Normal Forms of Type-0, Type-1, and Type-2 Grammars

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Chomsky Normal Form of Type-2 Grammars

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A type-2 grammar $G = (N, T, P, S)$ is in Chomsky normal form if every production $p \in P$ has one of these forms:

1. $A \rightarrow BC$
2. $A \rightarrow a$

where $A, B, C \in N$ and $a \in T$.

Theorem

For every type-2 grammar $G = (N, T, P, S)$, there is an equivalent type-2 grammar $H = (M, T, R, S)$ in Chomsky normal form.

Greibach Normal Form of Type-2 Grammars

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A type-2 grammar $G = (N, T, P, S)$ is in Greibach normal form if every production $p \in P$ satisfies

$$A \to aB_1 \dots B_n$$

where $A \in N$, $a \in T$, and $B_1, \dots, B_n \in N$ for some $n \geq 0$.

Two-Standard Greibach Normal Form

Greibach normal form is in two-standard form if $n \leq 2$.

Theorem

For every type-2 grammar $G = (N, T, P, S)$, there is an equivalent type-2 grammar $H = (M, T, R, S)$ in two-standard Greibach normal form.

Kuroda Normal Form of Type-0 Grammars

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A type-0 grammar $G = (N, T, P, S)$ is in Kuroda normal form if every production $p \in P$ has one of these forms:

1. $AB \rightarrow CD$
2. $A \rightarrow BC$
3. $A \rightarrow a$
4. $A \rightarrow \varepsilon$

where $A, B, C, D \in N$ and $a \in T$.

Theorem

For every type-0 grammar $G = (N, T, P, S)$, there is an equivalent type-0 grammar $H = (M, T, R, S)$ in Kuroda normal form.

Kuroda Normal Form Proof I

Let $G = (N, T, P, S)$ be a type-0 grammar. Transform G to $H = (M, T, R, S)$ in Kuroda normal form as follows:

0
- $M := N$
- If $p \in P$ satisfies Kuroda normal form, move p from P to R

1
- In every $p \in P$, replace each $a \in T$ with nonterminal a'
- Move every production that satisfies Kuroda normal form from P to R
- Add $a' \rightarrow a$ to R and a' to M

2
- In P, replace every

  $$A_1 \dots A_m \rightarrow B_1 \dots B_n$$

  where $n < m$ with

  $$A_1 \dots A_m \rightarrow B_1 \dots B_n C \dots C,$$

  where C is a new nonterminal and $|C \dots C| = m - n$
- Add C to M
- Add $C \rightarrow \varepsilon$ to R
- Move every production that satisfies Kuroda normal form from P to R $(A_1 A_2 \rightarrow B_1 C)$

Kuroda Normal Form Proof II

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- In P, replace $A \rightarrow B$ with

$$A \rightarrow BC \text{ and } C \rightarrow \varepsilon,$$

  where C is a new symbol
- Move $A \rightarrow BC$, $C \rightarrow \varepsilon$ to R
- Add C to M

4

- If $A \rightarrow B_1 \dots B_n \in P$ with $3 \leq n$, add

$$\begin{aligned} A &\rightarrow B_1\langle B_2 \dots B_n\rangle \\ \langle B_2 \dots B_n\rangle &\rightarrow B_2\langle B_3 \dots B_n\rangle \\ &\vdots \\ \langle B_{n-2} \dots B_n\rangle &\rightarrow B_{n-2}\langle B_{n-1}B_n\rangle \\ \langle B_{n-1}B_n\rangle &\rightarrow B_{n-1}B_n \end{aligned}$$

  to R
- Add $\langle B_2 \dots B_n\rangle, \dots, \langle B_{n-1}B_n\rangle$ to M
- Remove $A \rightarrow B_1 \dots B_n$ from P

Kuroda Normal Form Proof III

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- For every
$$A_1 \dots A_m \to B_1 \dots B_n \in P$$
with $2 \leq m$ and $3 \leq n$ (observe that $m \leq n$), add
$$A_1 A_2 \to B_1 C \text{ to } R$$
and C to M (C is a new symbol)
- If $|B_2 \dots B_n| \leq 2$, then the rule is in the form
$$CA_3 \to B_2 \dots B_n \text{ or } C \to B_2 \dots B_n,$$
so we can add it to R.
Otherwise, add
$$CA_3 \dots A_m \to B_2 \dots B_n \text{ to } P$$
- Remove $A_1 \dots A_m \to B_1 \dots B_n$ from P
- Repeat 5 or 4 until $P = \emptyset$

Kuroda Normal Form of Type-1 Grammars

Theorem

For every type-1 grammar G, there is an equivalent type-1 grammar H in Kuroda normal form; that is, H has every production in one of these forms:

1. $AB \rightarrow CD$
2. $A \rightarrow BC$
3. $A \rightarrow a$

where $A, B, C, D \in N$ and $a \in T$.

Penttonen Normal Form

Theorem

For every type-0 grammar G, there is an equivalent type-0 grammar H in Penttonen normal form; that is, H is in Kuroda normal form and, in addition, every production $AB \to CD$ satisfies $A = C$.

Theorem

For every type-1 grammar G, there is an equivalent type-1 grammar H in Penttonen normal form; that is, H is in Kuroda normal form and, in addition, every production $AB \to CD$ satisfies $A = C$.

First Geffert Normal Form for Type-0 Grammars

First Geffert Normal Form for Type-0 Grammars

A type-0 grammar

$$G = (\{S, A, B, C\}, T, P \cup \{ABC \to \varepsilon\}, S)$$

is in the first Geffert normal form if every production $p \in P$ has one of these forms:

1. $S \to uSa$,
2. $S \to uSv$,
3. $S \to uv$,

where $u \in \{A, AB\}^*$, $a \in T$, and $v \in \{BC, C\}^*$.

Theorem

For every type-0 grammar $G = (N, T, P, S)$, there is an equivalent type-0 grammar H in the first Geffert normal form.

Second Geffert Normal Form for Type-0 Grammars

Second Geffert Normal Form for Type-0 Grammars

A type-0 grammar

$$G = (\{S, A, B, C, D\}, T, P \cup \{AB \to \varepsilon, CD \to \varepsilon\}, S)$$

is in the second Geffert normal form if every production $p \in P$ has one of these forms:

1. $S \to uSa$,
2. $S \to uSv$,
3. $S \to uv$,

where $u \in \{A, C\}^*$, $a \in T$, and $v \in \{B, D\}^*$.

Theorem

For every type-0 grammar $G = (N, T, P, S)$, there is an equivalent type-0 grammar H in the second Geffert normal form.

Third Geffert Normal Form for Type-0 Grammars

Third Geffert Normal Form for Type-0 Grammars

A type-0 grammar

$$G = (\{S, A, B\}, T, P \cup \{ABBBA \rightarrow \varepsilon\}, S)$$

is in the third Geffert normal form if every production $p \in P$ has one of these forms:

1. $S \rightarrow uSa$,
2. $S \rightarrow uSv$,
3. $S \rightarrow uv$,

where $u \in \{AB, ABB\}^*$, $a \in T$, and $v \in \{BBA, BA\}^*$.

Theorem

For every type-0 grammar $G = (N, T, P, S)$, there is an equivalent type-0 grammar H in the third Geffert normal form.

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