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Morphological Templates and Conceptual Mechanisms: Toward Grounding the Al-Khalīlian Mathematical System within Cognitive Linguistics

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Abstract:
This paper addresses a pivotal topic that bridges rigorous Khalīlian mathematics with contemporary cognitive linguistics. It investigates the mechanisms by which the abstract mathematical principles of morphological templates are embodied in the genuine cognitive processes employed by Arabic speakers. Furthermore, it seeks to answer a fundamental question: How can strict mathematical structures transform into real, perceivable cognitive mechanisms?
To answer this problem, the paper presents an integrative equation linking mathematics and cognitive linguistics, alongside an applied study of verbs derived from a single root. The paper concludes that the Arabic morphological system represents an integrated model combining mathematical rigor with cognitive vitality, and that cognitive linguistics provides the theoretical bridge connecting abstract formalism with pragmatic language use.
Keywords: Mathematical thinking; morphological templates; cognitive linguistics; conceptualization; Arabic grammar; mathematical system.

Introduction:

Contemporary linguistic studies have affirmed that the morphological system in Arabic, both among ancient and modern scholars, rests upon a precise mathematical structure characterized by rigor and regularity. Returning to recent developments in methods and models for probing language—particularly with the emergence of cognitive linguistics and its mechanisms, strategies, and modern cognitive approaches—we find that it provides an effective theoretical framework linking this abstract, formal mathematical structure to aspects of actual linguistic performance. This is evident in the practice of Arabic speakers within natural and pragmatic language contexts. This interrelation between the mathematical rigor of the morphological system and the cognitive dynamism of language constitutes a growing focus of modern linguistic research, enabling the revelation of the cognitive foundations governing the interaction between formal language structures and processes of thought and mental conceptualization.
Based on this perspective, this research paper is founded on an attempt to investigate the interrelated relationship among the formal structure of language, the cognitive principles governing its perception and use, and the mathematical concepts governing the Arabic

morphological system.[8] By revealing this relationship, the research seeks to answer a central problem, which is:

- How are the abstract mathematical principles organizing morphological structure embodied in the living, effective cognitive processes of Arabic speakers?

Or in other words:

- What is the nature of the relationship between the mathematical abstraction of morphological templates and the conceptual representations built by the mind and stored in the linguistic memory?

The Mathematical Structure of Templates as an Abstract System:

For Al-Khalīl ibn Aḥmad, the morphological template is not merely an arrangement of letters; rather, it is an abstract, fixed structure subject to a strict logical law, just as mathematical equations adhere to their deterministic laws[1]. It can be represented as a precise mathematical formula distinguishing between what is constant and what is variable: the letters are variables subject to substitution, while the positions are fixed and immovable.

This distinction reflects a genuine mathematical depth, indicating a profound understanding of the morphological process among ancient Arab linguists.[2] We can observe this, for example, when applying the template "faʿala" (فَعَل) to different roots; the same rule generates multiple words: from "d-r-s" (د ر س) comes "darasa" (دَرَس), from "ḍ-r-b" (ض ر ب) comes "ḍaraba" (ضَرَب), and from "k-t-b" (ك ت ب) comes "kataba" (كَتَب).

This mechanism of regular application achieves what we might call "economical generality":[3] a single rule covers thousands of words and provides an unlimited (i.e., infinite) probability for generating new speech not previously heard, according to the Khalīlian principle of regularity. In this context, the morphological system falls under several mathematical properties that may be uncovered through precise analysis, including:

- **First:** Regularity and Total Applicability**:**The same template applies to an unlimited number of roots with no significant exceptions, thereby achieving the principle of generality.[4]
- **Second:** Hierarchical Stratification**:** Templates are not randomly scattered but are organized in a graded hierarchical system.[5] Thus, basic templates ("faʿala", "fiʿl", "faʿila") lie at the base, from which secondary templates ("fāʿil", "mafʿūl", "tafaʿʿul") are derived, reaching tertiary templates ("istafʿala", "iftiʿāl").
- **Third:** Transformational Relations: Templates relate to one another through logical transformational equations,[6] moving from "faʿala" to "fāʿil" by a regular addition (alif + lām). All these transformations are governed by clear, specific, unambiguous rules.

Cognitive Mechanisms and Mental Conceptualization Processes:

Cognitive linguistics, led by Ronald Langacker and Leonard Talmy,[7] has revealed that language is not an isolated formal system but a direct reflection of the complex internal processes occurring at the mental level, which humans exercise in their real-world environment.

