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Minimal model of a cell connecting amoebic motion and adaptive transport networks

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A cell is a minimal self-sustaining system that can move and compute. Previous work has shown that a unicellular slime mold, *Physarum,* can be utilized as a biological computer based on cytoplasmic flow encapsulated by a membrane. Although the interplay between the modification of the boundary of a cell and the cytoplasmic flow surrounded by the boundary plays a key role in *Physarum* computing, no model of a cell has been developed to describe this interplay. Here we propose a toy model of a cell that shows amoebic motion and can solve a maze and a spanning tree problem. Only by assuming that cytoplasm is hardened after passing external matter through a cell can the shape of the cell and the cytoplasmic flow be changed. Without cytoplasm hardening, a cell is easily destroyed. This suggests that cytoplasmic hardening caused by external perturbation can keep a cell in a critical state leading to a wide variety of shapes and motion.

Keywords: Physarum; Natural computing; Cell model; Amoebic motion; Adaptive network.

1. Introduction

A new paradigm of computing which utilizes biological or natural intelligence has been advocated(Paun et al., 1998; Adamatzky, 2007a; Paun 2002; Agladeze et al., 1997). It has been shown that a unicellular system, *Physarum*, can solve a maze(Nakagaki et al., 2000; Nakagaki, 2001), compute a logical operation(Tsuda et al., 2004; 2006), and solve a spanning tree problem(Adamatzky 2007a) by means of an adaptive network. *Physarum's* intelligence is described as the ability to remove redundant paths from all possible paths(Tero et al., 2007). Since a cell has not only intelligence but the ability of self-movement, amoebic motion has been studied in terms of the physico-chemical interaction of actin fibers(Bottino et al., 2002; Karakozova et al., 2006) and dynamic boundary(Varela 1979; McMullin & Varela, 1997; Zeleny, 1977; Suzuki & Ikegami 2007). However, no proposal has been made to connect amoebic motion with network formation. The relationship between them plays an essential role in computing, since computing redundant paths, for example, is carried on by the cytoplasmic flow encapsulated in a membrane(Adamatzky 2007b) thus producing amoebic motion. The mechanism of amoebic motion is implemented by cytoplasmic flow accompanying cytoskeleton transport, and the effective cytoplasmic flow is guided by the assembly of fibers (Verkhovsky et al., 1999; Pollard & Borisy, 2003). Many cell movements appear to be driven by polymerization of the cytoskeleton, such as actin filaments, and that cell movement is dependent on the distribution of the cytoskeleton, and motion re-organizes the distribution. Although network formation of *physarum* can be driven by the same mechanism, most researchers do not pay attention to the mechanisms with respect to *Physarum's* intelligence.

A cell is regarded as a minimal life form which makes its own boundary from membrane components, in the context of the origin of life (Ganti 2003; Szoztak et al., 2001; Luisi, 2006). Models for a proto-cell based on cellular automata (McMullin & Varela, 1997; Suzuki & Ikegami, 2007) and their chemical implementations(Bachman et al., 1992; Zepik et al., 2001) have been proposed. In these, researchers focus on the self-sustainability of a cell that is implemented by the stable bonding of the membrane components. Due to the stable bondage, the shape of model cells is maintained not far from being oval, and never forms a network like *Physarum*. The question arises whether self-sustainability of a cell can allow a variety of cell shape from an amoeba to a network form.

Here we show that our cell model, CELL, moving like an amoeba can form an adaptive network to solve a maze and a spanning tree problem. By giving up the usual strong bonding of membrane components and introducing the rapid flexibility of cytoplasm, CELL produces a fragile but dynamic motion. Cytoplasmic flow is modeled by the transportation of external matter. A CELL continually takes in external matter, which leads to shape modification and a self-sustaining structure. External matter is transported with fibers that are deposited somewhere in a CELL. It is assumed that soon after transportation the cytoplasm hardens and loses the ability to flow and this creates an adaptive network from a sponge-like structure. Through the transport of external matter, the computing system interacts with its own boundary. When this transportation is combined with the rapid flexibility of the cytoplasm, the interplay between the computing system and its boundary is enhanced in a way which robustly sustains the system.

2. Definition of Model

Although our cell model, CELL, is very simple, it is consistent with many properties of real cells. CELL is based on the following assumptions. (i) A cell is a mass of cytoplasm surrounded by a membrane. (ii) The membrane is the marginal part of a cell where the cytoskeleton is concentrated and hardened. (iii) Once a cytoskeleton assembly is de-polymerized and part of the membrane is softened, the cytoplasm is distributed to other areas in the cell by the flow of the softened part. This leads to shape modification and cell locomotion. (iv) Cytoplasmic flow is accompanied by transportation of the cytoskeleton, and is guided by the distribution of cytoskeleton assemblies.

The model CELL has two phases: a development phase and a foraging phase. In the development phase, an aggregation of cell-components is derived from an initial seed. This makes CELL satisfy the property (i) and (ii) mentioned above. CELL in the foraging phase corresponds to the vegetative state of *Physarum* and/or an amoeba. Given a planar lattice, each site has state of 0, 1, …, m (final state, natural number) or –1 and a neighborhood (north, south, east and west). The state transition rule is shown in Fig. 1A, and the neighbors of each site are shown in Fig. 1B. Given a seed with state 1, neighbors of a seed that are state 0 become state 2, and the state 1 seed also becomes state 2. This leads to a diamond-shaped aggregation consisting of sites in state 2. Eventually, we obtain a diamond-shaped aggregation consisting of sites in state m. Since site in state m whose neighbors are all in state m becomes a site in state –1, we obtain an aggregation of sites in state –1 surrounded by sites in state m (Fig. 1C). This aggregation is the initial configuration of a CELL. After the development phase, a cell always consists only of states the boundary, m and the inside, –1. Thus, we hereafter label the state of the boundary by 2 and the state of the inside by 1.

