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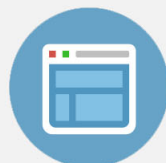
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Amoeba-inspired computing architecture implemented using charge dynamics in parallel capacitance network

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We propose an electronic system for implementing a biologically inspired computing architecture, called “amoeba-inspired computing,” for solving computationally demanding problems. The system consists of a parallel capacitance network. The spatiotemporal dynamics of an amoeboid organism exhibiting the sophisticated ability of exploring a solution space is mimicked using dynamics in charging the capacitors under charge conservation. The system for solving an instance of a four-variable constraint satisfaction problem (CSP) is implemented using an electronic circuit simulator, which successfully finds solutions. We also found that small fluctuations inherently involved in electronic devices can be used to explore solution space. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4826143>]

Biologically inspired computing architectures are expected to outperform conventional von Neumann-type computers in terms of solving computationally demanding problems, reducing energy consumption, and so on.^{1–3} In this context, a single-celled amoeboid organism, a plasmodium of the true slime mold *Physarum polycephalum*, is an attractive model organism. This amoeba connects optimal routes among food sources by deforming its amorphous body.^{4–6} Moreover, in the so-called “amoeba-based computer,” the amoeba finds high-quality solutions to complex combinatorial optimization problems, such as the traveling salesman problem, when its spatiotemporal dynamics involving stochastic fluctuations are controlled according to certain feedback dynamics.^{7–9}

Recently, Aono *et al.* abstracted an “amoeba-inspired model” from the solution-searching dynamics of an amoeba-based computer for solving one constraint satisfaction problem (CSP), satisfiability problem (SAT), which is the problem of judging whether a given set of logical constraints (a Boolean formula) can be satisfied.¹⁰ The SAT is a crucially important combinatorial optimization problem because it is related to diverse application problems in artificial intelligence, information security, and bioinformatics. However, it is a nondeterministic polynomial time (NP)-complete problem, which is believed to become intractable for conventional techniques when the problem size increases.¹¹ In fact, the number of all solution candidates of a Boolean formula, which should be examined to find satisfiable solutions, grows exponentially as a function of the number of variables in the formula.

The amoeba-inspired model can be implemented using various physical systems that exhibit appropriate spatiotemporal

dynamics resembling the amoeba’s fluctuating solution search process. Naruse *et al.* implemented these dynamics by exploiting the intrinsic quantum stochastic attributes of the energy transfer among quantum dots.¹² This nanophotonic computer can find a SAT solution with a smaller number of iterations than that of one of the fastest stochastic local search algorithms.^{13,14} It has also been developed to carry out efficient and adaptive decision making.¹⁵ These results confirm the potential of an amoeba-inspired computing architecture for developing a non-von Neumann-type paradigm. If amoeba-inspired dynamics can be reproduced using an electronic system, it will provide the most realistic and practical ways for solving the SAT. In this Letter, we propose an electronic amoeba-inspired computing architecture by using charge dynamics in a capacitor network and demonstrate a system for solving an elementary instance of CSP, which is used for testing if our system can be upgraded for solving the SAT.

One of the fastest stochastic local search algorithms for solving the SAT is WalkSAT, which finds a satisfiable solution with a reasonably large probability after a fairly small number of iterations.^{14,16} Given a Boolean formula f of m variables, $x_1, x_2, \dots, x_m$ ($x_j \in \{0, 1\}$), WalkSAT starts from a randomly chosen assignment $\mathbf{x} = (x_1, x_2, \dots, x_m)$. At each iteration, by checking whether every module (clause) in f is satisfied by $\mathbf{x}$, WalkSAT randomly selects one of the unsatisfied modules and satisfies it by flipping one of its variables selected at random. This routine is iterated until $\mathbf{x}$ satisfies f or we run out of time. The amoeba-inspired model¹⁰ and its nanophotonic version¹³ outperformed WalkSAT dramatically for hundreds of benchmark instances available online at SATLIB.¹⁷ The origin of the high performance of the amoeba-inspired model can be attributed to the concurrent nature of its spatiotemporal dynamics, which involves spatial and temporal correlations among the time evolution of the

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variables. That is, in contrast to WalkSAT, which flips a single state without implementing any interaction among the variables, the amoeba-inspired model updates many states at a time through a large number of interactions among the variables, which exchange information on the success and failure in their trial and error process through feedback control dynamics. This difference in the number of interactions might result in a huge difference in performance.

