Chapter 1

From reaction–diffusion to Physarum computing

Research in unconventional, or nature-inspired, computing aims to uncover novel principles of efficient information processing and computation in physical, chemical and biological systems, to develop novel non-standard algorithms and computing architectures, and also to implement conventional algorithms in non-silicon, or wet, substrates [Teuscher and Adamatzky (2005); Adamatzky and Teuscher (2006); Calude et al. (2006); Adamatzky et al. (2007)]. This emerging field of science and engineering is predominantly occupied by purely theoretical research, e.g. quantum computation, membrane computing and dynamical systems computing. Only a handful of experimental prototypes are reported so far, for example

- specialized and universal chemical reaction–diffusion processors [Adamatzky et al. (2005)],
- universal extended analog computers [Mills (2008)],
- maze-solving micro-fluidic circuits [Fuerstman et al. (2003)],
- gas-discharge analog path finders [Reyes et al. (2002)],
- maze-solving chemo-tactic droplets [Lagzi et al. (2010)],
- enzyme-based logical circuits [Katz and Privman (2010); Privman et al. (2009)],
- spatially extended crystallization computers for optimization and computational geometry [Adamatzky (2009)],
- Physarum computers [Nakagaki et al. (2000, 2001, 2007)],
- geometrically constrained universal chemical computers [Sielewiesiuk and Górecki (2001); Motoike and Yoshikawa (2003); Górecki et al. (2009); Yoshikawa et al. (2009); Górecki and Górecka (2006,a); Górecki et al. (2003)],
- molecular logical gates and circuits [Stojanovic et al. (2002, 2005); Lederman et al. (2006); Macdonald et al. (2006)].

In contrast, there are thousands of papers on quantum computation and hundreds on membrane computing and artificial immune systems. Such a weak representation of laboratory experiments in the field of unconventional computers could be explained by technical difficulties and costs of prototyping. Chemists and biologists are not usually interested in experimenting with unconventional computers because such activity diverts them from mainstream research in their fields. Computer scientists and mathematicians would like to experiment but are scared of laboratory equipment.

If there was a simple to maintain substrate, which requires minimal equipment to experiment with, then progress in designing novel computing devices would be much more visible.

The chapter is structured as follows. We introduce reaction–diffusion computers, because they are proved to be the most productive experimental implementations of unconventional computers. Then we bring in *P. polycephalum* and provide evidence that plasmodium of *P. polycephalum* can be seen as a reaction–diffusion and excitable medium encapsulated in an elastic membrane. Finally, we overview a brief history of Physarum computing.

1.1 Reaction–diffusion computers

A reaction–diffusion computer is a spatially extended chemical system, which processes information using interacting growing patterns, excitation and diffusive waves [Adamatzky et al. (2005)]. In reaction–diffusion processors, both the data and the results of the computation are encoded as concentration profiles of the reagents. The computation is performed via the spreading and interaction of wave fronts. A great number of chemical laboratory prototypes, designed by De Lacy Costello, are discussed in our previous book [Adamatzky et al. (2005)].

In terms of classical computing architectures, the following characteristics can be attributed to reaction–diffusion computers [Adamatzky (1994, 1996, 2001); Adamatzky et al. (2005)]:

- massive parallelism: there are thousands of elementary processing units, micro-volumes, in a standard chemical vessel;
- local connections: micro-volumes of a non-stirred chemical medium change their states, due to diffusion and reaction, depending on states of, or concentrations of reactants in, their closest neighbors;
- parallel input and output: in chemical reactions with colored prod-

uct the results of the computation can be recorded optically; there is also a range of light-sensitive chemical reactions where data can be inputted by localized illumination;

- fault tolerance: being in liquid phase, chemical reaction–diffusion computers restore their architecture even after a substantial part of the medium is removed; however, the topology and the dynamics of diffusive and particularly phase waves (e.g. excitation waves in a Belousov–Zhabotinsky system) may be affected.

These characteristics of reaction–diffusion chemical computers make them ideally tailored for the implementation of novel and emerging architectures of robotic controllers and embedded processors for smart structures.

Most experimental prototypes of reaction–diffusion computers use a one-to-all type of communication when transmitting information between elementary computing units. This is typical for a Belousov–Zhabotinsky (BZ) medium in excitable mode and precipitating chemical processors.