A CELL is described as an aggregation of lattice sites in a particular state: the inside (state 1) is surrounded by a boundary (state 2) in a lattice space consisting of the outside (state 0) (property (i)). It is assumed that the boundary state corresponds to an assembly of cytoskeleton fibers (property (ii)). After a development phase, a CELL "eats 0", and this gives rise to both migration and modification of the CELL. Eating 0 or invasion of the outside into a CELL corresponds to the process of softening a particular part of the membrane (property (iii)). Cytoplasmic flow toward the softened area is implemented by the transportation of the "eaten 0", which we call a bubble. During this transportation, the bubble is accompanied by cytoskeleton (i.e., state 2) which leads to a re-organization of the distribution of the cytoskeleton (property (iv)). The algorithm of "eating 0" is the following:

(1) Choose one site with state 2, and call the site the stimulus point.
(2) Randomly choose one of the stimulus point's neighbors in state 0. Replace the state of the stimulus point with the state of the chosen neighbor. Thus 0 invades the CELL, and that 0 is called a bubble.

(3) State 1 is replaced by 2. Thus all sites of the CELL are now in state 2. Set the number of moves to 0.

(4) Mark the site at which a bubble is present.

(5) Decide whether *s* sites of the bubble's neighbors are in state 0 or not. If yes, go to (8), otherwise go to (6).

(6) Decide whether the number of moves exceeds the threshold *n* or not. If yes, go to (8), otherwise go to (7).

(7) Randomly choose one of the bubble's non-marked neighbors which is in state 2. Replace the state of the bubble with the state of chosen neighbor. Add 1 to the number of moves. Go to (4).

(8) Reorganize the boundary and the inside, and i.e., if a site with state 2 is surrounded only by neighbors with state 2, its state is changed to 1. Return to (1).

Fig. 2 shows how a CELL is modified by applying the algorithm. We call the transportation of a bubble without crossing its own trace "memorized flow". The memorized flow is implemented by the procedure (4) and (7).

3. Basic Behavior of CELL

The algorithm (1)-(8) is common for all simulation studies described here. If the choice of a stimulus point is made randomly, a CELL moves like an amoeba. If a stimulus point is chosen from several active zones, a CELL forms an adaptive network. If there are several active zones, the forces moving a CELL oppose each other and a CELL forming an adaptive network stays in one place. Whether a CELL shows amoebic behavior or forms an adaptive network depends only on the way of choosing a stimulus point. A CELL allows a bubble to occur inside it. Due to the transition rule, the bubble is surrounded by the boundary component of sites in state 2. Thus we can choose a stimulus point inside the CELL such as the boundary of a bubble. If we do so, the existing bubble is moved and can be excluded from a CELL. If the position at which a bubble is present is not checked (step 4 is omitted), then there is no memorized flow. Without step 4 a CELL is easily destroyed.

Step 5 gives the condition for whether a bubble is excluded or not. In our simulations, *s* is set 3 or 4. This means that if at least three neighbors of a bubble have state 0, then the bubble is considered to be excluded from a CELL, the movement of the bubble is stopped and a new stimulus point is chosen. Step 6 limits the number of moves a bubble can make. In our simulations, $n = 1000$. Due to step 8, an aggregation of state 2 sites is changed to an aggregation of state 1 sites surrounded by state 2 sites. That is, the boundary and the interior are reorganized. Steps 3 and 8 mean that the boundary of an aggregation is always maintained at the outer edge of a CELL, and that external matter (bubble) is always combined with fibers (boundary component) when being transported. Due to step 7, a bubble avoids its own path, and that produces a memorized flow for the bubble. Memorized flow is why a bubble can easily explore new areas in a CELL such as narrow areas called tentacles (Fig. 2). On the other hand, memorized flow can easily lead to a bubble being deposited in a CELL if the bubble proceeds in a spiral way to reach a dead end (Fig. 2).

Amoebic motion. Eaten 0 passes through the CELL giving rise to the modification of the CELL shape. It reveals an amoebic motion. One site of the boundary (state 2) is randomly chosen, and its neighboring state 0 site swaps state with the chosen boundary site. This results in the invasion of a site of state 0 into the CELL which we call a bubble. Once a bubble invades a CELL, it diffuses in the CELL till the bubble is excluded or the step-wise motion of the bubble is terminated. It is assumed that a bubble never crosses its own path (Fig. 2). By this "memorized flow" we refer to effective cytoplasmic flow toward the front of motion, guided by the assembly of fibers(Verkhovsky 1997; Pollard 2003), because the cytoplasmic flow is implemented by reverse 0-flow. This "eating 0" is iterated, and that makes a CELL move or causes it to be modified.

