Self-Organized Pattern Formation in Coupled Electrochemical Cells Guided by Emergent Networks

Keywords: synchronization, pattern formation, network dynamics, batteries, neuromorphic computing

Extended Abstract

Electrochemical cells constitute the building blocks of biological and engineered systems. Batteries, most prominently, are complex systems in which highly nonlinear electrochemical reactions are coupled to a plethora of chemical, electrical, and mass transport effects [1]. Description and control of activity patterns in such systems are hindered by challenges in modeling due to the multiple time- and length-scales with large number of interacting units. While individual electrodes can exhibit complex behaviors such as bistability and oscillations [2], practical cells are composed of coupled anode-cathode systems organized into extensive battery pack networks [3]. Predicting and managing spatiotemporal patterns that arise in charge/discharge processes necessitates a system science approach [4], which integrates a multidisciplinary analyses of the interactions between chemical and physical processes.

In this contribution, we examine coupled electrochemical cells as a complex dynamical system by treating them as a network of interconnected units. Our objective is to extract interaction networks among the cells and utilize the derived network properties to explain spatiotemporal activity patterns. Common cell configurations are considered, such as serial and parallel coupled cells, which are expected to increase cell potential and current, respectively. With oscillatory cell charge/discharge processes, the emerging attractive and repulsive interactions are studied with in- and anti-phase synchronization patterns. With cells that can deactivate at large potentials, the impact of positive and negative coupling is demonstrated with symmetry-breaking electrode potential patterns reminiscent of Turing patterns. Finally, the emerging network of a four-cell system, comprising two serially and two parallelly coupled cells, are compared to Hopfield networks with Hebbian learning rules that are commonly used in pattern recognition learning tasks. The capability of performing in-situ chemical information processing without explicit learning, is tested by recalling activity patterns.

In conclusion, this study identifies emergent network structures within coupled electrochemical cells. The symmetry breaking patterns are interpreted through the interplay of features of reaction kinetics/dynamics and network properties. Our findings suggest that charge/discharge processes in energy storage systems may follow principles of self-organization similar to those observed in biological oscillator networks, offering insights into system degradation, reactivation, and recycling. Moreover, the spontaneous emergence of network templates akin to Hopfield networks from serially and parallelly coupled cells indicates that complex computational capabilities can arise without the need for mechanisms for supervised learning. This revelation provides an insight into aspects of origin of life, suggesting that the abiotic wiring of electrochemical cells, including neurons, could naturally develop sophisticated functionalities through inherent physicochemical interactions.

References

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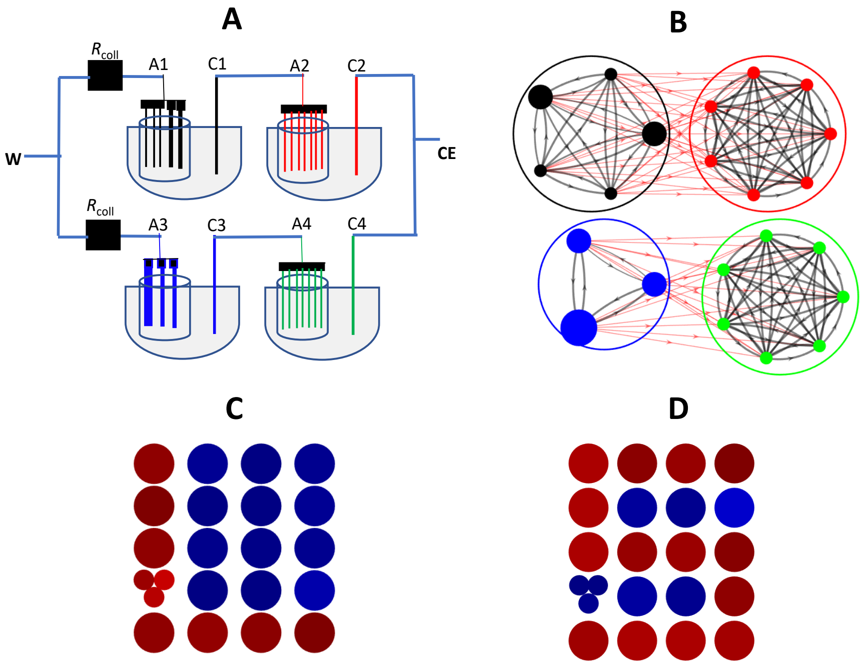

Figure 1. **Stationary Turing-like patterns induced by network interactions in electrochemical cells.** (A) Multielectrode electrochemical cells arranged in 2x2 configurations. (B) Inferred network interactions (black and red lines denote activatory and inhibitory coupling respectively). (C-D) Two experimentally detected, network induced Turing patterns. Red and black circles denote passive and active electrodes with large and low electrode potentials, respectively.