$$

$$S \Rightarrow aSb \Rightarrow aaSbb \Rightarrow aabb$$

\vdots

$$S \Rightarrow aSb \Rightarrow \dots \Rightarrow a^n S b^n \Rightarrow a^n b^n$$

\vdots

The language of this CFG is $\{a^n b^n \mid n \geq 0\}$

Nested brackets

Given the alphabet $\Sigma = \{ (,), [,] \}$, design a CFG that generates the language of properly nested brackets.

- ε
- $()$
- $[]$
- $([]) [] (())$
- \dots

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- ε
- $()$
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- \dots

$$S \rightarrow P \mid B \mid SS \mid \varepsilon$$

$$P \rightarrow (S)$$

$$B \rightarrow [S]$$

More CFG examples

Let $\Sigma = \{a, b\}$ Construct a CFG for the languages over Σ

- $A = \Sigma^*$
- $B = \{w \mid w \text{ contains at least three } b\}$
- $C = \{w \mid w \text{ starts and ends with different symbols}\}$
- $D = \{w \mid \text{the length of } w \text{ is odd and the middle symbol is } b\}$
- $E = \{w \mid w = w^{\mathcal{R}}\}$
- $F = \emptyset$

Formally speaking

A CFG is a 4-tuple $G = (V, \Sigma, R, S)$ where

- V is a finite set of **variables** (or **nonterminals**)
- Σ is a finite set of **terminals** ($V \cap \Sigma = \emptyset$)
- R is a finite set of **production rules**
- $S \in V$ is the start variable

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If $u, v, w \in (\Sigma \cup V)^*$ and G has a rule $A \rightarrow v$, then we say uAw **yields** uvw and write $uAw \Rightarrow uvw$

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We say u **derives** v , written $u \xRightarrow{*} v$ to mean either $u = v$ or there exist $u_1, u_2, \dots, u_n \in (\Sigma \cup V)^*$ such that

$$u = u_1 \Rightarrow u_2 \Rightarrow \dots \Rightarrow u_n = v$$

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The **language** of G is $L(G) = \{w \mid w \in \Sigma^* \text{ and } S \xRightarrow{*} w\}$

We say G **generates** a language A if $L(G) = A$

Arithmetic expressions

Given the alphabet $\Sigma = \{ (,), 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 \}$, design a CFG that generates the language of arithmetic expressions

- 37
- $8+22-8/6$
- $10*(8-2)$
- ...

An expression can be a number or two expressions separated by an operator or a parenthesized expression

A number is one or more digits

Arithmetic expressions

Given the alphabet $\Sigma = \{ (,), 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 \}$, design a CFG that generates the language of arithmetic expressions

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- $8+22-8/6$
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An expression can be a number or two expressions separated by an operator or a parenthesized expression

A number is one or more digits

$$E \rightarrow N \mid E * E \mid E / E \mid E + E \mid E - E \mid (E)$$

$$N \rightarrow DN \mid D$$

$$D \rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

Parse trees give a way to visualize a derivation

$$E \rightarrow N \mid E * E \mid E / E \mid E + E \mid E - E \mid (E)$$

$$N \rightarrow DN \mid D$$

$$D \rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

Derivation

E

Parse tree

E

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$$E \rightarrow N \mid E * E \mid E / E \mid E + E \mid E - E \mid (E)$$

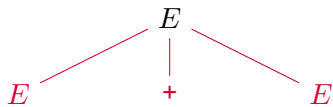
$$N \rightarrow DN \mid D$$

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Derivation

$$E \Rightarrow E + E$$

Parse tree



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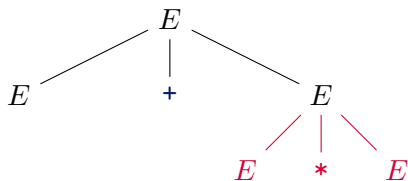
$$D \rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