The first ever experimental chemical processor, presented in [Kuhnert (1986); Kuhnert et al. (1989)], is architectureless and with parallel optical input the illumination gradients of the BZ reactor. Kuhnert's 'BZ-memory' processor [Kuhnert (1986); Kuhnert et al. (1989)] does not employ interaction of propagating excitations but only light sensitivity of the BZ reaction and global switching between excitation and refractory states. The ideas in [Kuhnert (1986); Kuhnert et al. (1989)] are further detailed in [Rambidi (1998); Rambidi et al. (2002)], where a BZ medium was used to extract the contour of a planar shape, detect particular features of the shape and implement negation and enhancement of images and shape restoration.

Other applications of a BZ medium in one-to-all communication mode include approximation of the shortest collision-avoidance path [Agladze et al. (1997)] and a set of all collision-free paths between two planar points [Adamatzky and De Lacy Costello (2002)]. A shortest path is approximated by running excitation waves first from start to destination, then from destination to start and detecting the intersection of wave fronts traveling in opposite directions [Agladze et al. (1997)]. A set of collision-free paths is generated by exciting the medium in all obstacles at once and recording distance fields approximated by traveling wave fronts [Adamatzky and De Lacy Costello (2002)].

A typical precipitating processor operates similarly to BZ processors. Not excitation but diffusive waves propagate. Reactants in the propagating wave fronts precipitate when they react with species in a substrate.

Domains of the substrate covered by diffusive fronts are ‘tagged’ by precipitate. All precipitating computing devices built so far are based on the single phenomenon: when two or more diffusive wave fronts meet, no precipitate is formed at the meeting loci. That is, the precipitating processor computes a bisector between two planar points. There are several non-trivial designs of precipitating processors which approximate a planar Voronoi diagram [Tolmachev and Adamatzky (1996); De Lacy Costello (2003); De Lacy Costello and Adamatzky (2003); De Lacy Costello et al. (2004a, 2009)] and a skeleton of a planar shape [Adamatzky and Tolmachiev (1997); Adamatzky and De Lacy Costello (2002)]. The recently discovered ‘hot ice computer’ [Adamatzky (2009)], which exploits crystallization in a supersaturated solution of sodium acetate, allows for ‘one-passage’ calculation of shortest path.

A one-to-all type of communication is typical for plasmodium of *P. polycephalum* growing on a nutrient substrate (Chap. 3.3).

To implement a one-to-one type of communication in a reaction–diffusion medium, we can use self-localized excitations, wave fragments, traveling in a BZ medium in a sub-excitable mode [Sedina-Nadal et al. (2001)]. The excitation wave fragments in a sub-excitable BZ medium behave like quasi-particles. They exhibit rich dynamics of collisions, including reflection, fission, fusion and annihilation [Adamatzky and De Lacy Costello (2007); Toth et al. (2009)]. Using the wave fragments, we implemented a collision-based computing scheme [Adamatzky (2004)].

Most Physarum machines discussed in the present book use the one-to-one type of communication by plasmodium self-localizations propagating on a non-nutrient substrate.

1.2 Limitations of reaction–diffusion computers

There are problems which reaction–diffusion chemical processors fail to solve. Shortest path and spanning tree problems are typical tasks failed by reaction–diffusion computers. Experimental techniques [Agladze et al. (1997)] and [Adamatzky and De Lacy Costello (2002)] on computation of shortest path in a Belousov–Zhabotinsky medium require significant assistance from conventional computers. Namely, snapshots of traveling excitations must be recorded at regular intervals and analyzed on a PC. Reaction–diffusion computers cannot calculate a spanning tree nor can they implement memory, unless it is ancient coil-type memory in a ring-constrained BZ medium. Geometrical constraining in general does not help to tackle these tasks. Encapsulation looks like the only solution [Adamatzky (2007a)].

A common way to encapsulate a BZ system is to disperse it in a water-in-oil micro-emulsion with surfactant [Epstein (2005)]. BZ reagents are thus enclosed in a mono-layer of anionic surfactant. The BZ droplets are immersed in oil through which intermediate reactants diffuse [Epstein (2005)]. The diffusion of reactants can be seen as a continuous supply of energy to BZ droplets. 'Unlimited' energy supply enables BZ droplets to stay excited for a very long time. This system exhibits a wide range of stationary (similar to Turing structures) and oscillatory patterns. A stationary pattern can be photo-printed on the medium. When imprinted, the patterns are represented by configurations of stationary excitations for as long as reagents are refilled [Kaminaga (2006)].