This knowledge derived from these processes manifests itself in linguistic practice. When an Arabic speaker receives a word with a complex form such as "istadrasa" (اِسْتَدْرَسَ), their mind performs sequential, internal, complex mental processes involving several stages, including:

- First Stage:

- **Gradual Retrieval:** The mind retrieves the root "d-r-s" (د ر س) from memory stores sequentially. Retrieval does not occur all at once but through gradual activation of mnemonic threads associated with this root.[8]

- Second Stage:

- **Template Recognition:** The mind identifies the template "istafʿala" (اِسْتَفْعَلَ) through a pattern-matching process between what is heard and the templates stored in long-term memory.[9]

- Third Stage:

- **Activation of the Semantic Frame:** Once the mind recognizes the template, a complete semantic frame associated with that template is activated. The template "fāʿil" (فَاعِل) activates a frame related to "the one who performs the action," while "mafʿūl" (مَفْعُول) activates a frame related to "the one affected by the action."[10]

- Fourth Stage:

- **Integrated Semantic Construction:** The mind constructs the complete mental image of the meaning by integrating the root's meaning and its semantic potential with the template's meaning and its semantic frame, along with the context in which the word appears.[11]

Talmy's[12] theory of conceptual space has developed a new understanding of templates: each morphological template specifies a particular location within a multidimensional conceptual space.

This theory is exemplified by conceiving multiple dimensions:

- **First Dimension:** Extending from simplicity to complexity.
- **Second Dimension:** Extending from event to object.
- **Third Dimension:** From singular to collective.
- **Fourth Dimension:** Extending temporally from past to present to future.[13]

- Through this understanding, it becomes clear that:

The template "faʿala" occupies a specific location [simple + event + singular + past], the template "fāʿil" occupies a different location [relatively complex + object + singular + present], and the template "tafaʿʿul" occupies a third location [very complex + event + iterative + continuous].[14]

- **Integrative Linking Between Mathematics and Cognitive Linguistics:**

An equation unifying the mathematical and cognitive dimensions of the morphological process can be formulated as:

Received Meaning = (Meaning of Root) × (Meaning of Template) + (Cognitive Context) [15]

Thus, this formula reflects the fact that meaning is not merely an automatic multiplication of two separate elements but a dynamic, interactive process involving: the meaning of the root—the stable semantic essence that does not shift (like the meaning of movement and transition in the root "d-r-s"); the meaning of the template—the semantic transformation applied to the root

(like "faʿala" transforming to mean "simple, completed action"); and the cognitive context—the cognitive, cultural, and social frame activated from memory.[16]

On the other hand, modern neuroscience studies have revealed justifications for this, showing that the brain possesses "mirror neurons" in Broca's area and elsewhere.[17] These neurons fire when we perform an action, but they also fire when we see or hear someone else performing a particular movement.

This discovery has direct practical applications for understanding how morphological templates are processed.[18] When a speaker hears a word like "darrasa" (دَرَّس), there occurs: activation of the sound trace in the temporal lobe, retrieval of the root from the mental database, activation of the semantic frame for the template "faʿʿala" (فَعَّل) meaning "intensification and exaggeration," followed by activation of motor simulation neurons associated with the concept of "intensive, continuous teaching."[19] All these processes happen at lightning speed, unconsciously, culminating in the formation of the complete mental image and arriving at meaning through the brain's analysis of the form: "a person who engages in continuous, intensive teaching." Notably, all these processes occur in fractions of a second, reflecting immense mental complexity hidden beneath the apparent simplicity of the word.

Indeed, the interconnection among the formal structure of language, the cognitive principles governing its perception and use, and the mathematical concepts governing the Arabic morphological system is also revealed by what cognitive linguistics has termed an important principle: ""conceptual inheritance."" [20] Subordinate templates inherit conceptual structures from basic templates, allowing for the extrapolation of new meanings based on known patterns. The template "istafʿala" inherits the basic structure from "faʿala" and then adds the meaning of "requesting or seeking something." Thus, "istadrasa" means "to request study or seek education."