Derivation

$$E \Rightarrow E + E$$

$$\Rightarrow E + E * E$$

Parse tree



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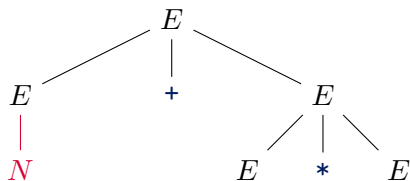
Derivation

$$E \Rightarrow E + E$$

$$\Rightarrow E + E * E$$

$$\Rightarrow N + E * E$$

Parse tree



Parse trees give a way to visualize a derivation

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Derivation

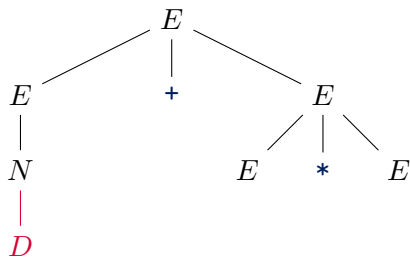
$$E \Rightarrow E + E$$

$$\Rightarrow E + E * E$$

$$\Rightarrow N + E * E$$

$$\Rightarrow D + E * E$$

Parse tree



Parse trees give a way to visualize a derivation

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Derivation

$$E \Rightarrow E + E$$

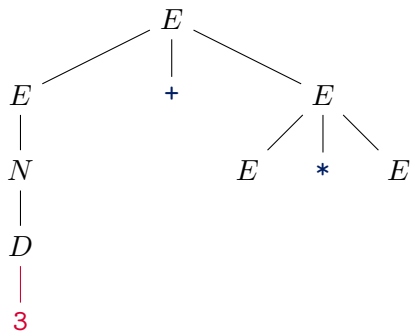
$$\Rightarrow E + E * E$$

$$\Rightarrow N + E * E$$

$$\Rightarrow D + E * E$$

$$\Rightarrow 3 + E * E$$

Parse tree



Parse trees give a way to visualize a derivation

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Derivation

$$E \Rightarrow E + E$$

$$\Rightarrow E + E * E$$

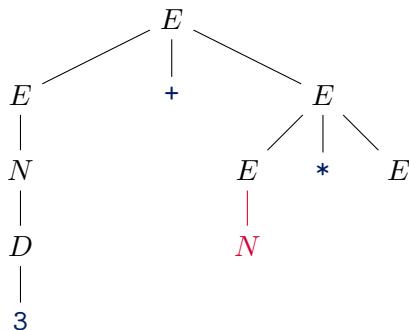
$$\Rightarrow N + E * E$$

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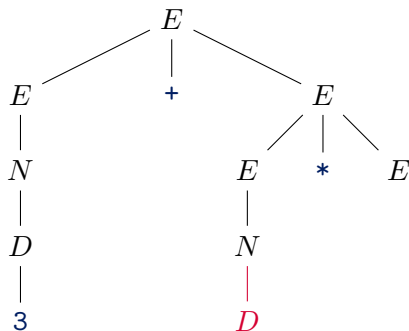
$$\Rightarrow D + E * E$$

$$\Rightarrow 3 + E * E$$

$$\Rightarrow 3 + N * E$$

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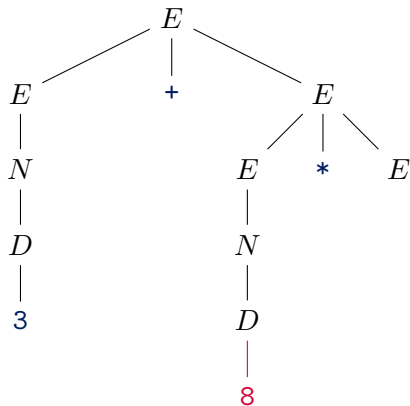
$$\Rightarrow 3 + E * E$$