Experiments with encapsulated chemical media require a certain level of chemical expertise and at least some kind of laboratory equipment. Certainly, it would be quite difficult for you to make a DIY BZ droplet in your kitchen. We went in search of an easy-to-experiment-with analog of an encapsulated reaction–diffusion system and picked plasmodium of *P. polycephalum* as a suitable one.

1.3 *Physarum polycephalum*

Physarum polycephalum belongs to the species of order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomycetes*, division *Myxostelida.* It is commonly known as a true, acellular or multi-headed slime mold. The life cycle of *P. polycephalum* is exciting (Fig. 1.1).

Plasmodium — a 'vegetative' phase – is a single cell with a myriad of diploid nuclei (Fig. 1.1a–l). The plasmodium looks like an amorphous yellowish mass with networks of protoplasmic tubes (Fig. threeexampelsa). The plasmodium behaves and moves as a giant amoeba. It feeds on bacteria, spores and other microbial creatures and micro-particles [Stephenson and Stempen (1984)]. When foraging for its food the plasmodium propagates towards sources of food particles, surrounds them, secretes enzymes and digests the food. Typically, the plasmodium forms a congregation of protoplasm covering the food source. When several sources of nutrients are scattered in the plasmodium's range, the plasmodium forms a network of protoplasmic tubes connecting the masses of protoplasm at the food sources.

PHYSARUM MACHINES - Computers from Slime Mould

http://www.worldscibooks.com/compsci/7968.html

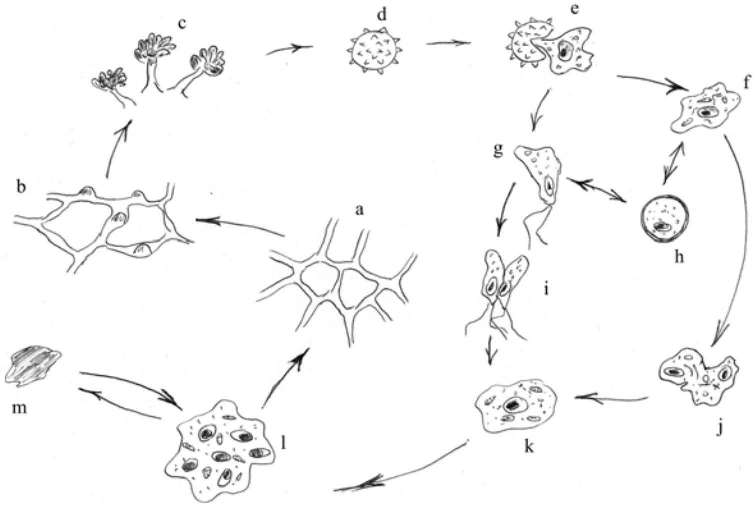
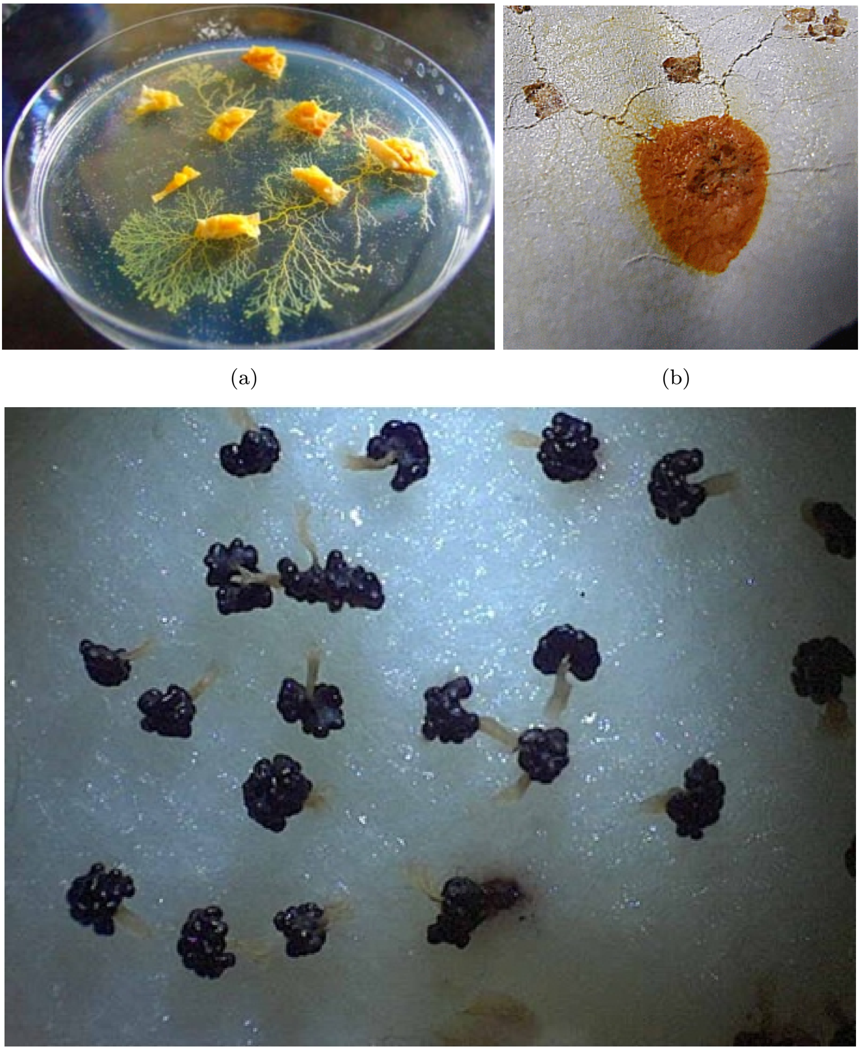


