The Concept of Cognition as Categorization in the Development of New Metaheuristics and Algorithms Inspired by Nature

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***Abstract* - The sensorimotor system is a crucial mechanism that enables organisms to categorize information in their environment, a skill necessary for survival. According to cognitive scientist Steven Harnad's "To Cognize is to Categorize: Cognition is Categorization", all living things are essentially sensorimotor systems. This approach is proposed to serve as a novel concept for the development of algorithms inspired by swarm intelligence. Many authors of such algorithms have drawn inspiration from animal species, attempting to emulate their abilities to interact with and navigate their environment. However, these abilities are essentially rooted in the organisms' categorization skills, which are a fundamental characteristic of all sensorimotor systems. Therefore, when designing new algorithms and metaheuristics, it is unnecessary to seek out new species with specific behaviors; instead, the entire sensorimotor system can be observed, and its sensor capabilities can be incorporated even if they do not exist in nature. In order to justify this, abstraction was used as a way to demonstrate the creation of concepts. The paper offers a new perspective on the development of swarm intelligence algorithms and promotes a holistic approach to algorithm design based on Steven Harnad's viewpoint of sensory motor systems.**

Keywords - Sensorimotor system, nature inspired algorithms, swarm intelligence inspired algorithms, natural computing, cognition, categorization, bio-inspireda algorithms, metaheuristic

I. INTRODUCTION

Algorithms that draw inspiration from nature fall under the category of metaheuristics, which distinguishes them from exact algorithms. These algorithms are classified based on specific characteristics [1], with one category being algorithms inspired by swarm intelligence. This category is rapidly expanding, with researchers attempting to model various animal behaviors, ranging from the smallest insects [2] to slightly larger species like squirrels [3], doves [4] and even larger animals such as monkeys [5] and whales [6].

The significant advancements in algorithm development are largely attributed to the implementation of metaheuristics. Metaheuristics encompass a collection of algorithmic concepts that can be applied to various problems [7]. To put it simply, metaheuristics are like metaphors - they have their limitations, despite their accuracy [8]. The limitations of algorithmic concepts (or metaphors) are thoroughly discussed, with the primary concern being the potential for existing algorithms to be concealed or for inefficiencies to be overlooked under new algorithmic concepts or metaphors [8] [9]. Therefore, the problem of metaphors and their limited knowledge is explained in Section II and further elaborated on in Section III. Additionally, recreating such algorithms requires a thorough understanding of animal behavior in their environment and the mathematical models representing both the animals and the environment. This task is daunting, given that the effectiveness of metaheuristic algorithms is problem-specific.

The first swarm intelligence to be named a metaheuristic was ant colony optimization (ACO) [7]. The ACO author couldn't have predicted the vast number of algorithmic concepts related to animals that would emerge, such as bees, bacteria, bats, wolves, bumblebees, cats, cuckoos, eagles, fireflies, fish, krill, glowworms, monkeys, squirrels, whales, and so on. All of these animals are sensorimotor systems that interact with their environment and can communicate through it, much like ants. Therefore, a more feasible option for researchers is to use a named general framework or master strategy consisting of algorithmic concepts or metaphors.

To truly have a master strategy, which is what metaheuristics represent [10], we need a fundamental concept that applies to all living beings. This can be achieved by viewing each animal as a sensorimotor system. For this purpose, in Section III Steven Harnad's work "To Cognize is to Categorize: Cognition is Categorization" is used to determine characteristics of sensorimotor systems applicable to all living beings [11]. These set of characteristics or elements which can be called the "Concept of Cognition as Categorization" define fundamental concept of all living beings. In Section IV this fundamental concept is linked to concept of ant colony as an algorithmic concept for swarm intelligence (collective intelligence). If there is relation between concepts, what is shown in Section IV, then because of transitivity law intermediate concept is unnecessary, which means there is no need for developing algorithmic metaheuristic or metaphor of specific animal. "Concept of Cognition as Categorization" is sufficient.

The key takeaway is that designers of swarm-inspired algorithms can create new components with a strong theoretical foundation in cognitive science. They do not need to delve deeply into the specific behaviors of various animals, ranging from insects to mammals. Rather, they can focus on the sensorimotor systems that define these animals and their communication abilities within specific environments. By doing so, they can build algorithms that are effective and efficient without getting bogged down in unnecessary details.