The amoeba-based computer is schematically shown in Fig. 1(a).⁷⁻⁹ An amoeba is placed in a multi-lane template on an agar plate. The state transition is represented by the amoeba's shape deformation under optical feedback control. The i th lane of the template, called "unit i " ($i \in \{1, 2, 3, 4\}$) with a state variable x_i , is in the active state $x_i = 1$ whenever the fraction of the area occupied by the amoeba's branch exceeds a certain threshold value; otherwise, it is in the inactive state $x_i = 0$. The amoeba inherently attempts to extend all branches to occupy the entire agar region, keeping its total volume constant; thus, each unit attempts to become active in principle. We can inactivate the unit by illuminating the corresponding region because the amoeba's branch shrinks due to its photoavoidance response. The conservation of the volume results in the spatial correlations in the time evolution of the variables; a volume increment in one branch is immediately compensated by volume decrement(s) in the other branch(es).

The optical feedback control system updates the illumination according to a rule that is determined by a given CSP instance. Let us consider a simple instance stated as follows: find a configuration $\mathbf{x} = (x_1, x_2, x_3, x_4)$ such that all units satisfy $x_i = \text{NOR}(x_{i-1}, x_{i+1})$.⁷ This instance is represented by introducing the following rule, called the "NOR rule," which updates the illumination y_i at each interval in the following manner: if $x_{i-1}(t) = 1$ or $x_{i+1}(t) = 1$, then unit i is illuminated as $y_i(t + \Delta t) = 1$; otherwise, non-illuminated as $y_i(t + \Delta t) = 0$. Namely, unit i is illuminated to be inactive when at least one of its adjacent units is active. There are two solutions to this

instance, (1, 0, 1, 0) and (0, 1, 0, 1), which are stably maintained because the amoeba's shape representing one of them is no longer forced to reshape by illumination (i.e., if $y_i = 1$ then $x_i = 0$) while maximizing the total volume (i.e., if $y_i = 0$ then $x_i = 1$). When $\mathbf{x}$ satisfies $x_i + y_i = 1$ for all i , we can obtain $\mathbf{x}$ as a solution.

It should be mentioned that concurrent processing of the circularly connected NOR operators become deadlocked when all operations are executed in a synchronous manner. Suppose that all branches extend or shrink with the same velocity. From the initial configuration (0, 0, 0, 0), the synchronous extension of all branches will lead to (1, 1, 1, 1). When all units are illuminated, all branches shrink simultaneously to escape the illuminations. Then they return to the initial configuration synchronously. This means that the system never reaches a solution. The amoeba-based computer, however, solves this problem since its movement involves intrinsic fluctuations to break the synchronization.⁸

Our electronic system implementing the amoeba-inspired computing architecture is shown in Fig. 1(b). This is a parallel capacitance network, and the dynamics of the amoeba are represented by charging of the capacitors. The system consists of four units that are counterparts of the branches of an amoeba. A feedback circuit is also added to the system to give the NOR rule. Each unit includes two capacitors, a resistor, diode, and bypass field-effect transistor (FET). Every unit connects to a common hub node. The state variable x_i of this system is represented by the voltage V_{x_i} across the capacitor C_i connected to the cathode of the diode. A charge conservation law at the hub represents the constraint of the mass conservation of the amoeba volume. For charging the capacitor, a constant current is supplied from a current source to the hub. In this configuration, the total current in the hub is conserved in accordance with Kirchhoff's current law, which is the dynamic version of the charge conservation. Only charging occurs in C_i by the unidirectional diode current. A capacitor, C_{pi} , and resistor, R_i , are inserted in the anode side of the diode to adjust the timing to turn the diode on. The bypass transistor discharges the capacitor when voltage V_{y_i} is provided to the gate from the feedback circuit as the inhibit signal y_i . We examined the unit and its integrated system using a conventional electronic circuit simulator.

Figure 2 shows the basic response of a unit. The parameters of the unit are $C_i = 5 \mu\text{F}$, $C_{pi} = 1 \mu\text{F}$, and $R_i = 100 \Omega$. The injected DC current, I_i , is $1 \mu\text{A}$. When the current is injected into the unit, C_{pi} is charged and the diode turns on. Similar to the unidirectional growth of the amoeba's branch, voltage V_{x_i} linearly increases with time in accordance with $V_{x_i} = I_i \Delta t / C_i$, where Δt is elapsed time. When the bypass transistor turns on by V_{y_i} , C_i is discharged and V_{x_i} decreases, corresponding to the illumination. In Fig. 2, the output of the unit is followed by a buffer inverter to transfer the state variable to the logic circuit. The state variable is binarized and inverted by the sigmoid-like voltage transfer characteristic of the inverter. Once V_{x_i} reaches the threshold, C_i maintains the charge and V_{x_i} holds the previous value. It is held even if I_i decreases because the diode turns off.