A bubble sometimes remains and grows in a CELL(Fig. 3A). Figure 3A shows how the memorized flow contributes to the complex amoebic motion. A bubble grows bigger and makes a large chamber of sites in state 0 in the CELL. Due to the transition rule, the bubble is surrounded by boundary material (also see Fig. 2). When a bubble stops moving in the boundary, the chamber is broken and that makes a tentacle. Once a bubble is transmitted along the tentacle, it is immediately expelled via the open end because the memorized flow prohibits reverse flow or bubble's wandering along the tentacle. Thus a tentacle is shrunk by one bubble length. Even when a part of the CELL exhibits amoebic behavior and the rest of it is left as a long tentacle, the tentacle is shrunk and the oval shape of the CELL is recovered (Fig. 3A). If a bubble flows without regard to its previous path, it is more difficult to exclude a bubble, and more bubbles remain in the CELL. This destroys the CELL itself (Fig. 3B). It shows that memorized flow keep CELL in critical state. The memorized flow sometimes drives a bubble into dead end in CELL (Fig. 2 right bottom), and that makes a big 0-chanmer and many branches in CELL. It is close to destruction of CELL. However, also due to the memorized flow, any tentacles is shrunk and CELL cannot be broken.

Adaptive network. The formation of adaptive networks by *Physarum* can also be explained only by "eating 0" process or by the mechanism of tentacle formation in a CELL (Fig. 4). The body of *Physarum* consists of tubular actin-myosin fibers and cytoplasm. If fibers are distributed heterogeneously, the body becomes a sponge. If fibers are transported by cytoplasmic flow in a preferred orientation, a tube is made up of fibers(Naib-Majani et al., 1982; Stockem & Brix, 1994). Since the transport of a bubble entails the deposition of the boundary material (state 2 sites) in the CELL, the boundary material can be interpreted as fibers. The binding of state 2 sites leads to a tubular structure in the CELL. When given active sites made by food in a triangular layout *Physarum* forms an adaptive network connecting the three sites with an approximation to the minimal path(Nakagaki et al., 2004). Given an expanded CELL, we let bubbles invade the CELL from the boundary within three active zones (Fig. 4 top left). Iterated invasion grows the parts of the CELL in the active zones, and many bubbles are left in the CELL. Coalescence of bubbles leads to the formation of a large chamber of state 0 sites (Fig. 4 top center and top right). The boundary is destroyed and tentacles are formed. An open ended tube always shrinks like a tentacle (Fig. 4 bottom). This can lead to the removal of redundant paths, where the paths are continually generated and destroyed through the transport of fibers. The CELL approximates the minimal path connecting the three active zones like *Physarum* does. Once a loop structure is removed, a network is maintained by a CELL. Fig. 5 shows the formation of adaptive network under the four active zones. As well as three active zones, the CELL approximates the minimal path connecting active zones.

Maze-solving. While it is known that *Physarum* solves a maze(5,6), it is easy to see that CELL has the ability of solving a maze. After generating a CELL along a maze, we set two active zones representing the start and the goal of a maze (Fig. 6A left). Because of the transport of a bubble invading a CELL from the active zones, cell components with state 1 (the inside) are transported from the maze area to the active zones (Fig. 6A center). Finally the minimal path connecting the start and the goal is left, and most of the CELL is at the active zones (Fig. 6A right). CELL mimics *Physarum's* maze solving by cytoplasmic flow from the maze area to the active zones.

Spanning tree problem. It is also known that *Physarum* can solve a spanning tree problem. Given points of planar set, if all points are connected with minimal edges and without loops, the graph is called a spanning tree. If points are set as active zones made of food, *Physarum* approximates the spanning tree. In Fig. 6B, a CELL eats 0 from any boundary, then it moves like an amoeba. When the CELL encounters active zones, bubbles invade the CELL mainly from the active zones. Then the state 1 sites of the CELL are concentrated in active zones and other regions are shrunk. Although loops are kept for a while, they are finally removed and a spanning tree is obtained.

Amoeba encountering food. Fig. 6C shows that a CELL moving like an amoeba forms an adaptive network and then moves again. In this simulation three active zones are fixed in a plane, where "food" is assumed to be limited (i.e., the number of bubble-invasion is limited). Stimulus points of CELL are chosen randomly before CELL's encountering active zones. Thus, CELL first moves like an amoeba to search for food (Fig. 6C top left). Once a CELL encounters active zones, cytoplasm of CELL (state 1) flows toward active zones and then CELL shows a pattern connecting three active zones like reverse V-shaped pattern. After that CELL approximates the minimal path connecting three active zones, in showing reverse Y-shaped pattern. In this simulation, mass of cytoplasm of CELL is so small that cytoplasm concentrated at active zones is unstable and is perpetually moved. However CELL concentrated at three active zones are dynamically changed, the minimal path can be kept till the food is consumed (Fig. 6C top). The CELL breaks up the adaptive network after finishing eating, and the three regions are unified again (Fig. 6C bottom).