II. THE PROBLEM OF METAPHOR

Various fields of study offer differing definitions of metaphors. In this paper, we adopt the definition of metaphor used in cognitive linguistics. In this field, metaphor is viewed as a cornerstone of the human conceptual system, leading to the development of what are called "conceptual metaphors."

A common example of metaphor in everyday life involves people using the concept of a roundabout to describe a situation where they are unable to find a solution to a problem. However, this simple metaphor belies the complexity of the concept of a roundabout, which includes multiple entrances and exits. In other words, while people may use the idea of a roundabout to describe a challenging situation, the full implications of this metaphor go beyond the surface level.

Metaphors are not only prevalent in everyday life, but they also abound in science. The field of metaheuristic algorithms, in particular, is rife with metaphors. While using metaphors in research can have its benefits, it is important to acknowledge their limitations and potential consequences. Some researchers who focus on developing new algorithms through the use of new metaphors fail to recognize that metaphors tend to emphasize certain characteristics of a topic or area while ignoring others [12] [13]. Instead, they should consider the need for new metaphors that highlight previously overlooked characteristics of complex relationships in intelligent swarms. The metaphors used by researchers studying intelligent swarms do not necessarily expand our knowledge about collective intelligence. In fact, they may even obscure it by avoiding a clear definition of an invariant for collective intelligence and describing only its external manifestations.

III. LEVELS OF ABSTRACTION AS A WAY OF CONCEALING METAPHORS

To demonstrate how metaphors can conceal certain aspects of knowledge while highlighting others, this paragraph will utilize the concept of abstraction. Additionally, this paragraph will provide a brief explanation of three metaphors: the ACO metaphor, the swarm intelligence or collective intelligence metaphor, and the metaphor based on Steven Harnad's work "To Cognize is to Categorize: Cognition is Categorization".

A. Mathematical explanation of abstraction

For mathematical explanation of abstraction Frege's axiom of abstraction that states:

$$(\exists y)(\forall x)(x \in y \Leftrightarrow F(x)), \quad (1)$$

is used. Here, set X is set of the concept or metaphor "Cognition as Categorization" that contains the elements that make up that concept. Set Y is set of the concept or metaphor of "Collective Cognition" with y elements that make up that concept. F(x) is arbitrary property of X set.

If the axiom of abstraction is true, then it follows that $Y \subseteq X$. Figure 1. illustrates concepts from the perspective of Venn Diagrams. This means that set X contains more elements than set Y since everything in set Y is also included in set X. In other words, all elements of Collective Cognition (Y elements) are encompassed by the concept of Cognition as Categorization (X elements). By reducing a concept's information content and retaining only its essential characteristics, we engage in abstraction and conceal certain knowledge. This also holds true for the ACO metaphor when compared to the metaphor of "Collective Intelligence".

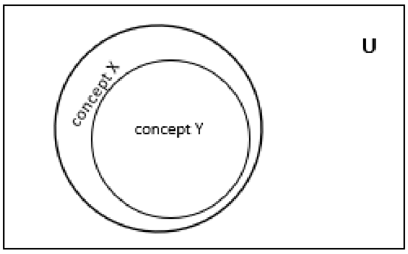

Figure 1. Y ⊆ X therefore an abstraction of Y is possible (author's work)

B. The Concept of Cognition as Categorization

The idea or comparison of how the mind works as a categorization process is explained by cognitive and computational neuroscientist Steven Harnad, who is known for his studies on consciousness, philosophy of the mind, and the significance of symbol processing in cognition. Harnad argues that living organisms are sensorimotor systems, making them a unique kind of dynamic system that can categorize information [11]. This sets them apart from other dynamic systems that are governed by the laws of physics. Harnad's definition of categorization highlights the systematic and distinct interaction that occurs between an independent and adaptable sensorimotor system and the surrounding environment.

Table 1. displays the main terms and sub-terms described in his work, serving as the essential foundation of the metaphor known as "Cognition as Categorization," which is established in this paper.

Table 1. The main elements of Harnad's description of cognition as categorization (author's work)

Main terms	Sub-terms
Sensorimotor system	/
Differential interaction	/
Autonomy	/
Adaptivity	/
Invariances in stimulation	/
Memory	Reinforcement Forgetting (amnesia)
Categories	Innate Learned
Types of learning	Unsupervised Supervised Instrumental
Ability of Categorization	Categorical perception Abstraction Absolute Discrimination Features weighting Dimension reduction

C. Ant Colony Optimization and Swarm Intelligence Concepts

After analyzing the concepts presented in the book "Ant Colony Optimization" [7], it can be concluded that there are two main concepts that form its basis. The first concept, which is pervasive throughout the book, is referred to as the Ant Colony Optimization (ACO) Metaheuristic. The second concept is the concept of natural optimization, which is described by the foraging behavior of ants and is essentially a form of swarm intelligence. This concept is based on the binary bridge experiment conducted by Deneubourg et al [14]. The two concepts are interconnected, as the second concept arises from the abstraction of the first.

