Parsing Beyond Context-Free Grammars: Linear Context-Free Rewriting Systems

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Overview

1. **Basic Ideas**
2. **LCFRS and CL**
3. **LCFRS and MCFG**
4. **LCFRS with Simple RCG syntax**

[Kal10]

Basic Ideas (1)

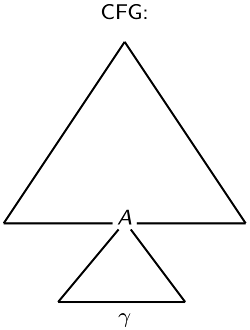
Linear Context-Free Rewriting Systems (LCFRS) can be conceived as a natural extension of CFG:

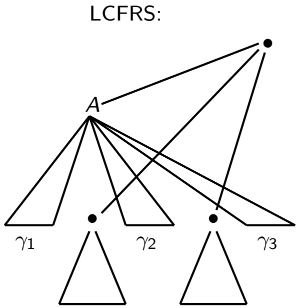
- In a CFG, non-terminal symbols A can span single strings, i.e., the language derivable from A is a subset of T^*.
- Extension to LCFRS: non-terminal symbols A can span tuples of (possibly non-adjacent) strings, i.e., the language derivable from A is a subset of $(T^*)^k$

$\Rightarrow$ LCFRS displays an extended domain of locality

Basic Ideas (2)

Different spans in CFG and LCFRS:





Basic Ideas (3)

Example for a non-terminal with a yield consisting of 2 components:

$$yield(A) = \langle a^n b^n, c^n d^n \rangle, \text{ with } n \geq 1.$$

The rules in an LCFRS describe how to compute an element in the yield of the lefthand-side (lhs) non-terminal from elements in the yields of the right-hand side (rhs) non-terminals.

$$\text{Ex.:} \quad A(ab, cd) \quad \rightarrow \quad \varepsilon \qquad\qquad A(aXb, cYd) \quad \rightarrow \quad A(X, Y)$$

The start symbol S is of dimension 1, i.e., has single strings as yield elements.

$$\text{Ex.: } S(XY) \rightarrow A(X, Y)$$

Language generated by this grammar (yield of S):
$\{a^n b^n c^n d^n \mid n \geq 1\}$.

Basic Ideas (4)

- In a CFG derivation tree (parse tree), dominance is determined by the relations between lhs symbol and rhs symbols of a rule.
- Furthermore, there is a linear order on the terminals and on all rhs of rules.

In an LCFRS, we can also obtain a derivation tree from the rules that have been applied:

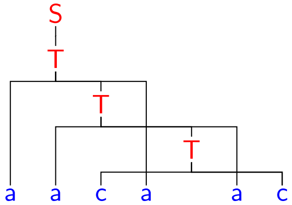
- Dominance is also determined by the relations between lhs symbol and rhs symbols of a rule.
- There is a linear order on the terminals. BUT: there is no linear order on all rhs of rules.
  As a convention, we draw a non-terminal A left of a non-terminal B if the first terminal in the span of A precedes the first terminal in the span of B.

Basic Ideas (5)

Ex.: LCFRS for $\{wcwc \mid w \in \{a, b\}^*\}$:

$$S(XY) \rightarrow T(X, Y) \qquad T(aY, aU) \rightarrow T(Y, U)$$
$$T(bY, bU) \rightarrow T(Y, U) \quad T(c, c) \rightarrow \varepsilon$$

Derivation tree for *aacaac*:



LCFRS and CL (1)

Interest of LCFRS for CL:

1. Applications in CL (parsing, grammar engineering, etc.).
2. Mild context-sensitivity.
3. Equivalence with several important CL formalisms.

LCFRS and CL (2)

Applications in CL

- **Grammar engineering and language modeling**: *Grammatical Framework* is a framework which is equivalent to LCFRS [Lju04]. It is actively used for multilingual grammar development and allows for an easy treatment of discontinuities [Ran11].
- **Grammar engineering and parsing**: In TuLiPA [KMPD10], a multi-formalism parser used in a development environment for variants of Tree Adjoining Grammar (TAG), LCFRS acts as a pivot formalism, i.e., instead of parsing directly with a TAG variant, TuLiPA parses with its equivalent LCFRS, obtained through a suitable grammar transformation [KP08].

