

The evolution of emergent computation

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ABSTRACT A simple evolutionary process can discover sophisticated methods for emergent information processing in decentralized spatially extended systems. The mechanisms underlying the resulting emergent computation are explicated by a technique for analyzing particle-based logic embedded in pattern-forming systems. Understanding how globally coordinated computation can emerge in evolution is relevant both for the scientific understanding of natural information processing and for engineering new forms of parallel computing systems.

Many systems in nature exhibit sophisticated collective information-processing abilities that emerge from the individual actions of simple components interacting via restricted communication pathways. Some often-cited examples include efficient foraging and intricate nest-building in insect societies (1), the spontaneous aggregation of a reproductive multicellular organism from individual amoeba in the life cycle of the *Dictyostelium* slime mold (2), the parallel and distributed processing of sensory information by assemblies of neurons in the brain (3), and the optimal pricing of goods in an economy arising from agents obeying local rules of commerce (4). Allowing global coordination to emerge from a decentralized collection of simple components has important advantages over explicit central control in both natural and human-constructed information-processing systems. There are substantial costs incurred in having centralized coordination, not the least being (i) speed (a central coordinator can be a bottleneck to fast information processing), (ii) robustness (if the central coordinator is injured or lost, the entire system collapses), and (iii) equitable resource allocation (a central controller must be allocated a lion's share of system resources that otherwise could go to other agents in the system) (e.g., see ref. 5). However, it is difficult to design a collection of individual components and their local interactions in a way that will give rise to useful global information processing. It is not well understood how such apparent complex global coordination emerges from simple individual actions in natural systems or how such systems are produced by biological evolution. This paper reports the application of new methods for detecting computation in nonlinear processes to a simple evolutionary model that allows us to address these questions directly. The main result is the evolutionary discovery of methods for emergent global computation in a spatially distributed system consisting of locally interacting processors.

We use the general term "emergent computation" to describe the appearance of global information processing in such systems (see refs. 6 and 7). Our goal is to understand the mechanisms by which evolution can discover methods of emergent computation. We are studying this question in a theoretical framework that, while simplified, still captures the essence of the phenomena of interest. This framework requires (i) an idealized class of decentralized system in which global information processing can arise from the actions of simple, locally connected units; (ii) a computational task that neces-

sitates global information processing; and (iii) an idealized computational model of evolution.

One of the simplest systems in which emergent computation can be studied is a one-dimensional binary-state cellular automaton (CA) (8)—a one-dimensional spatial lattice of N identical two-state machines ("cells"), each of which changes its state as a function only of the current states in a local neighborhood of radius r . The lattice starts out with an initial configuration (IC) of N cell states (0s and 1s). This configuration changes in discrete time steps according to the CA "rule"—a look-up table mapping neighborhood state configurations to update states. At each time step, all cells examine their local neighborhoods (subject to specified boundary conditions), consult the look-up table, and update their states simultaneously. The CA's radius places an upper boundary on the speed of information transmission through the lattice. It also limits the sophistication of the local dynamics: the number of look-up table entries is 2^{2r+1} . Thus, fixing $r \ll N$ constrains the sophistication of a CA's explicit information processing.

A simple-to-define computational task for CAs that requires global information processing is deciding whether or not the IC contains more than half 1s. We call this the $\rho_c = 1/2$ task, with ρ_c denoting a threshold density of 1s in the input. If ρ_0 denotes the density of 1s in the IC, the desired behavior is for all cells to quickly change to state 1 if $\rho_0 > \rho_c$ and to quickly change to state 0 if $\rho_0 < \rho_c$. The $\rho_c = 1/2$ task requires global communication, since ρ_0 is a global property of the entire lattice; no linear combination of local computations—such as the cells computing the majority of 1s in their neighborhood—can solve this problem. Designing an algorithm to perform the $\rho_c = 1/2$ task is trivial for systems with a central controller of some kind, such as a standard computer with a counter register or a neural network with global connectivity. But it is difficult to design a decentralized, spatially extended system such as a CA to perform this task, since there is no central counter or global communication built in. It can be shown that no finite-radius CA can perform this task perfectly across all lattice sizes (9, 10), but even to perform this task well for a fixed lattice size requires more powerful computation than can be performed by a single cell or any linear combination of cells. Since the 1s can be distributed throughout the CA lattice, the CA must transfer information over large space-time distances ($\sim N$), and information from distant parts of the lattice must interact so as to perform the computation. With $r \ll N$, such information transmission and interaction can be accomplished only through the coordination of emergent high-level signals. Thus, this task is well suited for investigating the ability of an evolutionary process to design CAs with sophisticated emergent computational abilities.

One class of computational models of evolution are genetic algorithms (GAs) (11), which evolve a population of candidate solutions to an optimization problem by propagating the most "fit" candidates to the next generation via genetic modifications. We carried out a set of experiments in which a GA was used to evolve one-dimensional binary-state $r = 3$ CAs (with

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Abbreviations: CA, cellular automaton; IC, initial configuration; GA, genetic algorithm.

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