The first concept, Ant Colony Metaheuristic, is described using pseudocode (as shown in Figure 2). It can be understood as the interplay of three procedures: ConstructAntsSolutions, UpdatePheromones, and DaemonAction [7]. Moving on to the second concept, which is the concept of swarm intelligence, we can refer to it as the concept of collective cognition in order to better understand its similarity to the concept of cognition as categorization. Here, cognition serves as the link between these terms. Since collective intelligence formed the basis for the development of ACO metaheuristics, it is reasonable to assume that ACO is an abstraction of collective intelligence (as depicted in Figure 3). The ACO metaphor simplifies the details involved in collective consciousness, but upon closer examination, these details become apparent once again.

```
procedure ACOMetaheuristic
  ScheduleActivities
    ConstructAntsSolutions
    UpdatePheromones
    DaemonActions          % optional
  end-ScheduleActivities
end-procedure
```

Figure 2. Concept of ACO Metaheuristic written in pseudocode. After Dorigo, Stutzle [3]

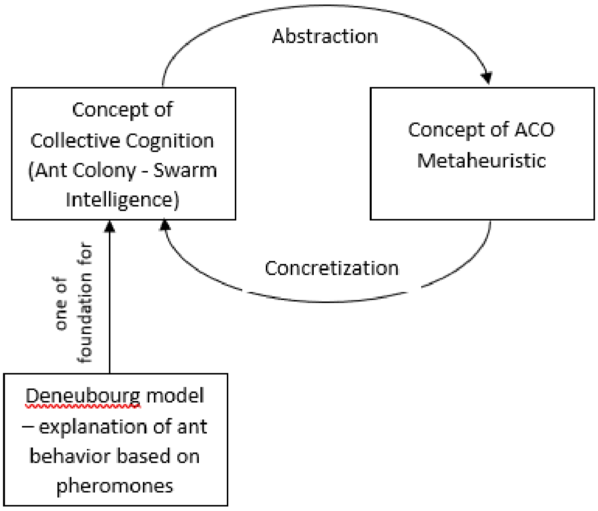

Figure 3. Concepts: Collective Cognition, ACO Metaheuristics and their relations (author's work)

D. Explanation of abstracting the concept of collective intelligence from the concept of cognition as categorization

Concept of Collective Cognition is formed by elements including self-organization and stigmergy. Self-organization relies on four basic ingredients: positive feedback (amplification), negative feedback that is counterbalance of positive feedback, amplification or fluctuations and multiple interactions [15]. Stigmergy refers to an indirect way of communication [15].

As ants, social insects, and other animals are sensorimotor systems, their behavior is not regulated by the laws of self-organization and stigmergy, but rather by the capabilities of each individual's sensorimotor system. To demonstrate this point, let's suppose that their sensorimotor system is incapable of systematic differential interaction with the environment. In such a scenario, ants would be unable to detect pheromone levels or select the most optimal path.

If we examine the elements of self-organization, particularly positive feedback, we can conclude that a sensorimotor system cannot function without feedback. Positive feedback is a property of every individual sensorimotor system, and when an ant colony searches for food, the collective positive feedback is a manifestation of the many positive feedbacks from each sensorimotor system. This positive feedback arises when stimuli undergo the process of cognitive categorization - from learning and memory to adaptation through systematic differential interactions.

The next ingredient in self-organization is negative feedback, which serves to counterbalance positive feedback. At the individual level of the sensorimotor system, this occurs in any situation where the sensorimotor system is engaged in categorization due to stimuli that indicate discrepancies in the environment.

Another ingredient of self-organization is amplification and fluctuation, which account for randomness and errors. At the level of the sensorimotor system, the categorization process is subject to errors such as misclassification and forgetfulness. However, in order for categorization to occur at all, the possibility of incorrect categorization must also exist.

