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FORMAL GRAMMARS AND THEIR APPLICATION TO TURKIC LANGUAGES

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Annotatsiya. Maqolada formal grammatikalar, ularning nazariy asoslari, tabiiy tillarni qayta ishlash tizimlaridagi ahamiyati va turkiy tillarga, xususan, o‘zbek tiliga qo‘llanilish xususiyatlari tahlil qilingan. Xomskiy iyerarxiyasi asosida regulyar, kontekstga bog‘liq va bog‘liq bo‘lmagan grammatik modellarning imkoniyatlari ko‘rib chiqilgan. Turkiy tillarning agglyutinativ xususiyati sababli morfologik va sintaktik tahlil jarayonlarida yuzaga keluvchi murakkabliklar yoritilgan. Shuningdek, Finite-State Transducer, Dependency Grammar va Transformer asosidagi gibrid modellarning afzalliklari tahlil qilingan.

Kalit so‘zlar. Xomskiy iyerarxiyasi, formal grammatika, turkiy tillar, agglyutinatsiya, NLP, morfologik tahlil, sintaktik parsing, Dependency Grammar, Transformer.

Аннотация. В данной статье анализируются теоретические основы формальных грамматик, их значение в системах обработки естественного языка, а также особенности их применения к тюркским языкам, в частности к узбекскому языку. На основе иерархии Хомского рассматриваются возможности регулярных, контекстно-свободных и контекстно-зависимых грамматик. В исследовании освещаются сложности морфологического и синтаксического анализа, возникающие вследствие агглютинативной природы тюркских языков. Кроме того, анализируются преимущества гибридных моделей, основанных на конечных автоматах с преобразованием состояний (Finite-State Transducers), грамматиках зависимостей и архитектурах Transformer. Результаты исследования показывают, что интеграция формальных грамматик с нейронными сетями позволяет создавать высокоэффективные NLP-системы для тюркских языков.

Ключевые слова: иерархия Хомского, формальная грамматика, тюркские языки, агглютинация, NLP, морфологический анализ, синтаксический парсинг, грамматика зависимостей, Transformer.

Abstract. This article analyzes the theoretical foundations of formal grammars, their importance in natural language processing systems, and their application to Turkic languages, particularly Uzbek. Based on Chomsky’s hierarchy, the capabilities of regular, context-free, and context-sensitive grammars are examined. The study highlights the complexities arising in morphological and syntactic

analysis due to the agglutinative nature of Turkic languages. Furthermore, the advantages of hybrid models based on Finite-State Transducers, Dependency Grammar, and Transformer architectures are discussed. The results demonstrate that integrating formal grammars with neural networks enables the development of highly efficient NLP systems for Turkic languages.

Keywords: Chomsky hierarchy, formal grammar, Turkic languages, agglutination, NLP, morphological analysis, syntactic parsing, Dependency Grammar, Transformer.

INTRODUCTION.

In recent years, the rapid development of Artificial Intelligence (AI) and Natural Language Processing (NLP) technologies has significantly increased the global demand for computational modeling of national languages. In particular, the formal modeling of Turkic languages, which belong to the agglutinative language family, has become increasingly important for improving the accuracy and efficiency of NLP systems.

Formal grammars represent a powerful theoretical framework that enables the mathematical and algorithmic modeling of linguistic units. These grammars are widely applied in tasks such as morphological analysis, syntactic parsing, machine translation, text generation, and semantic analysis.

Formal grammars constitute one of the major theoretical foundations for computational processing of Turkic languages. Especially in agglutinative languages such as Uzbek, formal grammatical models play a crucial role in automating morphological and syntactic analysis processes.

Although comprehensive grammatical models have been developed for many inflectional languages in technologically advanced countries, research related to Turkic languages remains insufficient. This situation necessitates the development of new scientific approaches in this field.

LITERATURE REVIEW.

Reference [1] is considered one of the fundamental sources in the theory of formal grammars. The Chomsky hierarchy proposed by the author constitutes the theoretical basis of modern computational linguistics and NLP systems. The study extensively explains the importance of context-free grammars in syntactic modeling.

Reference [2] is one of the most modern and comprehensive sources in the field of NLP. It provides detailed analyses of morphological analysis, syntactic parsing, Transformer architecture, and large language models. Particular attention is devoted to the integration of formal grammars with neural networks.

Reference [3] introduced the Transformer architecture for the first time. The implementation of the attention mechanism caused revolutionary changes in NLP

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research. This approach is particularly important for identifying long-distance syntactic dependencies in Turkic languages.

In Reference [4], the authors proposed the BERT model, which enables deep contextual understanding through a bidirectional Transformer architecture. The paper presents advanced methods for semantic analysis and language modeling.

Reference [5] comprehensively analyzes neural network theory and practical methods for NLP. The study demonstrates the effectiveness of deep learning technologies for morphological and syntactic analysis.

