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Slime mould logic gates based on frequency changes of electrical potential oscillation

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ABSTRACT

Physarum polycephalum is a large single amoeba cell, which in its plasmodial phase, forages and connects nearby food sources with protoplasmic tubes. The organism forages for food by growing these tubes towards detected foodstuff, this foraging behaviour is governed by simple rules of photoavoidance and chemotaxis. The electrical activity of the tubes oscillates, creating a peristaltic like action within the tubes, forcing cytoplasm along the lumen; the frequency of this oscillation controls the speed and direction of growth. External stimuli such as light and food cause changes in the oscillation frequency. We demonstrate that using these stimuli as logical inputs we can approximate logic gates using these tubes and derive combinational logic circuits by cascading the gates, with software analysis providing the output of each gate and determining the input of the following gate. Basic gates OR, AND and NOT were correct 90%, 77.8% and 91.7% of the time respectively. Derived logic circuits XOR, half adder and full adder were 70.8%, 65% and 58.8% accurate respectively. Accuracy of the combinational logic decreases as the number of gates is increased, however they are at least as accurate as previous logic approximations using spatial growth of *P. polycephalum* and up to 30 times as fast at computing the logical output. The results shown here demonstrate a significant advancement in organism-based computing, providing a solid basis for hybrid computers of the future.

1. Introduction

Physarum polycephalum is a single celled organism visible by the unaided eye (Stephenson and Stempen, 2000). It can span several centimetres in warm, dark and humid conditions, and has been discovered engulfing decomposing trees. When inoculated in the environment with distributed sources of nutrients, the slime mould spans the nutrients using a network of protoplasmic tubes. The topology of the network is controlled by gradients of chemical, optical and thermal attractants and repellents (Durham and Ridgway, 1976; Knowles and Carlilie, 1978). The flow of cytoplasm within these protoplasmic networks is governed by shuttle streaming (Kamiya, 1960, 1959) which controls locomotion and growth (Kamiya, 1981; Kamiya et al., 1957; Matsumoto et al., 2008); rhythmic contractions controlled by Ca^{2+} oscillations (Ridgway and Durham, 1976; Smith and Saldana, 1992; Yoshiyama et al., 2010) cause the actin myosin filaments to initiate peristaltic action of the cell membrane.

The oscillatory period of shuttle streaming is between 60 and 200 s (Adamatzky and Schubert, 2014; Kishimoto, 1958; Wohlfarth-Bottermann, 1977); this frequency is increased and decreased by attractant and repellent stimuli respectively (De Lacy Costello and Adamatzky, 2013; Durham and Ridgway, 1976; Whiting et al., 2014b,c). Chemotaxis is exhibited by *P. polycephalum* with food sources providing reliable attractant sources (Kincaid and Mansour, 1978; Latty and Beekman, 2009; Nakagaki et al., 2007, 2004), and heat (Durham and Ridgway, 1976; Kincaid and Mansour, 1978; Nakagaki et al., 2000; Wohlfarth-Bottermann, 1977) also having attractant properties; *P. polycephalum* avoids light sources (Block and Wohlfarth-Bottermann, 1981; Häder and Schreckenbach, 1984; Kakiuchi et al., 2001; Nakagaki et al., 1999) and certain chemicals (De Lacy Costello and Adamatzky, 2013; Ueda et al., 1975; Whiting et al., 2014b; Wolanin and Stock, 2004).

P. polycephalum responds to certain stimuli, this response can be measured either by observing growth or by electronic measurement of the surface electrical potential (Adamatzky and Jones, 2011; Kishimoto, 1958; Meyer and Stockem, 1979; Whiting et al., 2014b). The recordable electrical response of *P. polycephalum* to these stimuli is repeatable; thus several biosensors using *P. polycephalum*

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have been developed (Adamatzky, 2014, 2013a,b; Whiting et al., 2014a,b).

The main goal of *P. polycephalum* computing is to design a general purpose processing device from the plasmodial phase of slime mould (Adamatzky, 2010a; Adamatzky et al., 2012). Thus implementation of logical gates is the most important task of *P. polycephalum* computing. So far two types of *P. polycephalum* logic gates have been implemented with living *P. polycephalum* in laboratory experiments (Adamatzky, 2010b; Tsuda et al., 2004) and simulations (Jones and Adamatzky, 2010).

Tsuda, Aono and Gunji (Tsuda et al., 2004) developed the first ever *P. polycephalum* logic gates based on the slime mould's propagation along agar channels in specially laid out geometry. Their gates use the presence and absence of *Physarum* in a given loci of space for logic values 1 and 0 respectively. The *P. polycephalum* gates use both the foraging nature and plasmodial fusion avoidance properties to compute the logic calculation, with the agar geometry determining the type of gate. The accuracy of Tsuda et al. gates AND, NOT and OR are 69%, 83% and 100% respectively. One factor to consider however, is the computation time, Tsuda et al. documented that time to completion ranged from 11 to 18 h per gate; the limitation is a direct result of the speed of growth.