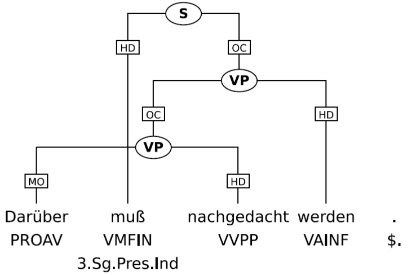
LCFRS and CL (3)

- Modeling of **non-concatenative morphology** [BB13], such as stem derivation in Semitic languages. In such languages, words are derived by combining a discontinuous root with a discontinuous template.
  Ex. (Arabic):

  k i t a b ("book"), k a t i b ("writer"), ma k t a b ("desk")

LCFRS and CL (4)

- **Syntax and data-driven parsing**:
  - Just like phrase structure trees (without crossing branches) can be described with CFG rules, trees with crossing branches can be described with LCFRS rules.
  - Trees with crossing branches allow to describe discontinuous constituents, as for example in the Negra and Tiger treebanks.

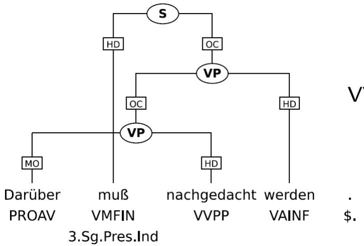


LCFRS and CL (4)

Trees with crossing branches can be interpreted as LCFRS derivation trees.

$\Rightarrow$ an LCFRS can be straight-forwardly extracted from such treebanks.

This makes LCFRS particularly interesting for data-driven parsing.



$$
\begin{array}{rcl}
\text{PROAV(Darüber)} & \to & \varepsilon \\
\text{VMFIN(muß)} & \to & \varepsilon \\
\text{VVPP(nachgedacht)} & \to & \varepsilon \\
\text{VAINF(werden)} & \to & \varepsilon \\
\text{S}(X_1 X_2 X_3) & \to & \text{VP}(X_1, X_3)\ \text{VMFIN}(X_2) \\
\text{VP}(X_1, X_2 X_3) & \to & \text{VP}(X_1, X_2)\ \text{VAINF}(X_3) \\
\text{VP}(X_1, X_2) & \to & \text{PROAV}(X_1)\ \text{VVPP}(X_2)
\end{array}
$$

LCFRS has been successfully used for data-driven probabilistic syntactic parsing [KM13, vC12, AL14].

LCFRS and CL (5)

- **Machine translation**: Synchronous LCFRS have been used for the modeling of translational equivalence [Kae15]. They can model certain alignment configurations that cannot be modeled with synchronous CFGs [Kae13].

(1) je ne veux plus jouer
I do not want to play anymore

$$\langle X(jouer) \to \varepsilon, X(to\ play) \to \varepsilon \rangle$$
$$\langle X(veux) \to \varepsilon, X(do, want) \to \varepsilon \rangle$$
$$\langle X(ne\ x_1\ plus\ x_2) \to X_{\boxed{1}}(x_1) X_{\boxed{2}}(x_2),$$
$$X(x_1\ not\ x_2 x_3\ anymore) \to X_{\boxed{1}}(x_1, x_2) X_{\boxed{2}}(x_3) \rangle$$

...

LCFRS and CL (6)

Mild Context-Sensitivity:

- Natural languages are not context-free.
- Question: How complex are natural languages? In other words, what are the properties that a grammar formalism for natural languages should have?
- Goal: extend CFG only as far as necessary to deal with natural languages in order to capture the complexity of natural languages.

This effort has lead to the definition of *mild context-sensitivity* (Aravind Joshi).

LCFRS and CL (7)

A formalism is mildly context-sensitive if the following holds:

1. It generates at least all context-free languages.
2. It can describe a limited amount of crossing dependencies.
3. Its string languages are polynomial.
4. Its string languages are of constant growth.

LCFRS and CL (8)

- LCFRS are mildly context-sensitive.
- We do not have any other formalism that is also mildly context-sensitive and whose set of string languages properly contains the string languages of LCFRS.
- Therefore, LCFRS are often taken to provide a grammar-formalism-based characterization of mild context-sensitivity.

BUT: There are polynomial languages of constant growth that cannot be generated by LCFRS.

LCFRS and CL (8)

Equivalence with CL formalisms:
LCFRS are weakly equivalent to

- *set-local Multicomponent Tree Adjoining Grammar*, an extension of TAG that has been motivated by linguistic considerations;
- *Minimalist Grammar*, a formalism that was developed in order to provide a formalization of a GB-style grammar with transformational operations such as movement;
- *finite-copying Lexical Functional Grammar*, a version of LFG where the number of nodes in the c-structure that a single f-structure can be related with is limited by a grammar constant.

