

Further thoughts on the paper by Sayed

# Impact of Networked Cognition and Learning on Engineered Systems

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The research community is witnessing expansive efforts aimed at understanding one of the most wondrous manifestations of cognition in nature. The Blue Brain Project and the Human Brain Project in Europe are examples of ambitious drives aimed at building a virtual brain machine and at understanding the complexities of the human brain. In the United States, the recently launched Brain Initiative aspires to understand the dynamics of the billions of neurons in the brain at the cellular level. These are laudable efforts that will likely lead to new insights and treatment methods. They will also influence progress in many supporting disciplines including biology, chemistry, physics, and engineering. We are only touching the surface of this immense landscape and even today, we continue to have limited understanding of how networks of simple neurons are capable of producing so much sophistication. It is an astounding feat that elements with limited sensing and processing abilities, interacting locally, are able to transcend into a complex system with superior sensing and cognitive abilities at the higher level.

Another fascinating area of inquiry relates to the study of cognition in animal groups. Here again we observe how coordination and local interactions among simpler individual agents lead to remarkable forms of organized behavior at the group level. Examples abound in nature from fish schooling, to bee swarming, bird formations, or predator evasion maneuvers. In these examples, the agents are now mobile. Several existing optimization tools have benefited from studies of these patterns of organized behavior, such as the particle swarm optimization algorithm and the ant colony optimization algorithm. Although individual ants are unsophisticated agents, the ant colony is still able to solve the problem of finding the shortest path, e.g., from its colony to a food source, through limited interactions involving signaling using pheromones.

It is not difficult to envision future engineering systems benefiting more strongly from similar bottom-up approaches

involving coordination among less powerful units to achieve higher levels of cognition and performance. Robotic swarms are one example where agents can work together through an evolving topology, and adjust their location and exploration space in response to environmental conditions. The robotic agents would cooperate with each other to enhance their sensing and inference abilities, and would also adjust their positions and topology dynamically according to the task at hand. Adaptation and learning abilities become critical requisites to endow such networked agents with cognitive abilities: learning would allow them to extract information continually from their interactions with their neighbors, while adaptation would allow them to adjust to changes in the environment, changes in the topology, malfunctioning of neighbors, and even suspicious or selfish behavior by other agents or intruders.

Another example is the use of networked learners to mine information from huge data sets, such as those related to health informatics, transportation networks, power grids, social networks, or surveillance applications. In these scenarios, it is often the case that information is already spread in dispersed locations. And it may not be practical to aggregate the data in a single location for processing due to cost considerations, or even privacy and secrecy considerations. In such applications, decentralized learning and adaptation offers an attractive approach to information and signal processing.

Motivated by these broad considerations, in our paper on adaptive networks, we described how a family of networked agents can be made to adapt and learn continually from streaming data and from limited interactions among neighboring agents. We also explained how such networks can be used to solve optimization problems in a decentralized manner. By tapping into the experience of neighbors, the agents become stochastic learners, and they are able to enlarge their domain of exploration and enrich their ability to learn more thoroughly. Elements of cognition become embedded into the operation of the network. Each agent is not only capable of experiencing the environment directly, but it also shares information

with its neighbors and processes and analyzes information to drive its own learning process.

In the operation of such adaptive networks, the spatial domain becomes integrated with the temporal domain. By doing so, the “wisdom” of the group is able to complement the limitations of the individual agents. In classical information and system sciences, analysis has often centered around optimizing standalone systems, and information has long had a strong temporal (or 1-D) flavor with signals flowing over time. In the networked domain, the

abstraction moves to a higher level where information is now extracted from a 2-D intertwined domain involving both time and space. Apart from deciding what information to share, and which strategies to employ to process the information, it also becomes important to devise strategies to allow the agents to adapt the topology itself, to guide their mobility, and to identify and isolate selfish or harmful agents. The interaction among agents adds a new compounding effect and opens up a plethora of interesting avenues for exploration. ■