Figure 3(a) shows a diagram of the system for solving the four-variable NOR instance. The NOR rule, which is

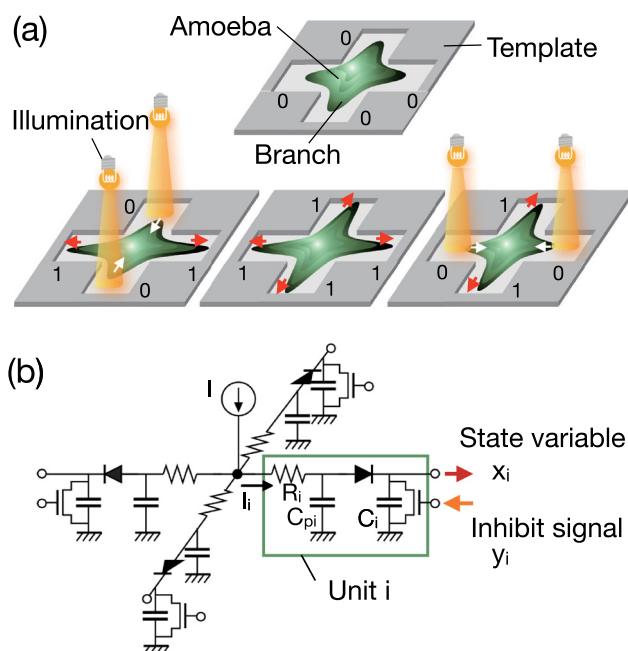


FIG. 1. (a) Basic behavior of amoeba with four branches and (b) capacitance network system implementing amoeba-inspired spatiotemporal dynamics featuring four units corresponding to branches.

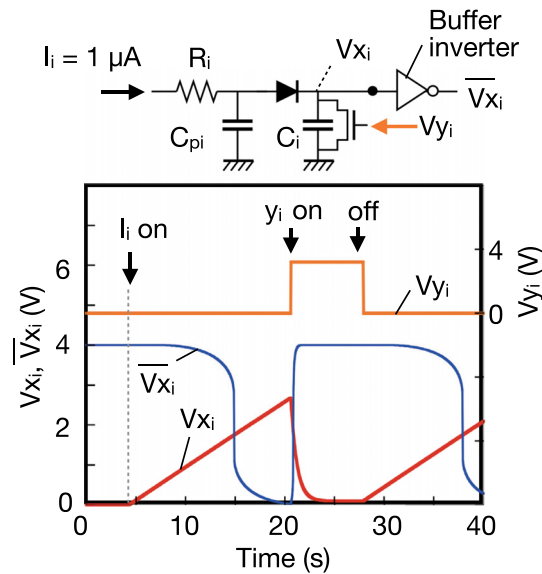


FIG. 2. Charging and discharging characteristics of unit in our electronic amoeba-inspired system together with output of buffer inverter.

represented by an equivalent form, $\overline{\text{NAND}}(\bar{x}_{i-1}, \bar{x}_{i+1})$, is implemented using logic gates in the feedback circuit, taking into account that the buffer inverts V_{x_i} and the inhibit signal V_{y_i} turns V_{x_i} to 0 so that $x_i = \bar{y}_i$. For simulation, a constant current, I , of $15 \mu\text{A}$ was supplied to the hub. Although the amoeba uses its intrinsic fluctuations for searching for solutions, the electronic circuit operates in a deterministic manner. Thus, we evaluated how our system behaves differently with the change in the resistance in the first unit, R_1 . The other resistances were fixed at 100Ω . Figures 3(b) and 3(c) show the results obtained when $R_1 = 95$ and 105Ω , respectively. All state variables started from 0 V (i.e., $\mathbf{x} = (0, 0, 0, 0)$) and linearly increased at the beginning. At 2.7 s, the variables suddenly bifurcated. After 8 s, the system gradually reached the quasi-equilibrium state. Two variables oscillated between 1.65 and 1.0 V, while the others kept constant at 1.75 V. These states continued for over 2 min, at which point the system found the solution. When we regarded the oscillating states as “0” and the constant states with $V_{x_i} > 1.7$ V as “1,” the solution vectors (1, 0, 1, 0) and (0, 1, 0, 1) were obtained for $R_1 = 95$ and 105Ω , respectively. These results confirmed that the solution space could be explored by varying the appropriate parameters in the circuit. The critical time of bifurcation, t_c , was estimated from the charging time of C_i to the threshold voltage, V_{th} , of the buffer inverter and the total number of units, n , as $t_c = C_i V_{th} / (I/n)$ when $C_{pi} \ll C_i$.