4. Discussion

We explain how the memorized flow of a bubble plays a part in making and withdrawing a tentacle and solving a maze. Fig. 7A shows how a loop is cut and tentacles are withdrawn. The left-hand diagram shows a CELL with a loop and a tentacle. If many bubbles are connected in a CELL, a big chamber consisting of state 0 appears. That leads to a loop in this CELL. Assume that a stimulus point is chosen randomly. The candidates are all black sites of the left-hand diagram of Figure 7A. If a point on the loop is chosen (indicated by thick arrow), it is transported either downward or upward. Assume downward. The bubble is transported to the chamber consisting of state 1 (gray), and it may enter the loop again. Assume that it enters the loop again. Since a bubble cannot cross its own path, it stops at the very position where a bubble invaded. As the number of moves is finite (step 6 in the algorithm), the stopped bubble cuts the loop at this position where the bubble invaded. Once a loop is cut, it produces tentacles, and we obtain the right-hand diagram in Fig. 7A. It is easy to see that any tentacle is withdrawn into a CELL. If a bubble invades from the boundary of a chamber consisting of state 1 and enters a tentacle, it eventually reaches the end of the tentacle since the threshold number of moves is large enough for it to reach that point (see step 6). If a bubble invades a CELL on a tentacle, it is transported either toward a chamber or the end of a tentacle. If it goes to the chamber, the tentacle is not changed. If it goes to the end of the tentacle, the tentacle is shrunk by one bubble length. That is why, eventually, any tentacle is withdrawn.

Fig. 7B shows how the shorter path is chosen to connect two chambers. Given the left-hand diagram of Fig. 7B, assume that a stimulus point is chosen randomly. If it is chosen from the boundary of two chambers, the bubble can be excluded through the boundaries of chambers and, with respect to the two paths, nothing happens. If a stimulus point is chosen from points on the long path, it is possible that a bubble is transported from the point indicated by thick arrow, to the one of chambers, to the short path, to the other chamber, and to the long path again. Note that the diagram contains a loop. As mentioned above in the tentacle discussion, the bubble stops at the position indicated by the thick arrow, and the long path is cut. In general, it is the longer path which is cut because the probability of choosing a stimulus point is dependent on the length of paths. Therefore, longer paths are invaded by a bubble more frequently. Since cut paths are withdrawn, we obtain the right-hand diagram of Fig. 7B. Now there is no loop in this diagram. Therefore, even if a bubble invades from a path, it is transported into either of two chambers, and never enters a path again due to the “memorized flow” (i.e., step 7). Thus the remaining path is robustly kept.

The properties of a CELL mentioned above—(i) loop cutting, (ii) tentacle withdrawal, and (iii) choice of shorter paths—yield a mechanism for solving a maze or a spanning tree problem. In previous models for explaining the adaptive network of *Physarum*, the essential mechanism of solving a maze is Kirchhoff’s law (the sum of flows on a node is 0) and removal of redundant paths. Although this mechanism looks consistent with the real *Physarum*, it does not give a reason why redundant paths are deleted. In reality, the deletion of a path occurs by the decomposition of tubes into free actin-myosin fibers. This means that any tubular path is continually exposed to decomposition, and redundant longer paths have high probability of being decomposed. The CELL implements this tendency as a longer path has higher probability of being invaded, and that leads to the three properties (i), (ii) and (iii) mentioned above. Thus, a CELL’s ability to solve a maze is based on a realistic mechanism. The model CELL has an important additional property: (iv) fibers are created. In previous models for explaining adaptive networks, all possible paths are given initially, and the process for generating paths for cytoplasmic flow is neglected. By contrast, a CELL contains the process for making the distribution of fibers and paths.

Finally, we show the detailed process of solving a maze by CELL (Fig. 8). The CELL follows the procedure given in steps 1~8, where the stimulus points are chosen specially for a given maze. Given a CELL distributed along a maze, it is assumed that a bubble invades the CELL from two active zones indicated by arrows in Fig. 8. Actually there are two rectangular areas located below the points represented by arrows. A position with the boundary state (state 2, indicated by black dot) in these rectangular areas is chosen randomly, and a bubble invades the CELL at that position. Since a bubble is replaced with the inside state (state 1, indicated by a yellow dot), the inside cell-components are transported to two rectangular areas as shown in Fig. 6A. In Fig. 8, the two rectangular zones in which gray components are deposited are omitted. Although a corridor is filled with a CELL at first, cell components are removed. This makes a thin, wandering network. Due to the properties (i)–(iv), loops are cut and open ended branches are withdrawn, until a short path remains. As a result, the CELL approximates the minimal path connecting the start and the goal. That is, it solves the maze.

5. Conclusion

Physarum computing can contribute to graph theoretical computations. In particular it may implement a Kolmogorov-Uspensky machine (Kolomogorov & Uspensky 1963) that contains a Turing machine as a component. This is a storage modification machine in the form of dynamic undirected tree(Adamatzky 2007a, b). While *Physarum* can be regarded as a living undirected tree, the mystery remains as to the relationship between path generation and information flow in the body. The key is the transport of fibers within a robust body surrounded by tube materials. We found that memorized flow produces both robust transport and dynamic graph modification. If some fibers are left and deposited in the path of the transportation, it can inhibit cytoplasmic flow in such an area and it plays as an obstacle. If many bubbles aggregate to form a large vacant chamber, the boundary of the chamber becomes a path for the cytoplasmic flow and the wall of the chamber is eventually broken. The continual repetition of this process creates tubular networks from a sponge-like structure.