This inheritance is not absolute or deterministic but is subject to deviation and creativity, which explains the linguistic creativity and productivity of speakers.[21]

- Applied Study

- Analysis of Verbs from Root (d-r-s):

∨ - First Template Form (faʿala = darasa):

1. Mathematical Structure: Consists of C_1 + fatḥa + C_2 + fatḥa + C_3.
2. Conceptual Space: Occupies a location [simple] + [event] + [singular] + [past].
3. Cognitive Process: The mind activates the frame of "simple, completed action," activating the conception of an event fully accomplished in the past. Hence, the resulting meaning: "[he] carried out study in a simple, direct manner."[22]

∨ - Second Template Form (faʿʿala = darrasa):

1. Mathematical Structure: Consists of C_1 + fatḥa + C_2 + gemination + fatḥa + C_3.
2. Conceptual Space: Occupies a location [relatively complex] + [event] + [intensive] + [iterative].
3. Cognitive Process: Activates the frame of "intensification and exaggeration"; the gemination of the middle consonant is not merely a phonetic mark but a cognitive signal of

repetition and intensification of the event. Hence, the resulting meaning: "[he] taught in a continuous, intensive manner."[23]

∨ - Third Template Form (fāʿil = dāris):

1. Mathematical Structure: Consists of C_1 + fatḥa + alif + C_2 + kasra + C_3.
2. Conceptual Space: Occupies a location [complex] + [object] + [singular] + [present].
3. Cognitive Process: Activates the frame of "the living, acting entity"; we are not speaking of an action but of an entity that performs this action. Hence, neurons associated with "the conception of a person in an active state of studying" are activated. Thus, the resulting meaning: "a person who practices studying actively in the present."[24]

∨ - Fourth Template Form (mafʿūl = madrūs):

1. Mathematical Structure: Consists of mīm + C_1 + fatḥa + C_2 + ḍamma + C_3.
2. Conceptual Space: Occupies a location [complex] + [object] + [affected] + [passive of the action].
3. Cognitive Process: Activates the frame of "the entity affected by the action, the receiver of the event"; the initial mīm indicates that this entity is not an agent but an undergoer.[75] Hence, the resulting meaning: "the subject that was studied or will be studied."[25]

- Difference Between Mathematical and Cognitive Processing:

Mathematical processing is characterized by specific properties: starting from the form (i.e., the word's external shape), applying pre-determined rules with precision, with regular and accurate processing speed unaffected by external factors, and errors within this processing are rare and predictable.[26]

As for cognitive processing, it is characterized by entirely different properties: starting from meaning and context, activating semantic frames through complex cognitive networks, with variable speed depending on frequency and familiarity, and creative errors that are recurring but reflect creative understanding.[27]

In this context, we present an illustrative example of this comparison:

A child says "darrastu" (دَرَّسْتُ) instead of "darastu" (دَرَسْتُ). This is not a random error but a "creative error" reflecting his understanding of the principle of conceptual inheritance; he applies a rule he knows to a new situation.[28]

- Analysis of the Quadriliteral Verb (faʿlala) from Root (q-s-m):

∨ - First Quadriliteral Template Form (faʿlala = qasmal):

1. Mathematical Structure: Consists of C_1 + fatḥa + C_2 + sukun + C_3 + fatḥa + C_4. This structure reflects the regular sound sequence distinguishing quadriliteral verbs from triliteral ones.[29]
2. Conceptual Space: Occupies a location [complex] + [event] + [singular] + [past] + [semantically composite], reflecting the composite nature of the quadriliteral verb, combining structural and semantic complexity.[30]
3. Cognitive Process: The mind activates the frame of "the composite event of a special character"; the sukun on the second consonant is not merely a phonetic mark but a cognitive

signal separating the event's components, while the consecutive fatḥas indicate the continuous flow of the event. Thus, multilayered conceptions related to an intricately structured event are activated.[31]

The resulting meaning: "[he] performed the act of dividing/swearing in an unusual manner or in a manner carrying a special meaning," differing from "qasama" (simple triliteral verb) in that the quadriliteral adds an extra semantic dimension related to the manner or different modality of the action.[32]

- Difference Between Mathematical and Cognitive Processing of the Quadriliteral Verb:

- Mathematical Processing: Starts from the word's external form and applies pre-determined rules precisely, dissecting the quadriliteral verb into its four components and determining the locations of vowels and consonants, with regular processing speed unaffected by external factors. Errors are rare and predictable; for example, a machine can instantly determine that "qasmal" follows the template "faʿlala" without hesitation.[33]