Reference [6] is devoted to dependency parsing theory and scientifically substantiates the advantages of dependency grammar models for Turkic languages characterized by relatively free word order.

Reference [7] discusses the theoretical and practical foundations of Finite-State Transducer (FST) technologies and demonstrates their high efficiency in morphological analysis of Turkic languages.

Reference [8] is regarded as one of the fundamental sources on statistical NLP methods. It extensively covers language modeling, syntactic analysis, and probabilistic grammatical models.

Reference [9] specifically focuses on NLP technologies for Turkic languages and analyzes the application of formal and neural models for agglutinative languages.

Reference [10] presents computational approaches to morphological modeling. It provides important theoretical foundations for analyzing affixation systems and morpheme structures in Turkic languages.

Reference [11] investigates parsing algorithms for morphologically rich languages and discusses syntactic modeling challenges in Turkic languages.

Reference [12] analyzes the Universal Dependencies standard and its significance for multilingual NLP systems. The study also highlights the possibilities of integrating Turkic languages into universal parsing frameworks.

Reference [13] covers modern approaches in computational linguistics and NLP, with particular emphasis on the integration of formal grammars and neural models.

Reference [14] analyzes the internal architecture and operational mechanisms of the BERT model. Furthermore, the concepts of semantic representation and contextual embedding are comprehensively explained.

Reference [15] investigates the relationship between language modeling and linguistic structure and substantiates the importance of formal grammatical rules in NLP systems.

RESEARCH METHODOLOGY.

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A formal grammar can be defined as a mathematical system of rules used to generate correct linguistic constructions within a language.

The theory of formal grammars was mainly developed by Noam Chomsky, who classified grammars into four major categories:

- Regular grammars (RG);
- Context-free grammars (CFG);
- Context-sensitive grammars (CSG);
- Unrestricted grammars (UR).

The Chomsky hierarchy expresses the relationship among these grammar types in the above order:

$$RG \subset CFG \subset CSG \subset UR$$

Regular grammars are mainly applied in morphological analysis. For example, finite-state automata models are used to automatically generate Uzbek word forms such as "*kitob*", "*kitoblar*", "*kitoblarimiz*", and "*kitoblarimizdan*".

Context-free grammars play an important role in syntactic structure analysis. The following rules formally represent sentence structures:

Rule 1: A sentence consists of a noun phrase and a verb phrase (where S – sentence, NP – noun phrase, VP – verb phrase):

$$S \rightarrow NP + VP.$$

Rule 2: A noun phrase consists of an adjective and a noun (where Adj – adjective, N – noun):

$$NP \rightarrow Adj + N.$$

Rule 3: A verb phrase consists of a verb and a noun phrase (where V – verb):

$$VP \rightarrow V + NP.$$

In general, each type of formal grammar has its own advantages and disadvantages depending on its field of application (Table 1).

Table 1

Comparative Analysis of Formal Grammars

Grammar Type	Application Area	Advantage	Limitation
Regular Grammar	Morphology	High speed	Limited structure
CFG	Syntax	Simple parsing	Difficult for free word order
CSG	Semantic structure	Strong expressiness	Computationally expensive
Hybrid grammar	NLP	High accuracy	Requires significant resources

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Turkic languages belong to the agglutinative language family, where word forms are generated through numerous affixes. This feature causes several challenges:

- high variability of word forms;
- complex sequential attachment of morphemes;
- syntactic flexibility and free word order;
- importance of semantic context;
- variability of pragmatic emphasis.

Therefore, traditional CFG models do not always provide high efficiency for Turkic languages.

When discussing the application of formal grammars to Turkic languages, primary attention is paid to morphological analysis and syntactic parsing. In particular, Finite-State Transducer (FST) models are considered one of the most effective tools for morphological analysis in Turkic languages. For example, in the word "*kitob+lar+imiz+dan*", each morpheme is analyzed as a separate state within the automaton.

Dependency Grammar and Context-Free Grammar models are widely used for syntactic parsing and sentence structure analysis. For example, in the sentence "Talaba kitobni o'qidi", "talaba" functions as the subject, "kitobni" as the object, and "o'qidi" as the predicate. The relatively free word order in Turkic languages increases the importance of dependency parsing models.

Modern NLP systems effectively employ hybrid approaches such as "CFG + Transformer", "FST + Neural Network", "Dependency Parser + Attention", and "Morphological Analyzer + BERT". These models help reduce syntactic and semantic ambiguities (Table 2).

Table 2

NLP Challenges in Turkic Languages

Problem	Cause	Solution
Large number of word forms	Agglutination	FST
Free word order	Syntactic variability	Dependency Parser
Semantic ambiguity	Context	Transformer
Morpheme combinations	Affix chains	Hybrid model

Modern NLP systems are organized around multiple interconnected linguistic and algorithmic modules. The agglutinative nature of Turkic languages requires NLP architectures to be designed in a multilayered and hierarchical manner because morphological variation, syntactic flexibility, and semantic context are strongly interconnected.

