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Computational Arabic Morphology and Its Pedagogical Applications in Arabic Language Instruction
La morphologie computationnelle de l'arabe et ses applications pédagogiques dans l'enseignement de la langue arabe

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Abstract:
Natural Language Processing (NLP) has emerged as a cornerstone of artificial intelligence, enabling computational systems to process human language across diverse technological and educational domains. Owing to its complex morphology, high degree of inflection, and non-concatenative root-and-pattern system, Arabic presents distinct computational challenges. Although significant methodological advancements have been achieved through state-of-the-art frameworks—such as CAMeL Tools, Farasa, and MADAMIRA—their integration into Arabic language pedagogy remains insufficiently explored.
This descriptive-analytical study investigates the theoretical foundations of computational Arabic morphology and evaluates its practical pedagogical applications. The findings demonstrate that automated morphological analyzers significantly enhance language learning by demystifying structural word analysis, mitigating cognitive load, and providing real-time instructional feedback, while highlighting the necessity for advanced models to address persistent contextual and morphophonemic ambiguities.
Keywords: Arabic Morphology; Computational Linguistics; Natural Language Processing (NLP); Arabic Language Education; Morphological Analysis; Intelligent Computer-Assisted Language Learning (ICALL).

Résumé:
Le Traitement Automatique des Langues (TAL) est devenu un domaine fondamental de l'intelligence artificielle, permettant aux systèmes informatiques de traiter le langage humain dans des applications technologiques et éducatives. En raison de sa morphologie complexe, de son degré élevé d'inflexion et de son système non concaténatif fondé sur la racine et le schème, la langue arabe présente des défis computationnels majeurs. Malgré les progrès méthodologiques réalisés grâce à des outils performants tels que CAMeL Tools, Farasa et MADAMIRA, leur intégration dans l'enseignement de la langue arabe demeure encore limitée.

Cette étude descriptive et analytique examine les fondements théoriques de la morphologie computationnelle arabe et évalue ses applications pédagogiques pratiques. Les résultats montrent que les analyseurs morphologiques automatiques améliorent considérablement l'apprentissage en simplifiant l'analyse structurelle des mots, en réduisant la charge cognitive des apprenants et en fournissant une rétroaction immédiate, tout en soulignant la nécessité de développer des modèles avancés pour mieux traiter les ambiguïtés contextuelles et morphophoénologiques.
Mots-clés : Morphologie arabe ; Linguistique informatique ; Traitement automatique des langues (TAL) ; Enseignement de la langue arabe ; Analyse morphologique.

1. Introduction :

As Natural Language Processing (NLP) continues to transform educational technology, Arabic presents unique computational hurdles. Its highly inflected, non-concatenative root-and-pattern system and complex morphophonemic shifts require specialized parsing approaches rather than standard language models. Recent advancements in Arabic NLP—specifically open-source frameworks like CAMeL Tools, Farasa, and MADAMIRA—have made major strides in automated morphological parsing and disambiguation. Nevertheless, practical ways to apply these tools directly within classroom pedagogy remain noticeably under-explored.

This study bridges computational linguistics and classroom pedagogy by evaluating how morphological analyzers can clarify word structure for language learners. By examining foundational theoretical frameworks alongside practical applications, we explore how automated parsing lowers learning barriers, supports learner autonomy, and strengthens structural linguistic competence.

Accordingly, the overarching research question guiding this inquiry is:

How can computational Arabic morphological processing be effectively integrated into Arabic language pedagogy to enhance structural learning?

To answer this primary question, the study addresses the following specific research questions:

1. What theoretical and computational foundations support modern Arabic Natural Language Processing?
2. Why does Arabic morphology (*'ilm al-sarf*) serve as the core engine for Arabic NLP systems?
3. How do contemporary computational analyzers process Arabic roots (*judhūr*), patterns (*wazn*), and morphosyntactic features?
4. What key educational benefits and technical limitations accompany the classroom integration of computational morphology?
5. What practical steps can optimize the instructional impact of computational Arabic morphology in digital learning environments?

To tackle these questions, this study uses a descriptive-analytical methodology rooted in a systematic review of computational Arabic linguistics and NLP literature. It evaluates core theoretical concepts, analyzes representative morphological tools, and assesses their pedagogical

value to identify ongoing structural issues and outline future steps for intelligent learning environments.

2. Definition of Fundamental Concepts

This section delineates the core theoretical concepts underlying the study—encompassing linguistics, computational linguistics, computer technology, and Arabic morphology—to establish the foundational conceptual framework required to understand computational Arabic morphological processing and its pedagogical applications.

2.1. Definition of Didactics

Hans Aebli defines Didactics as *"a science upon which pedagogy relies in various classroom activities"*[1]; that is, the method through which the learner achieves the set objectives for which they attend school.