LCFRS and MCFG (1)

- *Multiple Context-Free Grammars (MCFG)* have been introduced by [SMFK91] while the equivalent *Linear Context-Free Rewriting Systems (LCFRS)* were independently proposed by [VSWJ87].
- The central idea is to extend CFGs such that non-terminal symbols can span a tuple of strings that need not be adjacent in the input string.
- The grammar contains productions of the form $A_0 \to f[A_1, \dots, A_q]$ where $A_0, \dots, A_q$ are non-terminals and f is a function describing how to compute the yield of A_0 (a string tuple) from the yields of $A_1, \dots, A_q$.
- The definition of LCFRS is slightly more restrictive than the one of MCFG. However, [SMFK91] have shown that the two formalisms are equivalent.

LCFRS and MCFG (2)

Example: MCFG/LCFRS for the double copy language.

Rewriting rules:

$S \to f_1[A] \qquad A \to f_2[A] \qquad A \to f_3[A] \qquad A \to f_4[\,] \qquad A \to f_5[\,]$

Operations:

$f_1[\langle X, Y, Z\rangle] = \langle XYZ\rangle \qquad f_4[\,] = \langle a, a, a\rangle$

$f_2[\langle X, Y, Z\rangle] = \langle aX, aY, aZ\rangle \qquad f_5[\,] = \langle b, b, b\rangle$

$f_3[\langle X, Y, Z\rangle] = \langle bX, bY, bZ\rangle$

LCFRS and MCFG (3)

Definition 1 (Multiple Context-Free Grammar)

A *multiple context-free grammar (MCFG)* is a 5-tuple $\langle N, T, F, P, S\rangle$ where

- N is a finite set of non-terminals, each $A \in N$ has a *fan-out* $dim(A) \geq 1, dim(A) \in \mathbb{N}$;
- T is a finite set of terminals;
- F is a finite set of mcf-functions;
- P is a finite set of rules of the form $A_0 \rightarrow f[A_1, \dots, A_k]$ with $k \geq 0, f \in F$ such that $f : (T^*)^{dim(A_1)} \times \cdots \times (T^*)^{dim(A_k)} \rightarrow (T^*)^{dim(A_0)}$;
- $S \in N$ is the start symbol with $dim(S) = 1$.

A MCFG with maximal non-terminal fan-out k is called a k-MCFG.

LCFRS and MCFG (4)

Mcf-functions are such that

- each component of the value of f is a concatenation of some constant strings and some components of its arguments.
- Furthermore, each component of the right-hand side arguments of a rule is not allowed to appear in the value of f more than once.

LCFRS and MCFG (5)

Definition 2 (mcf-function)

f is an mcf-function if there is a $k \geq 0$ and there are $d_i > 0$ for $0 \leq i \leq k$ such that f is a total function from $(T^*)^{d_1} \times \dots \times (T^*)^{d_k}$ to $(T^*)^{d_0}$ such that

- the components of $f(\vec{x_1}, \dots, \vec{x_k})$ are concatenations of a limited amount of terminal symbols and the components x_{ij} of the $\vec{x_i}$ $(1 \leq i \leq k, 1 \leq j \leq d_i)$, and
- the components x_{ij} of the $\vec{x_i}$ are used at most once in the components of $f(\vec{x_1}, \dots, \vec{x_k})$.

A LCFRS is a MCFG where the mcf-functions f are such that the the components x_{ij} of the $\vec{x_i}$ are used exactly once in the components of $f(\vec{x_1}, \dots, \vec{x_k})$.

LCFRS and MCFG (6)

- We can understand a MCFG as a generative device that specifies the yields of the non-terminals.
- The language of a MCFG is then the yield of the start symbol S.

Ex.: LCFRS for the double copy language.
$yield(A) = \{\langle w, w, w\rangle \mid w \in \{a, b\}^*\}$
$yield(S) = \{\langle www\rangle \mid w \in \{a, b\}^*\}$

LCFRS and MCFG (7)

Definition 3 (String Language of an MCFG/LCFRS)

Let $G = \langle N, T, F, P, S \rangle$ be a MCFG/LCFRS.