Memorized flow yields a huge diversity of CELL shapes. Memorized flow can make a bubble stay in a dead end surrounded by its own trajectory, which causes the outer boundary to be broken. This leads to complex outer shapes with many tentacles – a situation which is close to autonomous destruction. However, also due to the memorized flow, any open ended branch will be shrunk. It is clear to see that memorized flow leads to amoebic motion driven by the continuous alternation of cytoplasmic hardening and softening. Since cytoplasmic hardening and softening is realized by the polymerization and de-polymerization of cytoskeleton filaments, the time scale of the hardening-softening switch is different from that of cytoplasmic flow. This difference of time scales inhibits free cytoplasmic flow, leads to the stagnation of the softened or hardened cytoplasm, and produces the heterogeneous distribution of cytoplasm in a cell. The alternation of hardening and softening plays a key part in both amoebic motion and intelligent computing.

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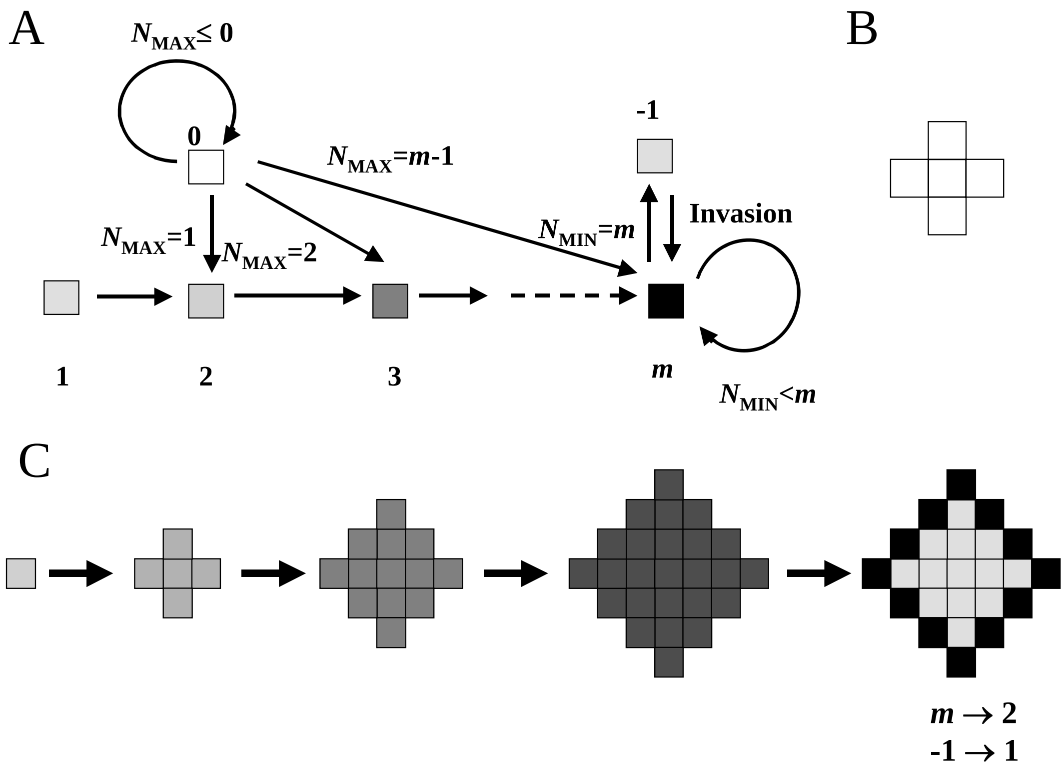

Fig. 1. (*A*) The transition of rule of state, where state is given by an integer. An arrow with a label represents the transition of state with a particular condition represented by the label. The symbol N_{MAX} means the greatest state of neighbors, N_{MIN} means the least state of neighbors. Thus $N_{\mathrm{MIN}} = m$ means that all neighbors are in state *m*. (*B*) The neighbors of each site. (*C*) Time development from a single seed with state 1.

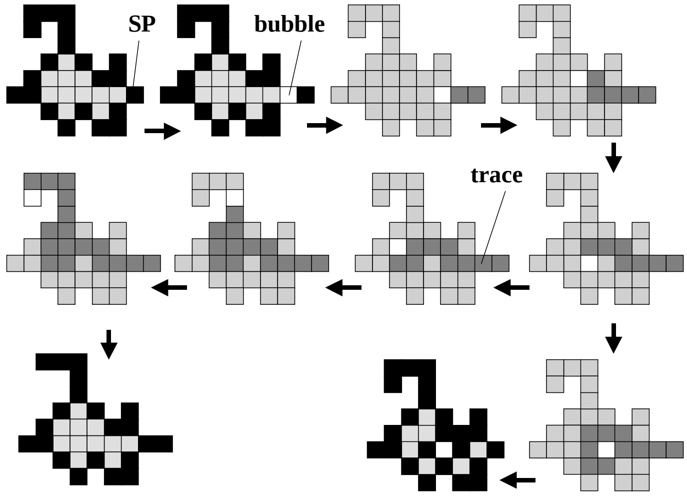

Fig. 2. The transport of a bubble in a CELL. A CELL consists of the boundary (state 2, black) and the inside (state 1, pale gray) components. A boundary site is randomly chosen (indicated by SP for "stimulus point"), and the external state (state 0, white), called a bubble, invades the CELL by swapping sites. After invasion, the inside and boundary are identified with state 2 (pale gray). The bubble diffuses in a CELL and never crosses the path of its own diffusion (shaded area). This makes the bubble move toward a new area. If the bubble is transported along an open-end branch (tentacle), the bubble moves toward the open end and is excluded. After excretion of a bubble, the boundary and interior components are re-organized and the tentacle has been shrunk (left bottom). If the bubble is not excluded and is deposited in the CELL, it is surrounded by cytoskeleton (state 2) (right bottom).