To observe the sensitivity of the state variables to the circuit parameter, we examined the computation by changing R_1 from 50 to 150Ω . Figures 4(a) and 4(b) show histograms of the obtained state variables when R_1 was decreased and increased from 100Ω , respectively. Solutions (1, 0, 1, 0) and (0, 1, 0, 1), out of 2^4 candidates with one exception of (1, 1, 1, 1) at $R_1 = 100 \Omega$, were found with our system. When all resistors had the same value, the system fell into a deadlock. As R_1 slightly changed, the symmetry broke and the system escaped from the deadlock. When $R_1 < 100 \Omega$, the system always reached (1, 0, 1, 0), as shown in Fig. 4(a). On the other hand, when $R_1 > 100 \Omega$, as shown in Fig. 4(b), the

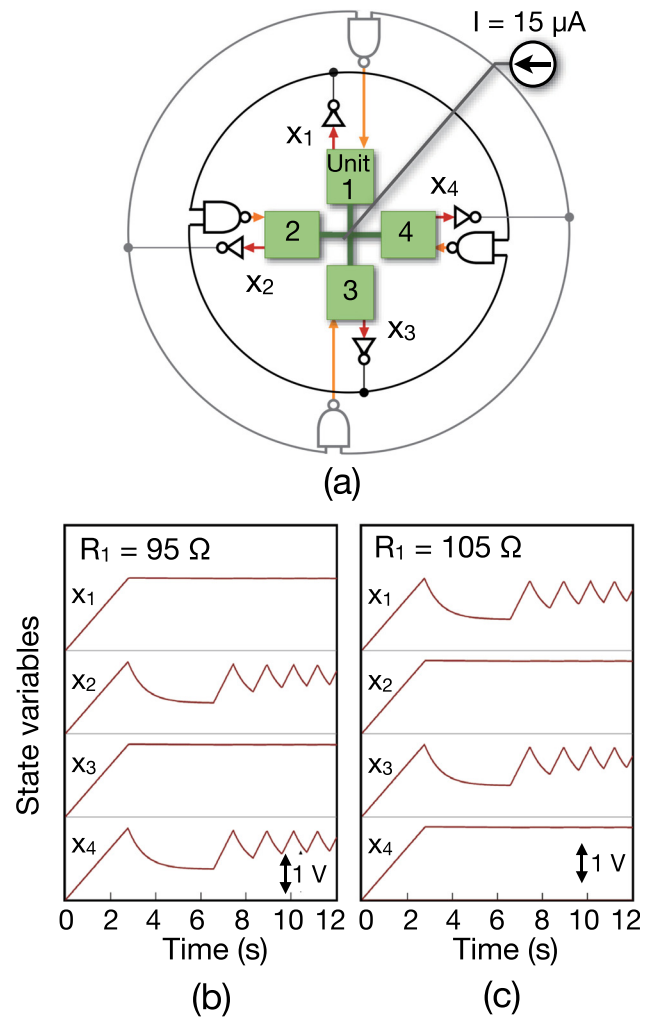


FIG. 3. (a) Diagram of computer system for solving 4-variable CSP instance of $x_i = \text{NOR}(x_{i-1}, x_{i+1})$ and examples of calculated state variables for different resistance values in 1st unit: (b) $R_1 = 95 \Omega$ and (c) $R_1 = 105 \Omega$. The other parameters were same as those in Fig. 2.

system almost reached (0, 1, 0, 1), but sometimes reached (1, 0, 1, 0). The solution depended on R_1 in an unsystematic manner; however, the calculated results were always the same when R_1 was the same.

The above unsystematic behavior is problematic since the system is described by deterministic circuit equations. However, the exponential nonlinearity of the system from the diodes and the FETs may be quite sensitive to the parameters and/or numerical errors. The unsystematic behaviors of the system are qualitatively discussed based on the framework of basic electronic circuit operation. The response of the unit in Fig. 2 shows that a smaller resistance accelerates the charging of the capacitors in the unit. Then, “1” is assigned to the state variable of the unit before other units. Considering the NOR rule, the unit that first becomes “1” inactivates the two adjacent units. Therefore, when $R_1 < R_2 = R_3 = R_4$, the system is expected to reach $\mathbf{x} = (1, 0, 1, 0)$. In fact, the results in Fig. 4(a) verify this estimation. In contrast, when R_1 is higher than the others, x_2 , x_3 , and x_4 simultaneously reach “1” and the system is expected to fall into unstable conditions. A possible reason for the breaking of the synchronization is unintentional fluctuation such as rounding errors in the numerical simulation.¹⁸ For example,