1. For every $A \in N$:
   - For every $A \to f[\,] \in P$, $f(\,) \in \mathit{yield}(A)$.
   - For every $A \to f[A_1, \dots, A_k] \in P$ with $k \geq 1$ and all tuples $\tau_1 \in \mathit{yield}(A_1), \dots, \tau_k \in \mathit{yield}(A_k)$, $f(\tau_1, \dots, \tau_k) \in \mathit{yield}(A)$.
   - Nothing else is in $\mathit{yield}(A)$.
2. The string language of G is $L(G) = \{w \mid \langle w \rangle \in \mathit{yield}(S)\}$.

LCFRS with Simple RCG syntax (1)

- *Range Concatentation Grammars (RCG)* and the restricted *simple RCG* have been introduced in [Bou00].
- Simple RCG are not only equivalent to MCFG and LCFRS but also represent a useful syntactic variant.

Example: Simple RCG for the double copy language.

$$
\begin{array}{l}
S(XYZ) \rightarrow A(X, Y, Z) \\
A(aX, aY, aZ) \rightarrow A(X, Y, Z) \\
A(bX, bY, bZ) \rightarrow A(X, Y, Z) \\
A(a, a, a) \rightarrow \varepsilon \\
A(b, b, b) \rightarrow \varepsilon
\end{array}
$$

LCFRS with Simple RCG syntax (2)

We redefine LCFRS with the simple RCG syntax:

Definition 4 (LCFRS)

A *LCFRS* is a tuple $G = (N, T, V, P, S)$ where

1. N, T and V are disjoint alphabets of non-terminals, terminals and variables resp. with a fan-out function *dim*: $N \to \mathbb{N}$. $S \in N$ is the start predicate; $dim(S) = 1$.
2. P is a finite set of rewriting rules of the form

$$A_0(\vec{\alpha_0}) \to A_1(\vec{x_1}) \cdots A_m(\vec{x_m})$$

with $m \geq 0$, $\vec{\alpha_0} \in [(T \cup V)^*]^{dim(A_0)}$, $\vec{x_i} \in V^{dim(A_i)}$ for $1 \leq i \leq m$ and it holds that every variable $X \in V$ occurring in the rule occurs exactly once in the left-hand side and exactly once in the right-hand side.

LCFRS with Simple RCG syntax (3)

In order to apply a rule, we have to map variables to strings of terminals:

Definition 5 (LCFRS rule instantiation)

Let $G = \langle N, T, V, S, P \rangle$ be a LCFRS.
For a rule $c = A(\vec{\alpha}) \to A_1(\vec{\alpha_1}) \dots A_m(\vec{\alpha_m}) \in P$, every function $f : \{x \mid x \in V, x \text{ occurs in } c\} \to T^*$ is an *instantiation* of c.
We call $A(f(\vec{\alpha})) \to A_1(f(\vec{\alpha_1})) \dots A_m(f(\vec{\alpha_m}))$ then an *instantiated clause* where f is extended as follows:

1. $f(\varepsilon) = \varepsilon$;
2. $f(t) = t$ for all $t \in T$;
3. $f(xy) = f(x)f(y)$ for all $x, y \in (T \cup V)^*$;
4. $f(\langle \alpha_1, \dots, \alpha_m \rangle) = (\langle f(\alpha_1), \dots, f(\alpha_m) \rangle)$ for all $(\langle \alpha_1, \dots, \alpha_m \rangle) \in [(T \cup V)^*]^m$, $m \geq 1$.

LCFRS with Simple RCG syntax (4)

Definition 6 (LCFRS string language)

Let $G = \langle N, T, V, S, P \rangle$ be a LCFRS.

1. The set $L_{pred}(G)$ of instantiated predicates $A(\vec{\tau})$ where $A \in N$ and $\vec{\tau} \in (T^*)^k$ for some $k \geq 1$ is defined by the following deduction rules:

   a) $\dfrac{}{A(\vec{\tau})}$ $A(\vec{\tau}) \rightarrow \varepsilon$ is an instantiated clause

   b) $\dfrac{A_1(\vec{\tau_1}) \dots A_m(\vec{\tau_m})}{A(\vec{\tau})}$ $A(\vec{\tau}) \rightarrow A_1(\vec{\tau_1}) \dots A_m(\vec{\tau_m})$ is an instantiated clause

2. The string language of G is

$$\{w \in T^* \mid S(w) \in L_{pred}(G)\}.$$

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