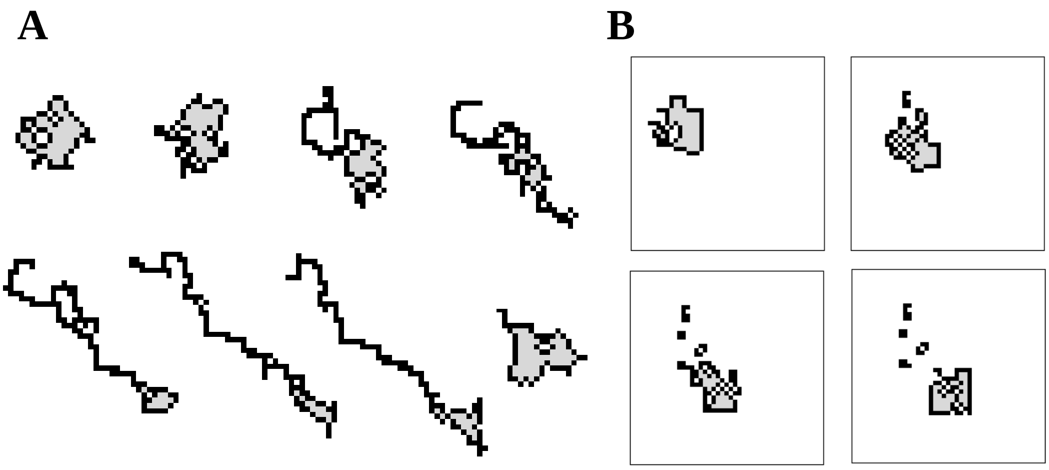

Fig. 3. (*A*) Amoebic behavior of a CELL with memorized flow. Since the diffusion of a bubble avoids its own path, long tentacles cannot be cut and that gives rise to complex amoebic behavior. Time proceeds from left to right and from top to bottom. (*B*) CELL moves rightward and downward without memorized flow. Because of deposited bubble excess CELL is destroyed. Time proceeds from left to right and from top to bottom.

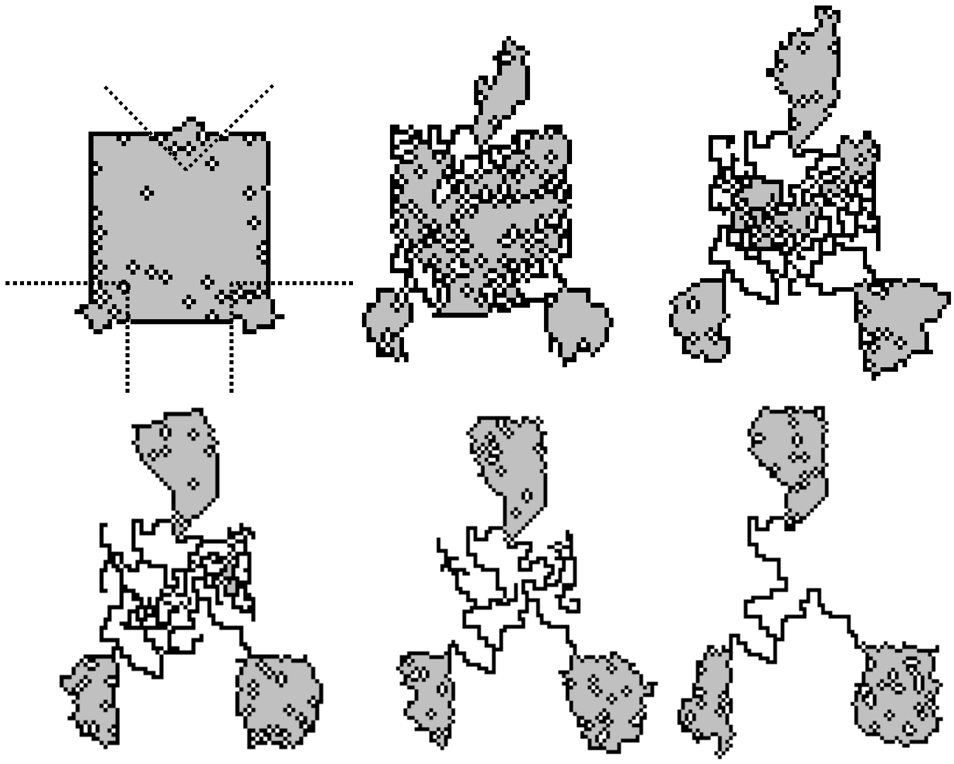

Figure 4. Development of an adaptive network in a CELL, where black, gray and white dots represent sites with state 2, 1 and 0, respectively. Time proceeds from left to right and from top to bottom. First a CELL is generated as a square, and it is assumed that a bubble invades from the boundary within the active zones surrounded by broken lines. For a while many bubbles surrounded by boundary components are deposited in CELL, and bubble chambers grow. This results in network formation. Finally the CELL approximates the minimal path connecting the three active zones.