Here, didactics is subsumed under pedagogy, which is concerned with teaching. Thus, pedagogy is broader and more comprehensive than didactics, as the latter focuses specifically on the instruction of subject matter[2]. For this reason, the duties assigned to a primary school teacher are referred to as pedagogical tasks, as the teacher instructs, educates, and supervises pupils in the schoolyard.

2.2. Linguistics

Linguistics—frequently referred to as general linguistics—is defined as "the objective, scientific study of human language"[3]. This definition underscores that linguistic inquiry demands strict adherence to empirical methodologies to systematically investigate and analyze the underlying structural organization of natural human speech.

2.3. Computational Linguistics

Computational linguistics represents a vital, interdisciplinary subfield within modern linguistics. Among its most prominent formulations:

"Computational linguistics constitutes the newest branch of modern linguistics and is among the most vital across all fields in the information age. It is evidently an interdisciplinary field, half of which belongs to linguistics—focusing on language—and the other half to computer science, focusing on translating language into mathematical symbols that a computer can process and manipulate." [4]

Accordingly, computational linguistics aims to exploit machine efficiency by developing algorithmic software systems capable of modeling and simulating human cognitive linguistic processing.

2.4. Computer Technology

The computer serves as the technological substrate for digital language processing, formally defined as:

"A machine that transforms data and programs into useful information, applying to all types of data, software, and information regardless of their size or domain. It represents a modern system of communication—an electronic device programmed to operate according to specific algorithms, storing data, performing calculations, and displaying results."[5]

Thus, computational infrastructure facilitates a qualitative advancement in linguistic data digitization, structural simplification, and high-speed processing.

2.5. Morphology ('Ilm al-Sarf)

In Arabic linguistics, morphology (*'ilm al-sarf*) is defined through two foundational perspectives:

- **Etymological Definition:** *Sarf* denotes alteration, transformation, and variation from one state to another. This semantic root is reflected in the Quranic expression regarding "the alternation of the winds" (*tasrīf al-riyāḥ*), referring to their shifts in direction, temperature, and intensityFrom an etymological standpoint, morphology is the discipline concerned with [6]. internal structural shifts, derivations, and formal pattern variations within lexical units.
- **Technical Definition:** Morphology is technically defined as "the science of the principles and rules by which one knows the structural states of words that are neither inflectional (*'iʿrāb*) nor uninflectional (*binā'*)"[7].

Bridging classical Arabic morphology with computational linguistics demonstrates that automated morphological processing is achievable by systematically categorizing non-concatenative root derivations (*judhūr*) and patterns (*wazn*) within computational databases for dynamic retrieval and generation.

3. Natural Language Processing (NLP)

Natural Language Processing (NLP) operates on two complementary dimensions: a theoretical dimension directed at uncovering human cognitive linguistic capabilities and formulating them into symbolic, mathematical models compatible with computational architectures; and an applied dimension that simulates human linguistic reasoning and production by leveraging these theoretical models. Consequently, NLP applications necessitate inspecting language across all spoken and written dimensions—including lexical units, sentences, texts, generation, and parsing—leading to multi-tiered processing across phonological, morphological, syntactic, semantic, and pragmatic levels [8].

From this foundational framework, it is evident that NLP serves as an interdisciplinary bridge between linguistics and informatics, enabling comprehensive digital processing across all linguistic tiers, with morphology occupying a central role.

3.1 Subsystems of Language Engineering

The computational processing of natural language systems requires several specialized subsystems:

- **Automated Morphological Parsing System:** Analyzes surface word forms into canonical roots (*judhūr*), strips affixes (prefixes, infixes, and suffixes), identifies structural patterns (*wazn*), or reconstructs lexical items by deriving them from core morphemes.
- **Automated Syntactic Parsing System:** Analyzes sentence structures with respect to constituent order and functional syntactic relationships, automatically assigning grammatical case markers (*ʾiʿrāb*) and contextual diacritization (*tashkīl*).
- **Automated Semantic Analysis System:** Focuses on contextual meaning representation. Because an isolated lexical item acquires nuanced semantic values dependent on its syntactic and textual environment, this subsystem resolves polysemy and extracts semantic representations from broader textual contexts [9].

3.2 The Role of Integrated NLP Subsystems in Computational Processing

The operational integration of morphological, syntactic, and semantic subsystems enables computational architectures to process complex Arabic texts with high precision. Rather than functioning in isolation, these complementary subsystems establish a unified processing pipeline that drives a wide array of Arabic Natural Language Processing (NLP) applications—including machine translation, information retrieval, automated grammar checking, question-answering systems, and intelligent computer-assisted language learning (ICALL) environments.