$$\Rightarrow 3 + N * E$$

$$\Rightarrow 3 + D * E$$

$$\Rightarrow 3 + 8 * E$$

Parse tree



Parse trees give a way to visualize a derivation

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Derivation

$$E \Rightarrow E + E$$

$$\Rightarrow E + E * E$$

$$\Rightarrow N + E * E$$

$$\Rightarrow D + E * E$$

$$\Rightarrow 3 + E * E$$

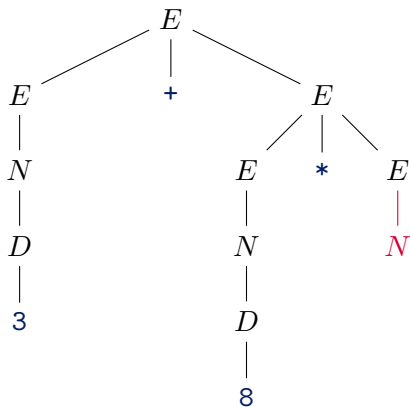
$$\Rightarrow 3 + N * E$$

$$\Rightarrow 3 + D * E$$

$$\Rightarrow 3 + 8 * E$$

$$\Rightarrow 3 + 8 * N$$

Parse tree



Parse trees give a way to visualize a derivation

$$E \rightarrow N \mid E * E \mid E / E \mid E + E \mid E - E \mid (E)$$

$$N \rightarrow DN \mid D$$

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Derivation

$$E \Rightarrow E + E$$

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$$\Rightarrow 3 + E * E$$

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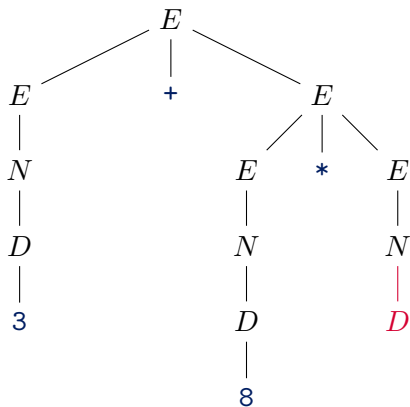
$$\Rightarrow 3 + D * E$$

$$\Rightarrow 3 + 8 * E$$

$$\Rightarrow 3 + 8 * N$$

$$\Rightarrow 3 + 8 * D$$

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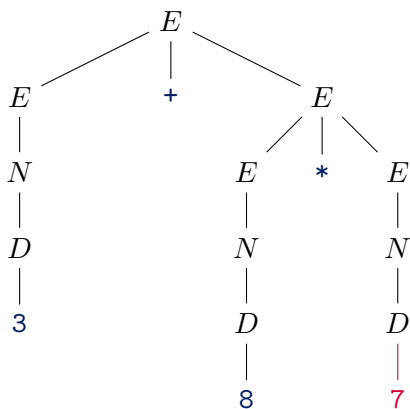
$$N \rightarrow DN \mid D$$

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Derivation

$$\begin{aligned} E &\Rightarrow E + E \\ &\Rightarrow E + E * E \\ &\Rightarrow N + E * E \\ &\Rightarrow D + E * E \\ &\Rightarrow 3 + E * E \\ &\Rightarrow 3 + N * E \\ &\Rightarrow 3 + D * E \\ &\Rightarrow 3 + 8 * E \\ &\Rightarrow 3 + 8 * N \\ &\Rightarrow 3 + 8 * D \\ &\Rightarrow 3 + 8 * 7 \end{aligned}$$

Parse tree



Parse trees give a way to visualize a derivation

$$E \rightarrow N \mid E * E \mid E / E \mid E + E \mid E - E \mid (E)$$

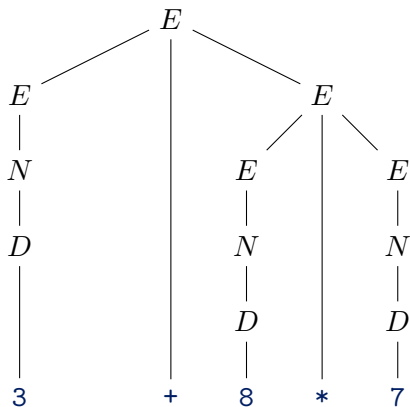
$$N \rightarrow DN \mid D$$

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Derivation

$$\begin{aligned} E &\Rightarrow E + E \\ &\Rightarrow E + E * E \\ &\Rightarrow N + E * E \\ &\Rightarrow D + E * E \\ &\Rightarrow 3 + E * E \\ &\Rightarrow 3 + N * E \\ &\Rightarrow 3 + D * E \\ &\Rightarrow 3 + 8 * E \\ &\Rightarrow 3 + 8 * N \\ &\Rightarrow 3 + 8 * D \\ &\Rightarrow 3 + 8 * 7 \end{aligned}$$