Fig. 1.1 Life-cycle scheme of *Physarum polycephalum*, inspired by [Stephenson and Stempen (1984)]: (a) protoplasmic tree formed by 'vegetative' state — plasmodium, (b) early stage of sporulation, (c) sporangia — fruiting bodies with spores, (d) a single spore, (e) germinated spore — cracked spore with myxamoeba crawling out, (f) myxamoeba, (g) swarm cell, (h) micro-cyst, (i) fusion of two swarm cells, (j) fusion of two myxamoebas, (k) zygote, (l) plasmodium, (m) sclerotium.

When plasmodium is deprived of water and/or nutrients and cannot migrate to better places, the plasmodium goes into 'hibernation' mode and forms a hardened mass called sclerotium (Figs. 1.1m and threeexampelsb). Sclerotia survive a range of very harsh conditions, including high temperatures of up to 70–80°C [Blackwell et al. (1984)]. A sclerotium of *P. polycephalum* consists of "crustose deposit containing nucleated spherules of cytoplasm enclosed within a honeycomb-like matrix of organic walls" [Chet and Henis (1975); Andreson (2007)]. When moistened, the sclerotium gradually returns to the state of plasmodium (Fig. 1.1l). Myxamoebas can live as they are for a long time. In the presence of water a myxamoeba is transformed into a swarm cell with two flagellas (Fig. 1.1g). Swarm cells can swim. Myxamoebas and swarm cells can reproduce asexually, by simple division. During changes of environment from good to bad, myxamoebas and swarm cells can form spheroidal micro-cysts (Fig. 1.1h) with cellulose walls.



(a) (b)

(c)

Fig. 1.2 Examples of life forms of *P. polycephalum*: (a) plasmodium, (b) sclerotium, dark-yellowish mass, (c) sporangia.

When exposed to bright light and starved, the plasmodium switches to fructification phase. It grows sporangia (Figs. 1.1b and c and threeexampelsc), finger-like globose enclosures of membrane filled with spiny spores.

When a spore (Fig. 1.1d) gets into a favorable environment, it cracks and releases a single-cell myxamoeba (Fig. 1.1e). When enough myxamoebas or swarm cells are present in the volume, they begin sexual reproduction (Fig. 1.1i and j) and form a zygote (Fig. 1.1k). The zygote divides mitotically and forms a multi-nuclear single cell — the plasmodium (Fig. 1.1l).

1.4 Physarum as encapsulated reaction–diffusion computer

The plasmodium is a network of biochemical oscillators [Matsumoto et al. (1988); Nakagaki et al (1999)]. Waves of excitation or contraction originate from several sources, e.g. induced by external stimuli and perturbations. The waves travel along the plasmodium and interact one with another in collisions. The oscillatory cytoplasm of the plasmodium is a spatially extended nonlinear excitable medium.

Growing and feeding plasmodium exhibits characteristic rhythmic contractions with articulated sources. The contraction waves are associated with waves of electrical potential change. The waves observed in plasmodium [Matsumoto et al. (1986, 1988); Yamada et al. (2007)] are similar to the waves found in excitable chemical systems, like a BZ medium.