Consequently, this integrated framework streamlines linguistic analysis for both learners and researchers, significantly reducing the cognitive load and temporal overhead required for structural language processing while enhancing the accuracy and reliability of computational outputs. Ultimately, these interconnected subsystems constitute a foundational framework for engineering intelligent digital ecosystems that support Arabic language pedagogy and advance modern Arabic language technologies.[10]

4. The Status of Morphology in Automated Processing

Morphology (*ʾilm al-sarf*) constitutes a foundational pillar of Arabic linguistics. The classical scholar Ibn 'Usfūr noted that morphology is the most noble half of Arabic, as demonstrated by the essential need of all linguists and grammarians for it, serving as the balance of the Arabic language (*mīzān al-ʾarabiyyah*)[11].

Modern linguistics similarly regards morphology as crucial for generating the lexical inventory that forms the cornerstone of linguistic output. As Tammām Ḥassān observed, the grammarian possesses no structural patterns except those provided by morphology[12].

Consequently, language engineers must design computational algorithms specifically tailored to the structural nuances of Arabic. This involves utilizing standardized encoding schemes for data exchange, processing Arabic orthography, structuring efficient information retrieval systems, and

building algorithmic models compliant with the non-concatenative Arabic morphological system[13].

To achieve this, contemporary Arabic Natural Language Processing (NLP) leverages state-of-the-art computational frameworks and open-source libraries—such as CAMeL Tools, Farasa, **MADAMIRA**, and the foundational Buckwalter Arabic Morphological Analyzer (BAMA)—to execute high-speed morphological parsing, segmentation, and contextual disambiguation.

5. Mechanics of Morphological Parsing

Automated morphological parsing involves evaluating a surface word form to determine its syntactic category (e.g., noun or verb), morphological composition, structural pattern (*wazn*—whether unaugmented, *mujarrad*, or augmented, *mazīd*), and underlying morphophonemic processes (such as affixation, deletion, vocalic alternation, or assimilation). By stripping affixes and peripheral clitics, the analyzer reduces thousands of surface inflections to a single canonical root[14].

In Arabic morphology, roots (*judhūr*) consist of consonantal sequences carrying abstract semantic concepts (e.g., $k-t-b$ for the general domain of *kitābah*, 'writing'). Morphological derivation operates on the non-concatenative interplay between these roots and structural patterns (*wazn*). The pattern interlocks with the root consonants alongside short vowels (*ḥarakāt*) and augmentation letters (*ḥurūf al-ziyādah*) to define the word's grammatical class (verb, noun, adjective), gender, number, definiteness, and syntactic case (*ʾiʿrāb*) or mood markers[15]."

Table (1): Structural Analysis of Roots, Patterns, and Affixes

Contextual Sentence	Target Word	Root	Identified Morphological Marker	Morphological Pattern
Idir is a scholar.	ʿĀlim (scholar)	ʿ-l-m	Internal vowel pattern: ā	Fāʿil (Active Participle)
The speech is well known.	Maʿlūm (known)	ʿ-l-m	Prefix m- and internal vowel pattern: ū	Mafʿūl (Passive Participle)
This is a magnificent mosque.	Masjid (mosque)	s-j-d	Prefix m- and pattern vowel insertion	Mafʿil (Noun of Place)
There is a library in our neighborhood.	Maktabah (library)	k-t-b	Prefix m-, suffix -ah (tāʾ marbūṭah), and pattern formation	Mafʿalah (Noun of Place)
The rose is red.	Aḥmar (red)	ḥ-m-r	Initial hamzah (a-) and pattern formation	Afʿal (Color/Adjective Pattern)

Quantitative studies of Arabic roots across classical lexicons increasingly rely on computational models to facilitate statistical analysis of biliteral, triliteral, quadriliteral, and quintiliteral roots[16]. This approach is consistent with the Modern Khalīlian Theory developed by Algerian scholars

Prof. Abderrahmane Hadj-Salah and Prof. Salah Belaid. The Khalīlian Theory corresponds with computational requirements by providing a comprehensive framework for text analysis, word relations, and morphophonemic variations. For example, when a subject pronoun is attached to the verb **kataba**, its morphological structure changes from a final **fatḥah** to a final **sukūn**, as in **katabtu**[17].

6. Case Study: Automated Verbal Conjugation Engine (Azzeddine Tourabi & Abdelhamid El-Jihad)

Researchers Azzeddine Tourabi and Abdelhamid El-Jihad developed an automated verbal conjugation model using the following algorithmic steps[18]:

- Categorizing conjugation paradigms into formal classes, assigning numerical codes to verbs to represent structural rules and identify verb requirements.
- Standardizing root classes, verbal patterns, vocalic shifts, and tense/aspect markers.
- Integrating complete morphological paradigms into system memory for automated lookup.
- Incorporating comparative metrics to facilitate cross-linguistic alignment.