Parse tree



Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

E

E

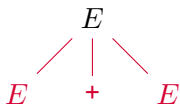
E

E

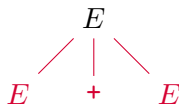
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Two different derivations give the same parse tree

$$E \Rightarrow E+E$$



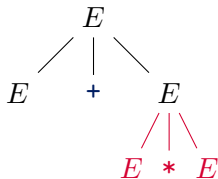
$$E \Rightarrow E+E$$



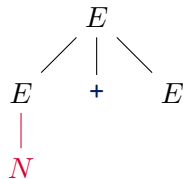
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

$$\begin{aligned} E &\Rightarrow E+E \\ &\Rightarrow E+E*E \end{aligned}$$



$$\begin{aligned} E &\Rightarrow E+E \\ &\Rightarrow N+E \end{aligned}$$



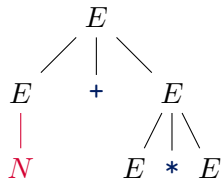
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$$E \Rightarrow E+E$$

$$\Rightarrow E+E * E$$

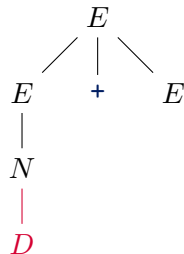
$$\Rightarrow N+E * E$$



$$E \Rightarrow E+E$$

$$\Rightarrow N+E$$

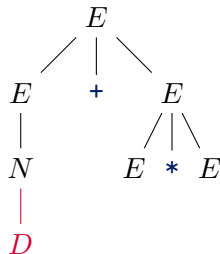
$$\Rightarrow D+E$$



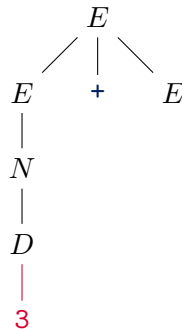
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 $\Rightarrow E+E*E$
 $\Rightarrow N+E*E$
 $\Rightarrow D+E*E$



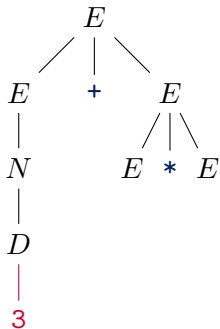
$E \Rightarrow E+E$
 $\Rightarrow N+E$
 $\Rightarrow D+E$
 $\Rightarrow 3+E$



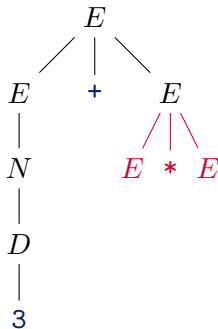
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

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 $\Rightarrow E+E * E$
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 $\Rightarrow D+E * E$
 $\Rightarrow 3+E * E$



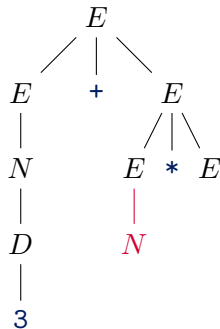
$E \Rightarrow E+E$
 $\Rightarrow N+E$
 $\Rightarrow D+E$
 $\Rightarrow 3+E$
 $\Rightarrow 3+E * E$



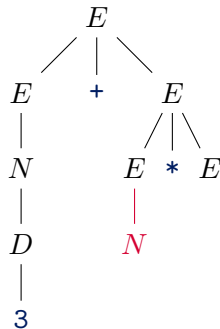
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

$E \Rightarrow E+E$
 $\Rightarrow E+E * E$
 $\Rightarrow N+E * E$
 $\Rightarrow D+E * E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$



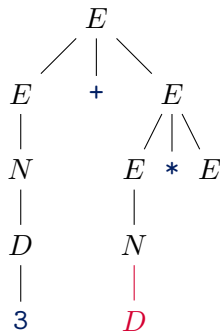
$E \Rightarrow E+E$
 $\Rightarrow N+E$
 $\Rightarrow D+E$
 $\Rightarrow 3+E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$



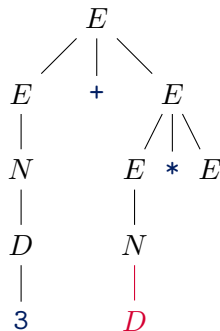
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

$E \Rightarrow E+E$
 $\Rightarrow E+E * E$
 $\Rightarrow N+E * E$
 $\Rightarrow D+E * E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$
 $\Rightarrow 3+D * E$