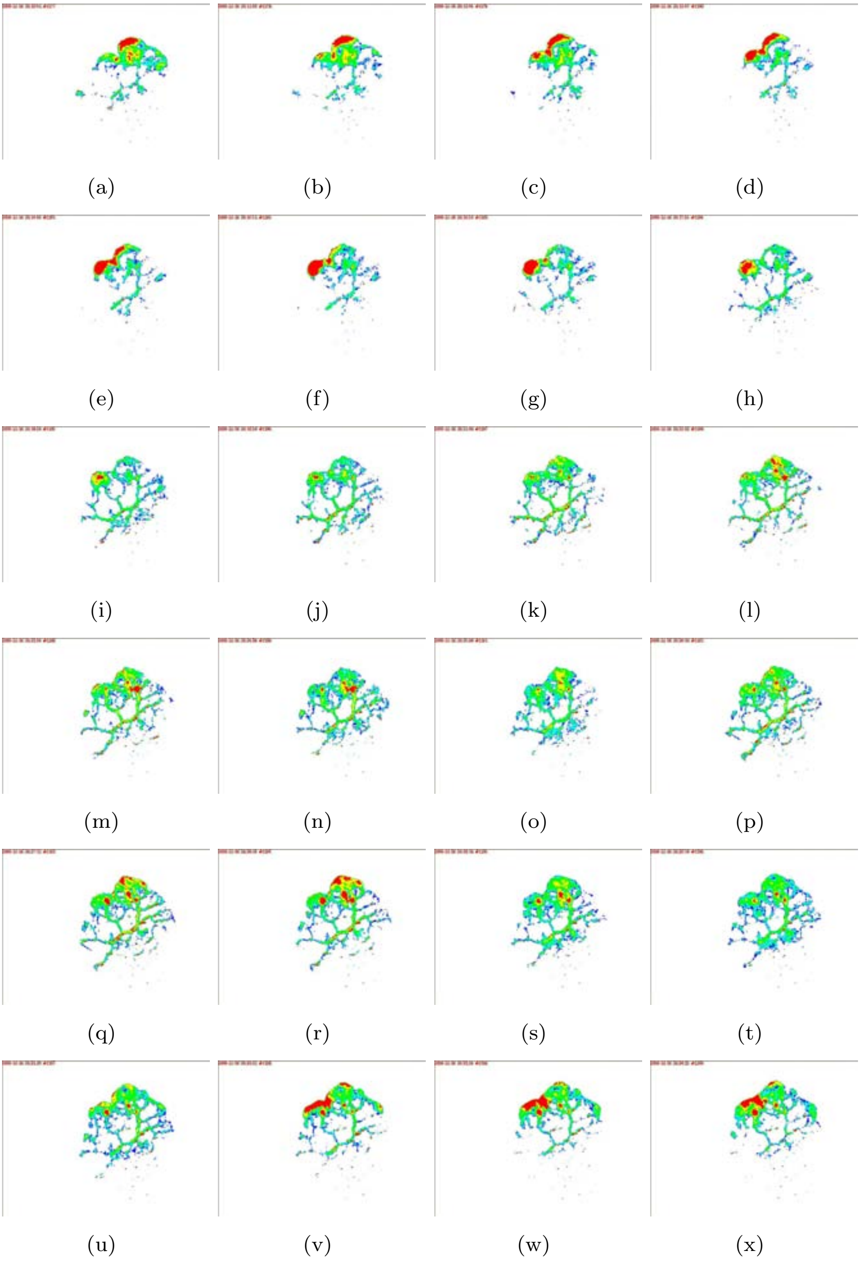
The following wave phenomena were discovered experimentally [Yamada et al. (2007)]:

- undisturbed propagation of contraction waves inside the cell body,
- collision and annihilation of contraction waves,
- splitting of the waves by inhomogeneity,
- the formation of spiral waves of contraction.

These are closely matching dynamics of pattern propagation in excitable reaction–diffusion chemical systems [Adamatzky et al. (2005)].

The plasmodium's behavior is determined by external stimuli and excitation waves traveling and interacting inside the plasmodium [Nakagaki et al (1999)]. The plasmodium can be considered as a reaction–diffusion [Adamatzky (2007a)] or an excitable [Achenbach and Weisenseel (1981)] medium encapsulated in an elastic growing membrane. Thus, the plasmodium joins the *Kunstkammer* collection of natural computing substrates additional to existing reaction–diffusion chemical computers [Adamatzky et al. (2005)].