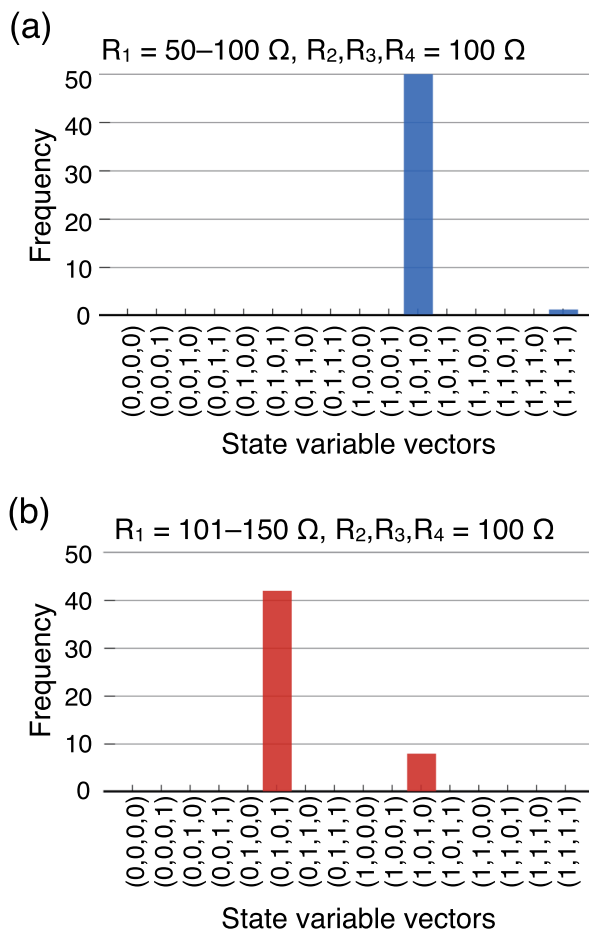


FIG. 4. Histogram of obtained solutions when R_1 was varied: (a) from 50 to 100 Ω and (b) from 101 to 150 Ω . Solutions of instance were $(1, 0, 1, 0)$ and $(0, 1, 0, 1)$.

we found that the appearance frequency of the two solutions and $(1, 1, 1, 1)$ changed when the time resolution in the numerical simulation was lowered. Note that the system always reaches one of the two solutions, except deadlock, even with some variations and errors in the computing. The more frequent appearance of $(0, 1, 0, 1)$ than $(1, 0, 1, 0)$ in Fig. 4(b) seems to be due to the short Hamming distance from $(0, 1, 1, 1)$, which requires less errors to occur.

The contribution of fluctuations to our system is similar to that in the ordinary differential equation model of the amoeba-based computer.¹⁸ Considering that our system always reaches one of the solutions except deadlock, this suggests the capability of spontaneous searching of more than one solution. In the physical electronic circuit, fluctuation is provided from the external electromagnetic noise, low frequency noise in FETs,¹⁹ statistical variation in nanodevices,²⁰ and so on. In addition, the degree of the parameter variation in our system affected the solution space that the system could search. Thus, our system is a non-equilibrium system featuring spatiotemporal charge dynamics, concurrent updating of state variables, and exploitation of tiny fluctuations. It is an important future issue to understand the optimal fluctuations, which will result in the fastest solution-searching ability, referred to as stochastic resonance.^{21–23}

In conclusion, we electrically implemented our amoeba-inspired computing architecture for solving a four-variable

CSP instance using charge dynamics in a parallel capacitance network. This suggests that our system can be developed to solve the SAT by modifying the feedback rule according to the procedure given in previous work.^{10,13} This indicates the possibility of developing a non-von Neumann-type computer that can be used to solve a wide variety of application problems with high-speed operation and low power consumption. In fact, the electronic implementation enables us to use sophisticated Si-based large-scale integration circuit (LSI) technology, and massive integration of the units shown in Fig. 2 of over a million/cm² is feasible. Assuming a current of 1 $\mu\text{A}/\text{unit}$ and a supply voltage of 1 V, the estimated power consumption of the million units is on the order of 1 W, comparable to that of the conventional microprocessor. Increased speed and reduced power consumption will be possible by decreasing the capacitance in each unit since these parameters are proportional to the capacitance. Thus, nanotechnology is feasible for our system, even when being affected by various fluctuations.

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