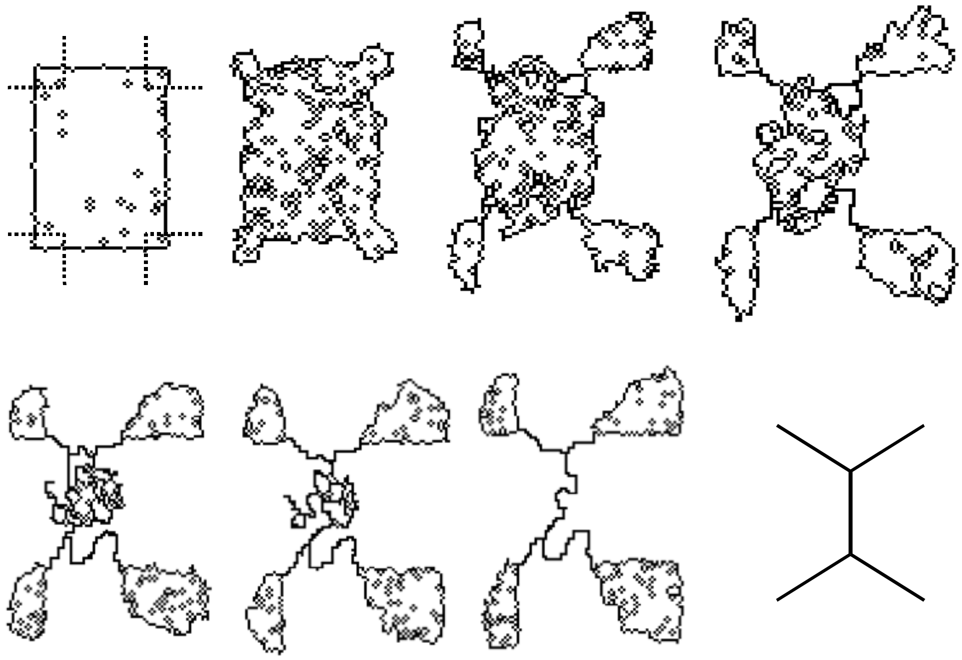

Figure 5. Development of an adaptive network in a CELL, given four active zones. First a CELL is generated as a square, and it is assumed that a bubble invades from the boundary within the active zones surrounded by broken lines. Finally the CELL approximates the “skeleton” connecting the four active zones (right bottom).

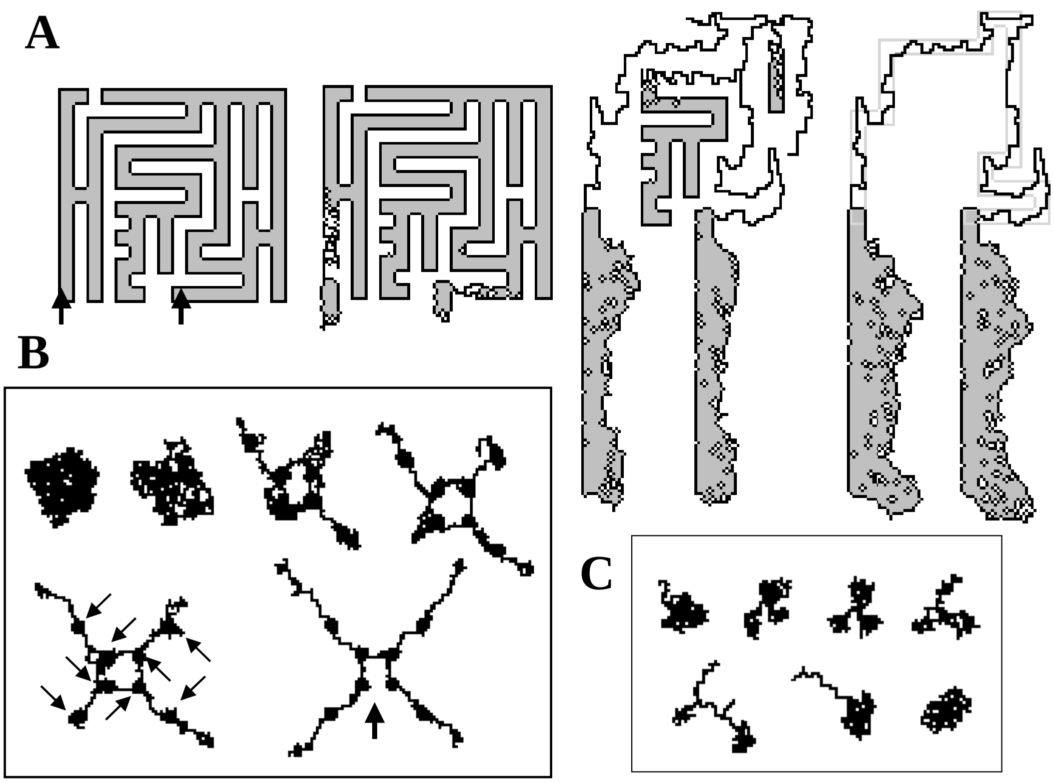

Figure 6. (*A*) The process of maze solving by a CELL. Given a CELL in the shape of the maze, it is assumed that a bubble invades CELL mainly from two active zones indicated by thick arrows (left). When a bubble invades a maze, the inside component of the CELL is transported toward the active zones. This results in the shrinking of the CELL in the maze area and in a thin network of state 2 sites including loops (center left). Eventually loops are cut and redundant paths are removed (center right). Finally the CELL approximates the solution of the maze. The gray corridor represents the minimal path. (*B*) The process of spanning tree solution by a CELL, where both state 1 and 2 are represented by black dots (from left to right and from top to bottom). First the CELL behaves like an amoeba, and finds eight active zones indicated by black thin arrows. Finally a loop is removed as indicated by the thick arrow, and the CELL approximates the spanning tree. (*C*) The transition between amoebic behavior and transport network of a CELL. Both state 1 and 2 are represented by black dots. A foraging CELL finds three active sites, then forms an adaptive transport network. After that the CELL returns to being an amoeba again.

