most experimental realizations of chemical computers were based on geometrically constrained media: classified as an architecture-based computing device. Personal computers, living neural networks, cells, and systems in such a manner that all elements of the circuit are represented by the system's stationary states. The architecture-based, or stationary, computation implies that a logical circuit is embedded into the states of the given system. This can be done in two ways: architecture-based and architecture-less. A device is called computationally universal if it computes a functionally complete set of logical operations. To prove a medium's universality one must represent quanta encoded as concentration profiles of the reagents. The computation is performed via the spreading and interaction of wave fronts. Reaction-diffusion chemical processors are now 'classical' examples of nong-linear medium computers.

Adamatzky, De Lacy Costello, Asai, 2005. A reaction-diffusion computer is a spatially extended chemical system, which process information using reactions of excitations. These ideas were rediscovered many times but mostly in a framework of theoretical design of novel algorithms, of these the grass fire transformation [Blum, 1968; Calabi & Hartnett, 1968] is the most famous example. In 1990's the new field of reaction-diffusion computing – computation with excitation and algorithms, of these the grass fire transformation [Blum, 1968; Calabi & Hartnett, 1968] is the most famous example. In 1990's the new field of reaction-diffusion computing – computation with excitation and algorithms, of these the grass fire transformation [Blum, 1968; Calabi & Hartnett, 1968] is the most famous example. The first thoughts on the implementation of computational operations with patterns propagated in spatially extended nong-linear systems date back to 1800's where Plateau experimented with the problem involving the calculation of the surface of smallest area bounded by a given closed contour in space [Courant and Robins, 1941] (the classical problem of calculating a minimal spanning tree of planar points using a soap film).

Thus we have come to the conclusion that a vegetative state, or plasmodium, of Physarum polycephalum also acts as a cul-de-sac of novel computing, because it is simply an implementation of conventional linear medium computers. These computational abilities arise because of the capacity of the plasmodium to perform complex and non-linear computations. The plasmodium is a highly interconnected network of cells which can self-organize and adapt to changes in the environment. It has been shown that the plasmodium can solve complex problems such as the traveling salesman problem and the knapsack problem, which are known to be NP-complete problems in classical computing. The plasmodium is able to do this by using a combination of diffusion and reaction processes, which are similar to those used in reaction-diffusion chemical processors. This is an example of how nature can perform complex computations using simple, non-linear processes.
Effective computation with limited resources: Belousov-Zhabotinsky and Physarum computers (2007).
wavefronts can be observed in the BZ medium: reflection, attraction, repulsion, sliding, and shifting. Growth patterns propagate, and then tree-like structures of protoplasmic tubes are formed. These medium returns to a state that is macroscopically identical to the initial resting state. In plasmodium exhibit mobile memories.

Both the BZ reaction and plasmodium of exhibit mobile memories.

Excitable mode.

Wavefronts propagate with a speed of 0.1 mm/min. This makes Physarum computer an order slower than BZ cultures. In our previous studies we have speculated, and have provided some argument that the plasmodium of initially computed and histories thereof affect all subsequent computations by subtle alterations of wave interactions/trajectories. The computational efficiency are altered by the original wave collisions/trajectories. Therefore, in principle, it would be inefficient to employ plasmodium in collision-based computing schemes. Due to the ability of controlling exactly the exact trajectories, velocity vectors etc. may limit the observation of more subtle (Dis)advantages of encapsulation while implementing computation.

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hardware' like cytoskeleton and membrane – spatiotemporal dynamics of localization is similar. At some significant physicogchemical difference – e.g. BZ media are homogeneous and Physarum have optional localization in these two types of nonglinear medium computes. We have demonstrated that despite pseudopodia in plasmodium of Physarum. We have provided a detailed comparison of the mobile Both BZ and Physarum computers exhibit travelling localizations: wavegfragments in BZ medium and the result of collision, and thus realize functionally complete sets of logical gates. [De Lacy Costello et al., 2004] De Lacy Costello B., Adamatzky A., Ratcliffe N., Zanin A.L., Liehr A.W. 63 Club Bull. Torrey Bot.

They perform computation using travelling mobile localizations (local perturbations of medium's predominantly based on geometricallygconstrained medium, where full power of parallel computation is not

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Figure 2. Snapshots of cellular automaton with retained excitation rules. For each automaton started its development in a circle radius 15 cells, assigned states at random. (a) 6, 2, 3, 3 (R), (b) 8, 2, 3, 3 (R), (c) 5, 3, 3, 3 (R), (d) 8, 3, 3, 3 (R).