- Cognitive Processing: Is characterized by entirely different properties, starting from context and the speaker's cognitive understanding, activating semantic frames through complex, interconnected cognitive networks. Speed varies depending on frequency and familiarity; a speaker might take longer to distinguish between "qasama" and "qasmal" if the quadriliteral verb is less frequent in their usage. Errors in this processing are creative and deep-meaning, recurring yet reflecting creative understanding and a process of cognitive inference.[34]

- **Illustrative Example:** A child says "qasmal al-shay'" instead of using the triliteral form "qasamahu". This is not a random error but a "creative error" reflecting his understanding of the principle of conceptual inheritance of morphological templates; he applies a quadriliteral rule he knows to a new context, attempting to impart a special or composite meaning to the simple triliteral verb. This error reveals a deep cognitive process wherein the child attempts to expand his linguistic repertoire by relying on acquired patterns, indicating genuine cognitive activity that goes beyond mechanical rule application to innovation and experimentation.[35]

√- Set of Probabilities Arising from the Template (faʿlala):

- **Cognitive-Mathematical Analysis:** From the simple quadriliteral verb form ("faʿlala"), a set of forms and derivations branch out, forming an integrated system of morphological probabilities. For analysis, we choose the verb "daḥraja" (دَحْرَجَ) as it is the most famous and clearest model in this category.[36]

- Analysis of Verbs from Root (d-ḥ-r-j):

√- Simple Quadriliteral Verb Form (faʿlala = daḥraja):

1. Mathematical Structure: Consists of C_1 + fatḥa + C_2 + sukun + C_3 + fatḥa + C_4. A balanced quadriliteral structure characterized by the alternation of vowel and consonant, giving it a special rhythmic quality.[37]

2. Conceptual Space: Occupies a location [composite] + [event] + [kinetic] + [transitive] + [past], indicating an event involving continuous and repeated movement in a specific direction.[38]

3. Cognitive Process: The mind activates the frame of "repeated circular movement"; the quadriliteral structure is not merely an increase in letters but a cognitive signal of the event's complexity and composition. The sukun on the second consonant indicates a separation between successive stages of movement.[39]

The resulting meaning: "[he] moved something in a repeated circular manner downward or forward."[40]

√ - First Masdar Form (faʿlalah = daḥrajah):

1. Mathematical Structure: Consists of C_1 + fatḥa + C_2 + sukun + C_3 + fatḥa + C_4 + tāʾ marbūṭa. The standard structure for the masdar of the non-geminated quadriliteral verb.[41]

2. Conceptual Space: Occupies a location [abstract] + [event] + [nominal] + [absolute], moving from temporality to the absolute of the event.[42]

3. Cognitive Process: Activates the frame of "abstracting the event from time"; the tāʾ marbūṭa is not merely a grammatical marker but a cognitive signal of transforming the verb into an independent abstract concept.[43]

The resulting meaning: "the abstract event of circular movement, regardless of time or agent."[44]

√ - Second Masdar Form (fiʿlāl = diḥrāj):

1. Mathematical Structure: Consists of C_1 + kasra + C_2 + sukun + C_3 + fatḥa + alif + C_4. An alternative structure sharing masdar meaning with the first form.[45]

2. Conceptual Space: Occupies a location [abstract] + [event] + [nominal] + [relatively intensive], where the lengthened alif adds a dimension of extension and continuity.[46]

3. Cognitive Process: Activates the frame of "the extended event"; the extra alif is a cognitive signal of the event's extension and expansion, making this masdar more inclined to express repetition and continuity.[47]

The resulting meaning: "the continuous and extended event of circular movement."[48]

√ - Form of Inchoativity (tafaʿlala = tadaḥraja):

1. Mathematical Structure:Consists of tāʾ + fatḥa + C_1 + fatḥa + C_2 + sukun + C_3 + fatḥa + C_4. The only form for the quadriliteral verb augmented by one letter.[49]

2. Conceptual Space: Occupies a location [complex] + [event] + [passive] + [automatic] + [past], where the agent shifts from the position of effector to that of the affected.[50]

3. Cognitive Process: Activates the frame of "reflexivity and being affected"; the extra initial tāʾ is not merely a phonetic letter but a cognitive signal of the action reflecting on the self. Thus, the thing moves by itself without an external direct agent.[51]

The resulting meaning: "the thing moved circularly by itself as a result of a prior action."[52]

√- Active Participle Form (mufaʿlil = mudaḥrij):