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From this perspective, the use of UML (Unified Modeling Language) technologies plays an important role in modeling NLP systems for Turkic languages. UML models make it possible to visually represent the internal architecture of NLP systems, the relationships between modules, and the flow of information.

In NLP architectures adapted for Turkic languages, morphological analysis, syntactic parsing, semantic analysis, and Transformer-based attention mechanisms operate in an integrated manner. In particular, Finite-State Transducer (FST) models are important for identifying morpheme chains in agglutinative languages, while CFG and dependency parsing mechanisms play a significant role in sentence structure analysis.

Furthermore, modern Transformer architectures improve semantic analysis by identifying long-distance dependencies between words. This provides an important theoretical basis for developing machine translation systems, intelligent chatbots, voice assistants, and semantic search systems for Turkic languages. Figure 1 presents the proposed UML model of NLP architecture for Turkic languages.

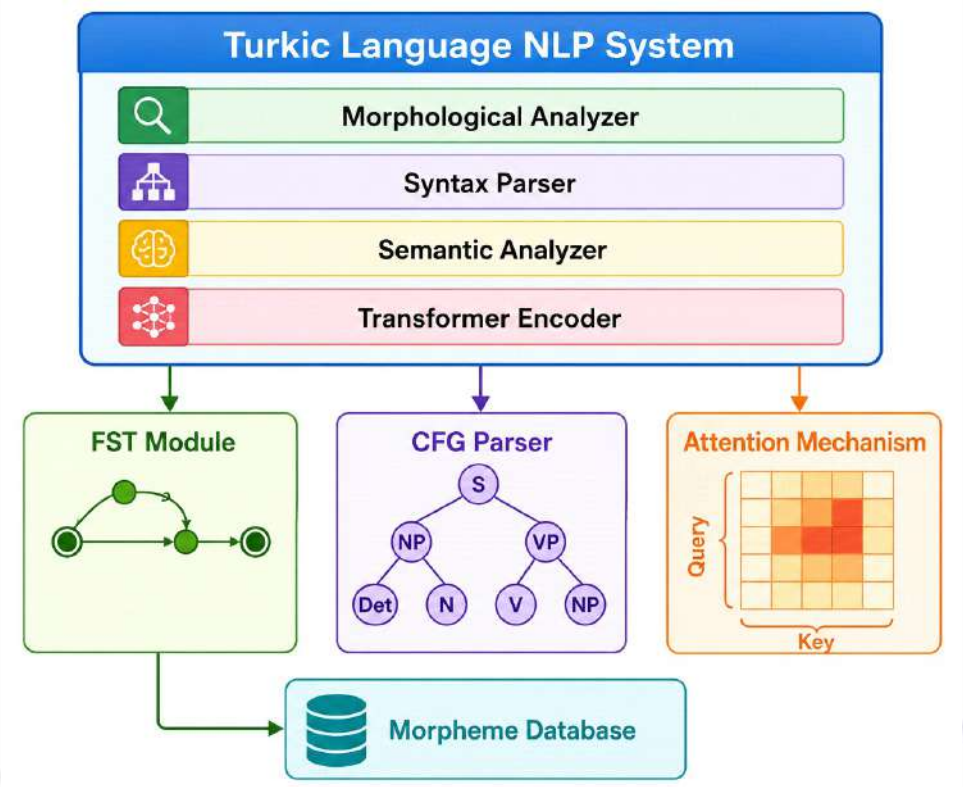


Figure 1. UML model of NLP architecture for Turkic languages

DISCUSSION AND RESULTS.

The study identified the following advantages of formal grammar-based models for Turkic languages:

1. Regular grammars provide high accuracy in morphological analysis;

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2. Dependency Grammar models are suitable for free word order;
3. Transformer-based hybrid models reduce semantic ambiguity;
4. The integration of formal rules and neural networks improves NLP system efficiency.

The analysis demonstrated that hybrid formal-neural models are more effective for Turkic languages than purely neural approaches (Table 3).

Table 3

Efficiency of Models for Turkic Languages

Model	Morphology	Syntax	Semantics
FST	High	Low	Low
CFG	Medium	High	Low
Dependency Parsing	Medium	High	Medium
Transformer	Medium	High	High
Hybrid NLP	High	High	High

Based on the obtained results, it can be concluded that FST models are among the most effective solutions for morphological analysis, Dependency Grammar for syntactic analysis, and Transformer architectures for semantic analysis.

CONCLUSION AND RECOMMENDATIONS.

In the future, improving hybrid grammatical-neural models and developing formal grammatical corpora for Turkic languages will remain one of the important scientific directions in computational linguistics.

The research results demonstrate that integrating formal grammars with neural networks enables the development of highly efficient NLP systems for Turkic languages.

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