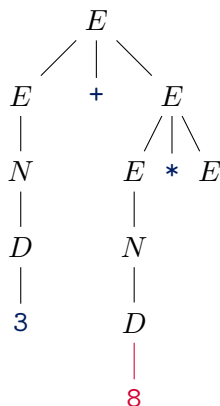
$E \Rightarrow E+E$
 $\Rightarrow N+E$
 $\Rightarrow D+E$
 $\Rightarrow 3+E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$
 $\Rightarrow 3+D * E$



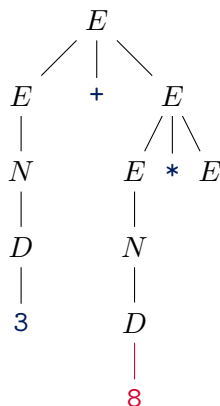
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

$E \Rightarrow E+E$
 $\Rightarrow E+E * E$
 $\Rightarrow N+E * E$
 $\Rightarrow D+E * E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$
 $\Rightarrow 3+D * E$
 $\Rightarrow 3+8 * E$



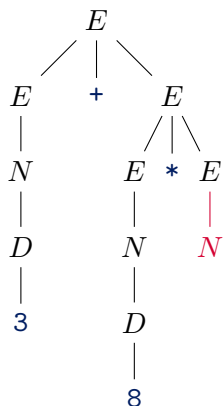
$E \Rightarrow E+E$
 $\Rightarrow N+E$
 $\Rightarrow D+E$
 $\Rightarrow 3+E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$
 $\Rightarrow 3+D * E$
 $\Rightarrow 3+8 * E$



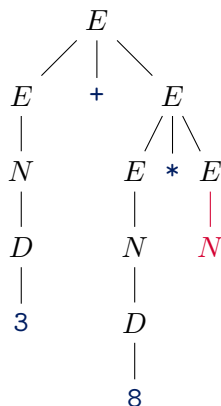
Different derivations can give rise to the same parse tree

Two different derivations give the same parse tree

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 $\Rightarrow 3+D * E$
 $\Rightarrow 3+8 * E$
 $\Rightarrow 3+8 * N$



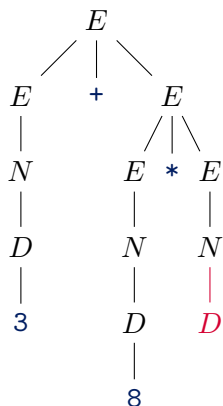
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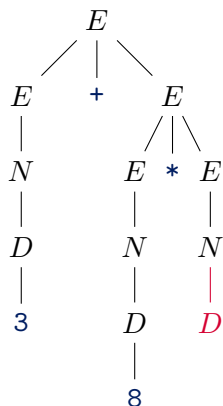
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 $\Rightarrow 3+8 * E$
 $\Rightarrow 3+8 * N$
 $\Rightarrow 3+8 * D$



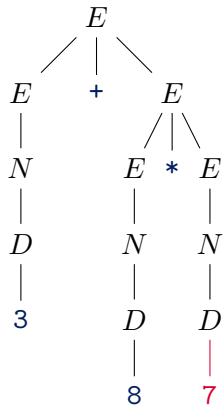
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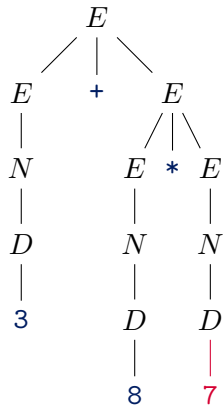
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 $\Rightarrow 3+D * E$
 $\Rightarrow 3+8 * E$
 $\Rightarrow 3+8 * N$
 $\Rightarrow 3+8 * D$
 $\Rightarrow 3+8 * 7$