We complete the section with two examples of wave-based 'decision' making in plasmodium.



(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k) (l)

(m) (n) (o) (p)

(q) (r) (s) (t)

(u) (v) (w) (x)

Fig. 1.3 Colorized snapshots of tiny plasmodium blob propagating on a nutrient agar gel. ×40 magnification. One frame per minute recording.

Control of the plasmodium's mobility via propagating waves is demonstrated in Fig. 1.3. We made a small incision in a wall of a thick protoplasmic tube. A drop (about 0.1-mm radius) of cytoplasm popped out. We picked up this drop and transferred it to a thin plate of oatmeal agar. The plate is illuminated from the south-eastern corner, so the gradient of illumination decreases towards the north-western corner of the plate. We record the behavior of the drop with ×40 magnification; the time interval recording is one frame per minute. To detect domains of plasmodium with increased concentration of cytoplasm, we colorize the original images (the values of red and green components of the original image pixels are discretized in five intervals). Pixels with the highest value of red or green components are assigned red color, then yellow, green, blue-green and blue. Pixels with red or green components below a certain threshold are assigned white color. We see that waves are generated on actively propagating parts of the plasmodium blob. The waves then travel inside the plasmodium and along its protoplasmic network, which trails the propagating wave front. The western part of the plasmodium wave front in Fig. 1.3 acts as a generator of traveling waves. Thus, the plasmodium gradually turns west to adjust its motion along the north-western axis Fig. 1.3.

In the experiment illustrated in Fig. 1.4, we show how a plasmodium behaves when faced with sources of repellents and attractants at once. A source of light positioned near the south-eastern corner of the agar plate acts as a repellent. An oat flake, seen as a stationary solid red domain in Fig. 1.4, acts as an attractant. We witness that two sources of contractile waves emerge in the plasmodium. One source, the generation of which is visible in Fig. 1.4a–p, is formed in the part of the plasmodium distant from the source of illumination. This wave source leads the plasmodium towards an escape route from the illumination. At the same time, a second source of waves (Fig. 1.4q–x) is generated in the part of the plasmodium close to the oat flake. This wave source leads the plasmodium towards the attractant, the oat flake. During about 30 h of experiment we observed that the plasmodium circles a few times, approaching the oat flake and then going away. Eventually, the 'need' to escape from light prevails and the plasmodium moves north-west.

