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RAIN Brains: Mammalian Neocortex as a Hybrid Analog-Digital Computer

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Abstract— What kind of computer is the mammalian brain? To improve upon simple rate-based artificial neural networks, computational neuroscience research over the past decade focused on more biologically realistic spiking neuron models—but still ascribing, on the millisecond time scale, a *digital* overtone to brain processing. A more recent development has been to explore the spectral properties of subthreshold membrane potentials, emphasizing an *analog* mode of computing. Together, by modeling the fine temporal structure of neural signals, these research trends have revealed a great diversity of collective *spatiotemporal regimes*: synchronization and phase locking, delayed correlations and traveling waves, rhythms and chaos, etc. Through recurrent (and plastic) synaptic connections, neural cells transiently interact as *dynamical subnetworks* that promise an immense richness of coding expression and computational power, combining the discrete and the continuous. What repertoire of dynamical regimes ("phase diagrams") can such subnetworks sustain? In the classical feedforward view, subnetworks (layers, cell assemblies) are initially mostly silent and have to be literally activated by an input or a "lower" area. Our work subscribes to a new paradigm, in which subnetworks already possess viable and complex endogenous activity modes that are only *perturbed* through coupling with an input or other subnetworks. Using spiking neuronal simulations, we describe here progress to-date towards building cohesive "analog-digital perturbation" principles that can underlie biological attention, pattern recognition, short- and long-term memory, and motor responsiveness to natural environmental stimuli. In particular, we describe the performance and sensitivity of dynamically igniting-and-quenching *R*ecurrent *A*synchronous *I*rregular *N*etworks (RAINs). We explore the regimes and phase transitions of RAINs under conditions of calibrated voltage-sensitive ionic membrane channels, synaptic facilitation and depression, and Hebbian spike-timing dependent plasticity (STDP). Specifically, we demonstrate the spontaneous emergence of alternating sub-100 millisecond states of subthreshold (i.e., analog) correlation-decorrelation, suggesting a natural mechanism of intrinsic clocking. We also study "lock and key" properties of RAIN activation, i.e., a model of pattern recognition and nondiscrete memory storage based on a dynamics of *coherence induction* triggered by input stimuli (the "keys"). Here, learning a pattern (a "lock") means tuning synaptic efficacies to a point of maximal postsynaptic response. Finally, we discuss the importance of embodied social robotics to "teach" intelligent behavior to RAIN brains, and speculate on the instantiation of RAIN brains in compact analog VLSI architectures.