1. Mathematical Structure: Consists of a mīm with ḍamma + C_1 + fatḥa + C_2 + sukun + C_3 + kasra + C_4. Derived from the present tense by replacing the present tense prefix with a ḍamma-marked mīm and marking the penultimate with kasra.[53]

2. Conceptual Space: Occupies a location [complex] + [object] + [agent] + [present], shifting focus from the event to the performer of the event.[54]

3. Cognitive Process: Activates the frame of "the agent entity"; the prefixed mīm with ḍamma is a cognitive signal of moving from the world of events to the world of objects, and the kasra before the last consonant signals agency and activity.[55]

The resulting meaning: "the person or thing that performs the action of rolling."[56]

√- Passive Participle Form (mufaʿlal = mudaḥraj):

1. Mathematical Structure: Consists of a mīm with ḍamma + C_1 + fatḥa + C_2 + sukun + C_3 + fatḥa + C_4. Distinguished from the active participle by the fatḥa on the penultimate instead of a kasra.[57]

2. Conceptual Space: Occupies a location [complex] + [object] + [passive] + [affected], shifting focus to the object upon which the action fell.[58]

3. Cognitive Process: Activates the frame of "the entity affected by the action"; the fatḥa before the last consonant is a cognitive signal of passivity and reception, in contrast to the kasra indicating agency.[59]

The resulting meaning: "the thing that was rolled or upon which the action of rolling took place."[60]

√- Active Participle of the Inchoative Form (mutafaʿlil = mutadaḥrij):

1. Mathematical Structure: Consists of mīm with ḍamma + tāʾ + fatḥa + C_1 + fatḥa + C_2 + sukun + C_3 + kasra + C_4.[61]

2. Conceptual Space: Occupies a location [very complex] + [object] + [self-moving/automatic] + [present].[62]

3. Cognitive Process: Activates the frame of "the self-moving entity"; the combination of mīm and tāʾ indicates an entity performing a reflexive action, and the kasra before the last consonant denotes the continuity of this self-directed action.[63]

The resulting meaning: "the thing that moves circularly by itself."[64]

√ - Difference Between Mathematical and Cognitive Processing:

- Mathematical Processing: Starts from the word's external form and applies pre-determined rules precisely, dissecting the quadriliteral verb into its four components and determining the positions of vowels and consonants with regular processing speed. For example, a machine can instantly determine that "mudaḥraj" (مُدَحْرَج) is a passive participle from "daḥraja" based solely on the formal structure.[65]

- Cognitive Processing: Starts from context and the speaker's cognitive understanding, activating semantic frames through complex cognitive networks. When a speaker hears "tadaḥraja" (تَدَحْرَجَ), they do not merely analyze the letters; rather, a mental image of spontaneous circular movement is activated in their mind. This linking of sound and image is the essence of cognitive processing.[66]

- Illustrative Example: A child says "daḥrajtu nafsī" (دَحْرَجْتُ نَفْسِي) instead of "tadaḥrajtu" (تَدَحْرَجْتُ). This is not a random error but a "creative error" reflecting his understanding of the principle of conceptual inheritance. He realizes there is a relationship between the two verbs but has not yet grasped the subtle cognitive difference between direct agency and self-directed inchoativity, thus revealing a living cognitive process that transcends the mechanical application of rules.[67]

Conclusion:

Finally, this research paper has sought to reveal the profound interconnection between the ancient Khalīlian mathematical perspective—which built a precise formal system subject to strict and consistent laws—and the contemporary cognitive perspective, which explains the mechanisms by which the human mind assimilates this system and activates it in living linguistic practice.

Upon contemplating the intertwined relationships and complex connections between these two perspectives, it becomes clear that the integrated model reconciling mathematical rigor with cognitive vitality explains how the Arabic language constructed a unique linguistic system combining mathematical elegance with complete expressive efficacy. This has enabled it to encompass the subtleties of meanings and human conceptions in all their comprehensiveness.

On this basis, morphological templates transcend being rigid laws or restrictive formal patterns to become living cognitive equations that, in their composition, combine precise mathematical form and dynamic cognitive process.

Morphological templates are multidimensional cognitive entities that contain a truly effective cognitive spirit and extend to include both the scientific and artistic dimensions simultaneously. With this unified understanding, it becomes clear that Arabic morphology is not a set of isolated rules disconnected from use, but rather a coherent system pulsating with cognitive life, combining rigorous scientific precision with renewed artistic creativity, thus achieving a unique balance between law and vitality, between abstraction and embodiment at one and the same time.

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