"This conjugation engine stores diverse verb classes. Upon input, it outputs complete paradigm inflections across pronouns (1st, 2nd, 3rd person) and tenses, accounting for structural additions and deletions based on stored database rules."[19]

Table (2): Algorithmic Output for the Verb *Darasa* (Present Tense, First and Second-Person Forms)

Subject Pronoun	Automated Conjugation Output	Stored Morphosyntactic Features
Ana (I - 1st Person Sing.)	Adrusu (ʾ**adrusu**)	Present, Indicative, 1st Person Singular, Nominative
Anta (You - Masc. Sing.)	Tadrusu (**tadrusu**)	Present, Indicative, 2nd Person Masc. Singular
Anti (You - Fem. Sing.)	Tadrusina (**tadrusīna**)	Present, Indicative, 2nd Person Fem. Singular
Antuma (You Two - Dual)	Tadrusani (**tadrusāni**)	Present, Indicative, 2nd Person Dual (Masc./Fem.)
Antum (You - Masc. Plural)	Tadrusuna (**tadrusūna**)	Present, Indicative, 2nd Person Masc. Plural
Antunna (You - Fem. Plural)	Tadrusna (**tadrusna**)	Present, Indicative, 2nd Person Fem. Plural (Indeclinable on Sukun)

Table 2 illustrates that the automated conjugation engine accurately generates the present-tense forms of the Arabic verb ***darasa*** (darasa) according to first-person and second-person subject pronouns, including ***Ana*** (ʾanā) and ***Anta /Anti /Antumā /Antum /Antunna*** (anta /anti /antumā /antum /antunna), by automatically applying the corresponding morphological rules. In addition to

producing the correct conjugated forms, the system identifies essential morphosyntactic features, including person, gender, number, tense, and mood. This demonstrates the effectiveness of computational morphology in simplifying Arabic verb conjugation and providing reliable support for Arabic language teaching and learning.

7. Conclusion:

This study investigated the role of Arabic computational morphology in enhancing Arabic language education by bridging computational linguistics and language pedagogy. The analysis demonstrated that the digitization of Arabic morphology—characterized by its non-concatenative root (*judhūr*) and pattern (*wazn*) system—provides a solid foundation for developing intelligent educational tools. Automated morphological analyzers and conjugation systems facilitate language learning by transforming complex morphological rules into interactive computational models that provide immediate feedback. As a result, Arabic computational morphology enhances learners' morphological awareness, reduces cognitive load, and supports more autonomous and technology-enhanced learning.

Despite these advantages, the structural complexity of Arabic morphology continues to present computational challenges, particularly in handling morphophonemic alternations, contextual ambiguity, and irregular derivational patterns. Therefore, continued collaboration among linguists, computer scientists, and Arabic language educators is essential for developing more accurate, context-aware, and pedagogically effective Arabic Natural Language Processing (NLP) applications.

7.1. Findings:

1. **Reduced Cognitive Load:** Arabic computational morphology simplifies structural language learning by transforming complex morphological rules into systematic computational processes, thereby reducing learners' cognitive load and improving learning efficiency.
2. **Immediate Diagnostic Feedback:** Automated morphological analyzers provide immediate feedback that enables learners to identify and correct morphological and morphosyntactic errors independently.
3. **Underutilized Pedagogical Potential:** Contemporary Arabic NLP frameworks, including CAMeL Tools, Farasa, and MADAMIRA, have significantly improved the accuracy of morphological analysis; however, their integration into Arabic language curricula remains limited.
4. **Persistent Computational Challenges:** The linguistic complexity of Arabic, particularly morphophonemic variation, contextual ambiguity, and irregular derivational patterns, continues to require further advances in computational models and algorithms.

7.2. Recommendations:

1. **Develop Advanced Morphological Analyzers:** Integrate traditional linguistic knowledge with modern artificial intelligence and deep learning techniques to enhance the precision and robustness of Arabic morphological parsing.
2. **Integrate Computational Morphology into Education:** Incorporate computational morphology tools into official Arabic language curricula and design specialized training programs for Arabic language educators.
3. **Expand Intelligent Learning Applications:** Accelerate the adoption of Intelligent Computer-Assisted Language Learning (ICALL) environments that support interactive morphological analysis, immediate feedback, and personalized learning pathways.
4. **Promote Empirical Research:** Conduct empirical classroom-based studies to evaluate the educational effectiveness of computational morphology and explore the pedagogical applications of Generative AI and Large Language Models (LLMs) in Arabic language education.

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