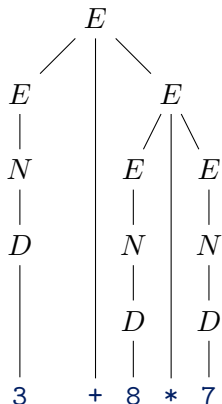
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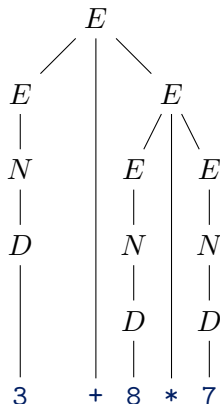
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 $\Rightarrow D+E$
 $\Rightarrow 3+E$
 $\Rightarrow 3+E * E$
 $\Rightarrow 3+N * E$
 $\Rightarrow 3+D * E$
 $\Rightarrow 3+8 * E$
 $\Rightarrow 3+8 * N$
 $\Rightarrow 3+8 * D$
 $\Rightarrow 3+8 * 7$



You can think of the derivations as filling out the tree in different orders

Different derivations can give rise to different parse trees

Two different left-most derivations give rise to different parse trees

$$E \Rightarrow E+E$$

$$\Rightarrow N+E$$

$$\Rightarrow D+E$$

$$\Rightarrow 3+E$$

$$\Rightarrow 3+E*E$$

$$\Rightarrow 3+N*E$$

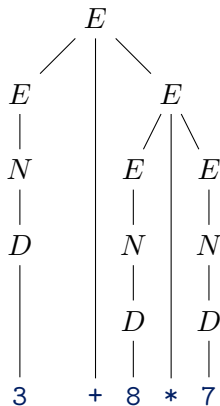
$$\Rightarrow 3+D*E$$

$$\Rightarrow 3+8*E$$

$$\Rightarrow 3+8*N$$

$$\Rightarrow 3+8*D$$

$$\Rightarrow 3+8*7$$



$$E \Rightarrow E*E$$

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$$\Rightarrow N+E*E$$

$$\Rightarrow D+E*E$$

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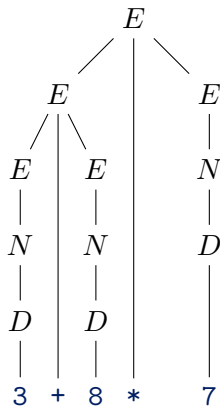
$$\Rightarrow 3+D*E$$

$$\Rightarrow 3+8*E$$

$$\Rightarrow 3+8*N$$

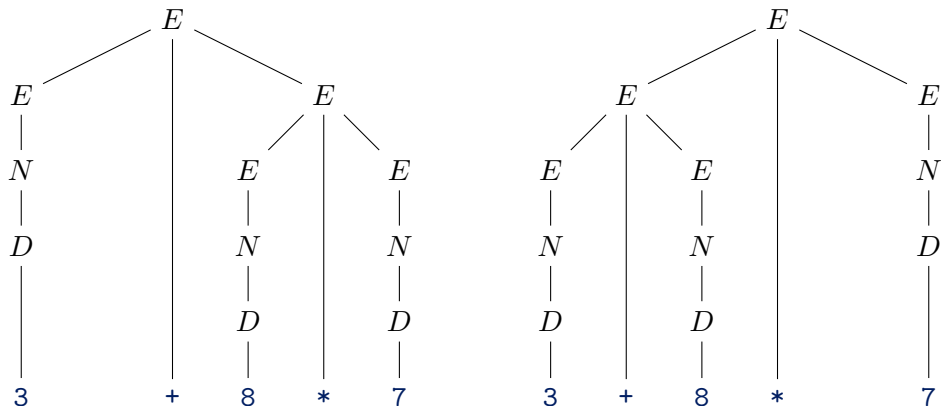
$$\Rightarrow 3+8*D$$

$$\Rightarrow 3+8*7$$



Ambiguity

Our grammar can derive this string in two different ways



This grammar is **ambiguous** because it has two different parse trees for the same string in the language

Imagine a calculator or a compiler parsing this expression
Depending on which parse tree it used, it gets different results

Resolving ambiguity

In some cases, we can redesign the grammar to get rid of ambiguity

Instead of just expressions, let's have expressions (E), terms (T), and factors (F)

$$E \rightarrow E+T \mid E-T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid N$$

$$N \rightarrow DN \mid D$$

$$D \rightarrow 0 \mid 1 \mid \dots \mid 9$$

This CFG has exactly the same language as the previous one but now there's exactly one way to parse $3+8*7$

