Neuromorphic Tissues: Intrinsic Recurrent Computing in Soft Biomolecular Networks

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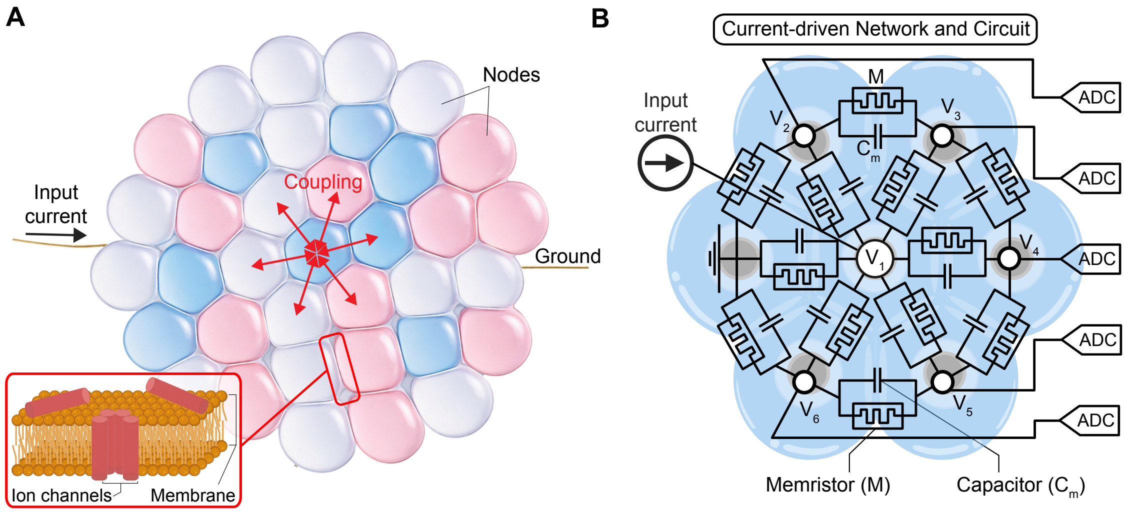

Figure 1: A. Heterogeneous interconnected droplets with voltage-gated membranes enabling dynamic coupling under current input. (Inset) Ion-channel-doped lipid membrane. **B.** Equivalent current-driven circuit with memristor–capacitor elements; nodal states are read as voltages.

Brains achieve efficient temporal processing through dense interconnectivity and recurrent dynamics. In contrast, most physical reservoir computing systems rely on parallel, uncoupled elements, limiting their effective dynamical order and computational capacity. Here, we introduce neuromorphic tissues as physical substrates for intrinsic recurrent computation. These systems consist of networks of aqueous compartments interconnected by lipid membranes containing voltage-gated ion channels. Input signals, encoded as current injections, polarize the capacitive lipid interfaces. Upon reaching a threshold, ion channels insert into the membrane, transiently forming conductive pathways that couple neighboring compartments. This mechanism enables dynamic, state-dependent connectivity, allowing signals to propagate, interact, and recur within the material. Unlike conventional architectures, where recurrence is externally imposed, it instead emerges directly from the physics of interconnection. We develop a current-driven operational framework and a physics-based state-space model that captures the coupled evolution of membrane voltage and pore density. This approach enables direct readout of network states via nodal voltages while preserving the nonlinear and fading-memory dynamics required for reservoir computing. Experimental measurements of multi-node networks show strong agreement with model predictions, validating the framework. These interconnected networks exhibit significantly enhanced computational capability compared to parallel reservoirs. In benchmark tasks, the system achieves accurate prediction of nonlinear temporal dynamics, including the NARMA-10 task, which is inaccessible to uncoupled memristive systems, and the Lorenz63 chaotic system, demonstrating the ability to process coupled, multivariate signals. Performance improves systematically with network size and nodal heterogeneity, highlighting key design principles for physical computation: interconnectivity enables reconstructive memory, while heterogeneous node dynamics expand the effective state space. Collectively, these results demonstrate that recurrence and higher-order dynamics can be embedded directly into matter. Neuromorphic tissues provide a pathway toward energy-efficient, in-materia computing systems for temporal inference, with potential applications in sensing, adaptive materials, and edge intelligence.