Figure 3. Growth points in cellular automaton with retained excitation rules. (a) 5, 3, 3, 3 (R), (b) 6, 2, 3, 3 (R), (c) 8, 3, 3, 3 (R).

Figure 4. Dynamics of localizations in hexagonal reaction-diffusion cellular automaton, imitating the following set of quasichemical reactions (see [Adamatzky et al., 2007] for details of converting cell-state transition rules into a set of reactions):

\[
\begin{align*}
V & \leftrightarrow \frac{1}{2} Z + V^2 \\
Z & \leftrightarrow \frac{1}{2} Z + V \\
V & \leftrightarrow \frac{1}{2} Z + V^2 \\
R & \leftrightarrow \frac{1}{2} Z + V
\end{align*}
\]
Figure 5. Two types of wave dynamics in experimental Belousov-Zhabotinsky system: (a) classical target waves in excitable medium, (b) travelling localizations, or wave fragments, in subexcitable medium.

Figure 6. Examples of a logical gate implemented in collision of travelling localizations (wavefronts) in numerical model of Belousov-Zhabotinsky system: (a)–(h) snapshots of wave fragment dynamics; (i) schematic representation of a gate. The two-variable Oregonator equations were integrated using the Euler method with five node Laplacian operator, time step $\Delta t = 3 \times 10^{-10}$ and grid point spacing, $\Delta x = 0.1$. The following parameters were used: $\varepsilon = 0.03$, $f = 4.1$, $q = 0.2$, $\Phi = 0.04$. The dynamics of collision-based gate in (a)–(h) represent the case when both input variables have values Truth. These values were represented by local disturbances of initial concentrations of species.

\[
\text{Two variables:} \quad x \quad \text{and} \quad y
\]

\[
\text{Gate operation:} \quad \neg x \land y
\]
Figure 7: (a) 20 mg of plasmodia were placed on 50 mg/ml crushed oat flakes containing 1.5% agar gel (left, nutrient-rich condition) or 100 mM potassium chloride containing 1.5% agar gel (right, nutrient-deficient and repellent potassium). (b) Configurations of plasmodium developed 5.5 hours later. In the nutrient-rich favourable condition the plasmodium formed circular pseudopodia, on the other hand in unfavourable condition the plasmodium developed branching structures.

Figure 8. Typical travelling localization in plasmodium of P. polycephalum on nutrient poor substrate. Plasmodium was placed on wet filter paper and cereal very sparsely scattered on the filter paper served as local nutrient sources.
Figure 9. Propagation of plasmodium of *P. polycephalum* in nutrient-rich, 50 mg/ml crushed oat flake containing 1.5% agar gel substrate.

Figure 10. (a) Propagation of plasmodium of *P. polycephalum* in a nutrient-bare agar gel substrate. (b) Magnified image of the area within the red rectangle in (a). Though the pieces are connected by bypassing tubes, pseudopodia avoid each other, as the gap between the pieces indicates.
Figure 11. Adamatzky & De Lacy Costello classification of binary collisions between mobile localizations in BZ medium: (a) reflection, (b) fusion, (c) attraction, (d) sliding, (e) repulsion. [Adamatzky & De Lacy Costello, 2007].

Figure 12. Interaction of pseudopodia of plasmodium: 1 mg of plasmodia were placed at opposite sides of the horizontal channel, 1.5% agar gel was a non-nutrient substrate.
Table 1. Comparative analysis of BZ and Physarum collision-based computers. Symbols indicate the relative advantage of Physarum versus BZ.

| Characteristic                  | BZ      | Physarum |
|--------------------------------|---------|----------|
| Programmability                | -       | +        |
| Richness of outcomes           | +       | -        |
| Architectural capacity         | +       | -        |
| Memory                         | -       | +        |
| Speed of operations            | +       | -        |
| Programmability                | -       | +        |
| Practicality                   | -       | +        |

Figure 13. Demonstration of possible space saving by Physarum. Plasmodium of Physarum polycephalum cultivated on nutrient poor nutrient poor oat flakes. Arrows point to points where pseudopodia cross over.

Figure 14. A series of snapshots of experimental BZ medium, demonstrating splitting/branching of waves.