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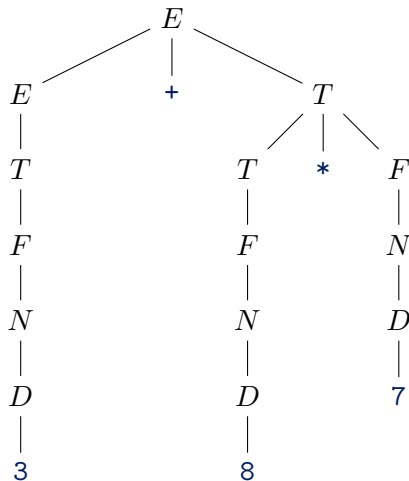
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This CFG has exactly the same language as the previous one but now there's exactly one way to parse $3+8*7$



Ambiguity

Equivalent statements about a CFG G

- 1 G is ambiguous if a word in $L(G)$ has two different parse trees
- 2 G is ambiguous if a word in $L(G)$ has two different left-most derivations
- 3 G is ambiguous if a word in $L(G)$ has two different right-most derivations

It is **not** the case that G is ambiguous if a word merely has two different derivations

Context-free languages

A language A is a **context-free language** (CFL) if there is a CFG G that generates A (i.e., $L(G) = A$)

Theorem

Context-free languages are closed under union, concatenation, and Kleene star.

Union

Proof.

Let $G_1 = (V_1, \Sigma, R_1, S_1)$ generate A and $G_2 = (V_2, \Sigma, R_2, S_2)$ generate B
(assume $V_1 \cap V_2 = \emptyset$, otherwise rename some variables)

Union

Proof.

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(assume $V_1 \cap V_2 = \emptyset$, otherwise rename some variables)

Construct a new CFG $G = (V, \Sigma, R, S)$ to generate $A \cup B$ where

$$V = V_1 \cup V_2 \cup \{S\}$$

$$R = R_1 \cup R_2 \cup \{S \rightarrow S_1 \mid S_2\}$$

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If $w \in A$, then G_1 derives w , $S_1 \xRightarrow{*} w$, and so G derives w via $S \Rightarrow S_1 \xRightarrow{*} w$.

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If $w \in B$, then $S_2 \xRightarrow{*} w$ so $S \Rightarrow S_2 \xRightarrow{*} w$. In either case $w \in L(G)$.

If $w \in L(G)$, then either $S \Rightarrow S_1 \xRightarrow{*} w$ or $S \Rightarrow S_2 \xRightarrow{*} w$. Thus $w \in A \cup B$. □

Concatenation

Proof.

Let $G_1 = (V_1, \Sigma, R_1, S_1)$ generate A and $G_2 = (V_2, \Sigma, R_2, S_2)$ generate B

Concatenation

Proof.

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Construct a new CFG $G = (V, \Sigma, R, S)$ to generate $A \circ B$ where

$$V = V_1 \cup V_2 \cup \{S\}$$

$$R = R_1 \cup R_2 \cup \{S \rightarrow S_1 S_2\}$$

A similar argument shows why $L(G) = A \circ B$



Kleene star

Proof.

Let $G_1 = (V_1, \Sigma, R_1, S_1)$ generate A .

Kleene star

Proof.

Let $G_1 = (V_1, \Sigma, R_1, S_1)$ generate A .

Construct a new CFG $G = (V, \Sigma, R, S)$ to generate A^* where

$$V = V_1 \cup \{S\}$$

$$R = R_1 \cup \{S \rightarrow SS_1 \mid \varepsilon\}$$



Regular languages are context-free

Theorem

Every regular language is context-free.

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Proof.

We can use induction on the structure of regular expressions.

Three base cases

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Three base cases

- \emptyset . $S \rightarrow S$

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Three inductive cases.

- $\underline{R_1 R_2}$
- $\underline{R_1 \mid R_2}$
- $\underline{R_1^*}$

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Three inductive cases.

- $\underline{R_1 R_2}$
- $\underline{R_1 \mid R_2}$
- $\underline{R_1^*}$

By the inductive hypothesis, $L(R_1)$ and $L(R_2)$ are context-free and context-free languages are closed under concatenation, union, and star.



Ambiguity

An **inherently ambiguous** context-free language is one in which every context-free grammar is ambiguous

$\{a^i b^j c^k \mid i = j \text{ or } j = k\}$ is inherently ambiguous