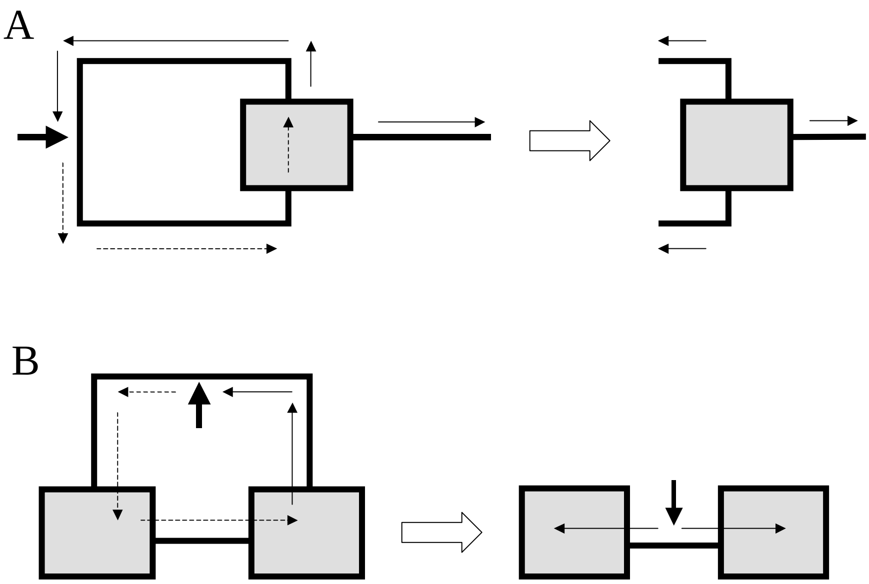

Fig. 7. (*A*) Schematic diagram showing how a loop is cut and an open end branch is shrunk. (*B*) Schematic diagram showing how a shorter path remains when two chambers are connected by two paths.

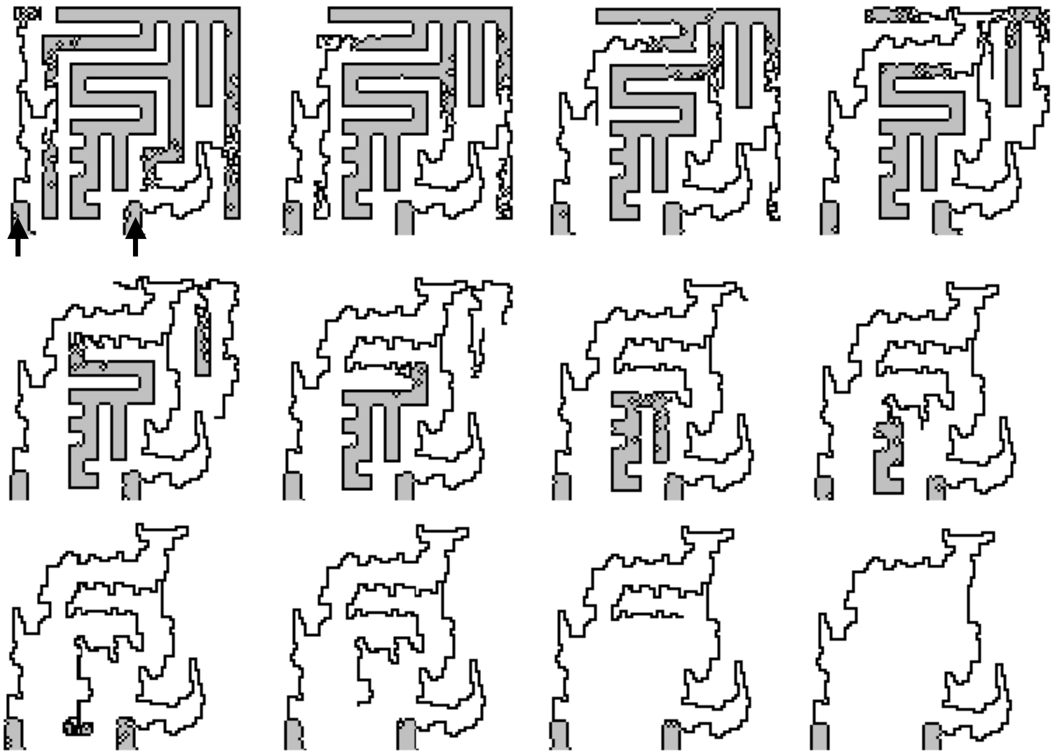

Fig. 8. The process of solving a maze, from left to right and from top to bottom. Black and yellow dots represent boundary state 2 and inside state 1, respectively. As bubbles invade a CELL from active zones, cell components with the inside state are transported to the active zones.