The fourth and final ingredient of self-organization is the possibility of multiple interactions. When considering this ingredient, we must also take into account stigmergy. The reason for this is that multiple interactions occur through the influence of pheromones, which is an indirect form of communication known as stigmergy. At the level of the sensorimotor system, this form of communication represents the interaction between the system and its environment. Therefore, every interaction between individuals that involves the use of pheromones is a process of categorization, where the intensity and existence of the pheromone is categorized. Additionally, stigmergy can be seen as a way for an individual to communicate with hundreds of others from the past and present simultaneously.

IV. CONCEPT OF COGNITION AS CATEGORIZATION: A FUNDAMENTAL CONCEPT FOR ALL SWARMS-BASED METAHEURISTIC ALGORITHMS

As demonstrated in the preceding chapter, the use of metaphor has the capacity to obscure knowledge. **This applies to the metaheuristics of swarm-inspired algorithms as well, which are themselves conceptual metaphors or concepts. One of these concepts is ACO metaheuristics, which builds on the Concept of Collective Cognition, which, in turn, is based on a more fundamental concept. For a concept to be considered fundamental, it must possess a requisite number of constituent elements that enable abstraction.** As demonstrated in the previous section, Stevan Harnad's work can provide a foundation for the creation of a fundamental concept known as the Concept of Cognition as Categorization. Moreover, in Section III.D it has been shown that certain constituent elements of this concept can be utilized to abstract the Concept of Collective Intelligence.

Figure 4. demonstrates how abstraction is possible by starting with a basic concept and progressing to an intermediate concept, and ultimately to the highest level of abstraction. The law of transitivity applies to this process, which means that if we have three abstract concepts A, B, and C, and we know that A is related to B in a particular way, and B is related to C in a specific way, we can deduce that A is related to C in the same way. **This knowledge of the fundamental concept is sufficient for creating the final concept**. **This means that the Concept of Cognition as Categorization is fundamental for all swarm-based metaheuristic algorithms.**

Figure 5. demonstrates that the law of transitivity allows for the omission of the middle concept (Concept of Collective Cognition). However, it is debatable whether this intermediate concept is essential or not. **This paper presents a new perspective that suggests that it may not be essential, as it operates as a conceptual metaphor that obscures more comprehensive knowledge that could be utilized in shaping the final metaheuristic concept.**

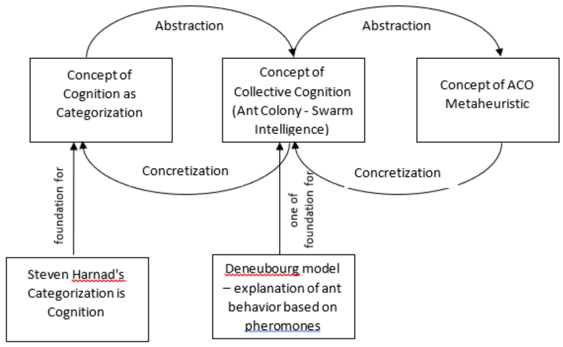

Figure 4. Concepts: Concept of Cognition as Categorization, Collective Cognition, ACO Metaheuristics and their transitive relation (author's work)

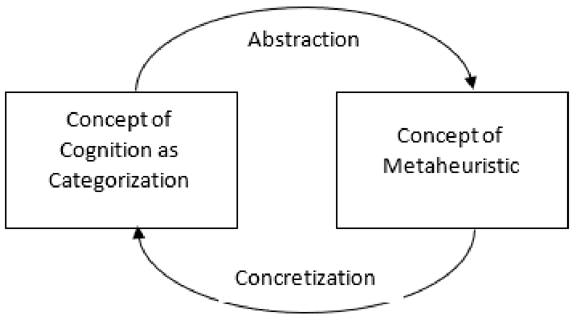

Figure 5. Concept of Metaheuristic is abstraction of fundamental concept Cognition as Categorization in the context of swarms (author's work)

V. CONCLUSION

After considering several algorithmic concepts, it became clear that they all shared a common basis - the concept of the organism as a sensorimotor system. The well-established concept of swarm intelligence and the concept of ACO were used to demonstrate how metaphors can conceal certain features through abstraction. This was applied to all three metaphors discussed in the paper. Ultimately, if algorithm designers can identify a basic metaphor, they can develop new components of algorithms that have a solid theoretical foundation in cognitive science. They do not need to delve deeper into the behaviors of various animals, from insects to mammals, as the abilities of the sensorimotor system define all of them and their communication features in specific environments.

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