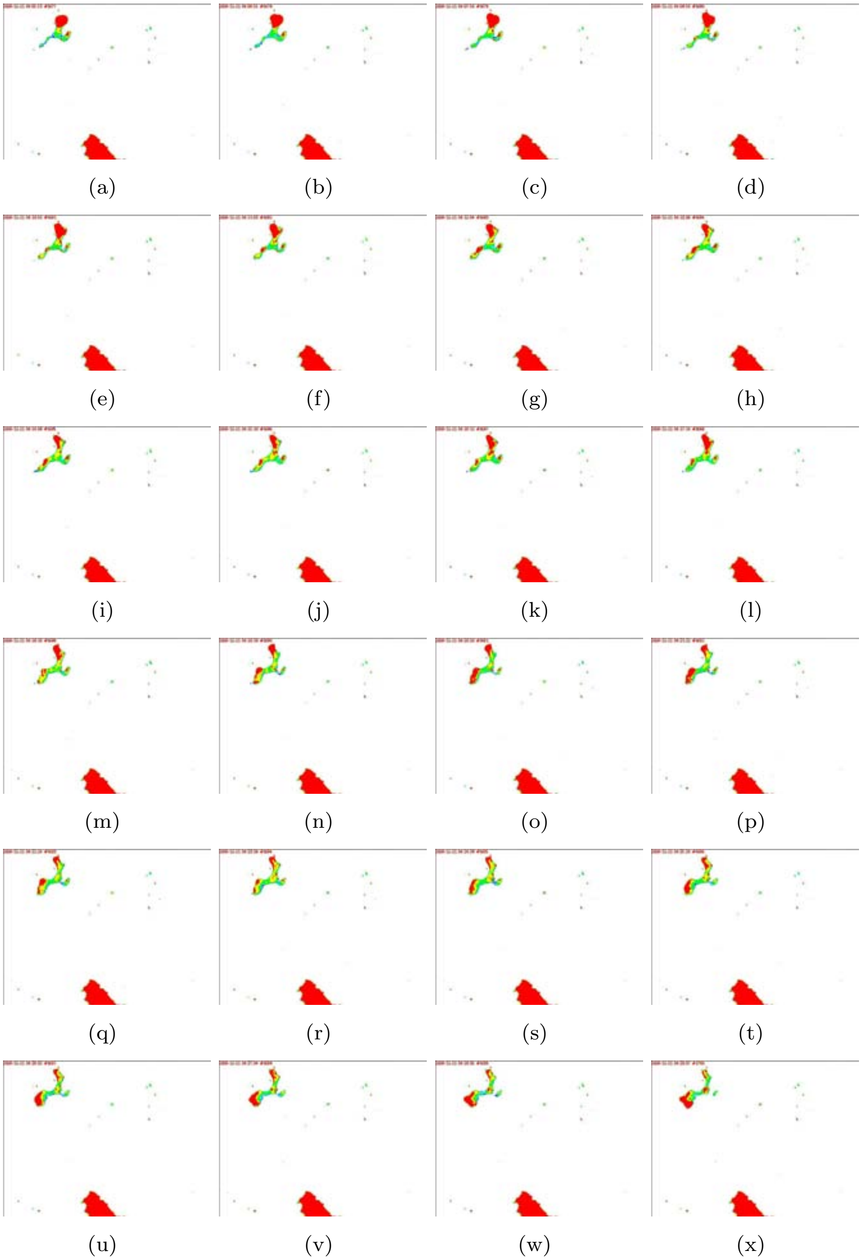

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Fig. 1.4 Wave-based decision making by plasmodium. Colorized snapshots of tiny plasmodium blob propagating on a non-nutrient agar gel. ×40 magnification. One frame per minute recording. Stationary red domain at the southern edge of the agar plate is an oat flake.

1.5 Dawn of Physarum computing

In 2000 *Nature* published a paper ‘Maze-solving by an amoeboid organism’ by Toshiyuki Nakagaki, Hiroyasu Yamada and Ágota Tóth [Nakagaki et al. (2000)]. The authors experimentally proved that — when source and destination are represented by sources of food — the plasmodium of *P. polycephalum* approximates a shortest path in the labyrinth by developing a thick protoplasmic tube connecting the source and the destination.

When placed in an environment with distributed sources of nutrients the plasmodium forms a network of protoplasmic tubes connecting the food sources. If we interpret sources of food (e.g. oat flakes) as nodes and protoplasmic tubes as edges, we see that the plasmodium constructs a planar graph on the sources of food. Nakagaki et al. [Nakagaki et al. (2001, 2007)] showed that the topology of the plasmodium’s protoplasmic network optimizes the plasmodium’s harvesting on the scattered sources of nutrients and makes more efficient the flow and transport of intracellular components.

In the last 10 years, experimental laboratory prototypes of Physarum computers were designed to

- compute a shortest path [Nakagaki et al. (2000, 2001, 2007); Shirakawa and Gunji (2009)],
- implement logical gates [Tsuda et al. (2004)],
- control a robot; plasmodium acts as an on-board controller for robot photo-avoidance [Tsuda et al. (2007)],
- approximate proximity graphs [Adamatzky (2008)],
- compute Voronoi diagrams [Shirakawa et al. (2009); Shirakawa and Gunji (2009)],
- construct spanning trees [Adamatzky (2007,a)],
- implement storage-modification machines [Adamatzky (2007)],
- solve resource-consuming computational problems [Aono and Gunji (2001, 2004); Tsuda et al. (2004); Nakagaki et al. (2001); Tsuda et al. (2006)],
- approximate Delaunay triangulation [Shirakawa et al. (2009)],
- implement primitive memory [Saigusa et el. (2008)],
- implement spatial logic and process algebra [Schumann and Adamatzky (2009)].

The plasmodium functions as a parallel amorphous computer with parallel inputs and parallel outputs. Data are represented by spatial configurations of sources of nutrients. A program of computation is coded via configurations of repellents and attractants. Results of the computation are presented by the configuration of the protoplasmic network and the localization of the plasmodium. In the book we demonstrate that plasmodium of *P. polycephalum* is a parallel computing substrate complementary to, and sometimes more efficient than, existing massively parallel reaction–diffusion chemical processors [Adamatzky et al. (2005)].