Adamatzky (Adamatzky, 2010b) used a collision-based computing approach (Adamatzky, 2013) to implement *P. polycephalum* gates. On a non-nutrient substrate the plasmodium propagates as a travelling localization, in the form of a compact wave-fragment of protoplasm; this *Physarum*-localization travels in its originally predetermined direction for a substantial period of time, even when no gradient of chemo-attractants is present. Adamatzky (Adamatzky, 2010b) utilized this property of *P. polycephalum* active growing zones to design two-input two-output Boolean logic gates <$\overline{X}$> → <x AND y, x OR y> and <x,y> → <x, NOT x AND y> verifying the designs in laboratory experiments and computer simulations, cascading the logical gates into a one-bit half-adder and simulating its functionality. Accuracy of experimental laboratory prototypes of gate <x, y> → <x AND y, x OR y> was over 69% and of gate <x,y> → <x, NOT x AND y> over 59%. The accuracy was comparable to the gates in the experiments of Tsuda et al. (Tsuda et al., 2004). Jones and Adamatzky (Jones and Adamatzky, 2010) designed yet another modification of collision-based, or ballistic logical gates and produced a 1-bit half adder using experimentally derived computational modelling.

With the right substrate geometry and attractant–repellent manipulation, *P. polycephalum* growth can calculate the output of basic and derived logic gates, with an acceptable degree of accuracy. The limitation with all these schemes is, as mentioned above, speed of growth and hence calculation time. In a previous paper (Whiting et al., 2014c), we presented a scheme of *Physarum* logical gates which used frequency change of shuttle streaming in response to stimuli to simulate the outputs of the basic logic gates AND, OR and NOT (Table 2); while these are not strictly logic gates as they have non-equivalent input and outputs, they show a significant improvement of computation time using *P. polycephalum* as a computation medium, with calculation time reduced to 20–30 min. Unconventional computing with *P. polycephalum* is significantly advanced with this scheme, and this paper presents expansion of this scheme into one that defines derived and combinational logic using stimuli frequency change in *P. polycephalum* using cascaded *P. polycephalum* logic gates whose output is evaluated by software analysis which determines the input of the following gate.

2. Method

2.1. *P. polycephalum* culture

P. polycephalum plasmodium was grown on non-nutrient 2% agar gel in 9 cm diameter Petri dishes (Fisher Scientific, UK) fed daily with organic rolled oats (Waitrose, UK). The plasmodium was moved to new agar-filled Petri dishes every week to limit unwanted microbial growth.

Table 1
Frequency change in response to stimuli and equivalent logic input.

Stimuli type	Logic input (A,B)	Median frequency change (%)	Standard deviation
No stimulus	0,0	2.1	6.9
Oat flake	0,1	12.2	12.6
Heat	1,0	19.8	8.8
Heat and oat flake	1,1	33.2	9.6

2.2. *Polycephalum response to stimuli*

Data on *P. polycephalum's* response to stimuli was collected for previous research and is described in full in (Whiting et al., 2014c). The data collected is processed and presented here (Table 1) in order to derive additional *P. polycephalum* based gates. Fig. 1 shows the experimental set up in order to produce and measure a single protoplasmic tube. 1 ml of non-nutrient Agar is placed on each of the aluminium electrodes (Farnell, UK) in a customised 9 cm Petri dish (Fisher Scientific, UK) to form a cell interface. A *P. polycephalum* inoculated oat flake from culture is placed on 1 agar hemisphere while a bare oat flake is placed on the remaining agar hemisphere. The agar acts as a growth medium for the organism on the electrode. After a minimum of 5 h and maximum of 12 h, a single protoplasmic tube grows between the two electrodes, allowing recording of the surface potential of the tube. Electrical measurement of the protoplasmic tube were performed by connecting the aluminium electrodes to a PicoLog ADC-24 high resolution analogue-to-digital data logger (Pico Technology, UK) connected via USB to a laptop installed with PicoLog Recorder software for data capture. The PicoLog ADC-24 recorded ±39 millivolts at 1 Hz for the duration of the experiment, with a 24 bit resolution; the originally inoculated agar hemisphere was connected to ground, while the newly connected agar hemisphere was connected to an analogue recording channel.

Stimulation of the organism was performed by adding an oat flake on the recording electrode or by heating the recording electrode to 10 °C above room temperature using a 1.4 W Peltier element (RS Components, UK) placed underneath the Petri dish at the site of the recording electrode. Simultaneous heating and oat

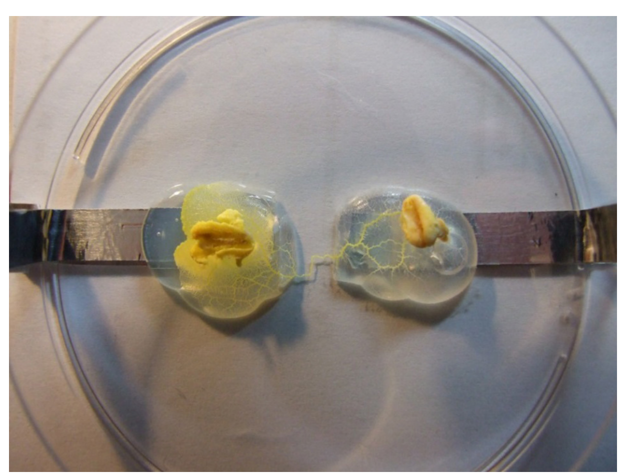

Fig. 1. A single protoplasmic tube branching two agar hemispheres. Logic computation is performed by inducing frequency change of shuttle streaming along this tube; the stimuli are applied to the left hemisphere.