Community Computing

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Cellular Computing

Biological perspectives on filamental automata

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Overview

- Introduction
- Biological motivation
- Previous work
- Inducing waves
- Conclusions

Introduction

- Fundamentally, we are interested in how *coordinated* behaviour arises through purely *local* interactions between large numbers of simple components
- *Self-organisation*; of particular interest to (computational) biologists
- We study it in the context of *filaments*

Filaments

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- 1D strings of identical finite automata (*cells*)
- *Filament state*: string of cell states, read (say) left to right
- Individual cells take only input from their immediate neighbours, which determines (along with the current state) the cell's next state, and so on, in synchronised cycles

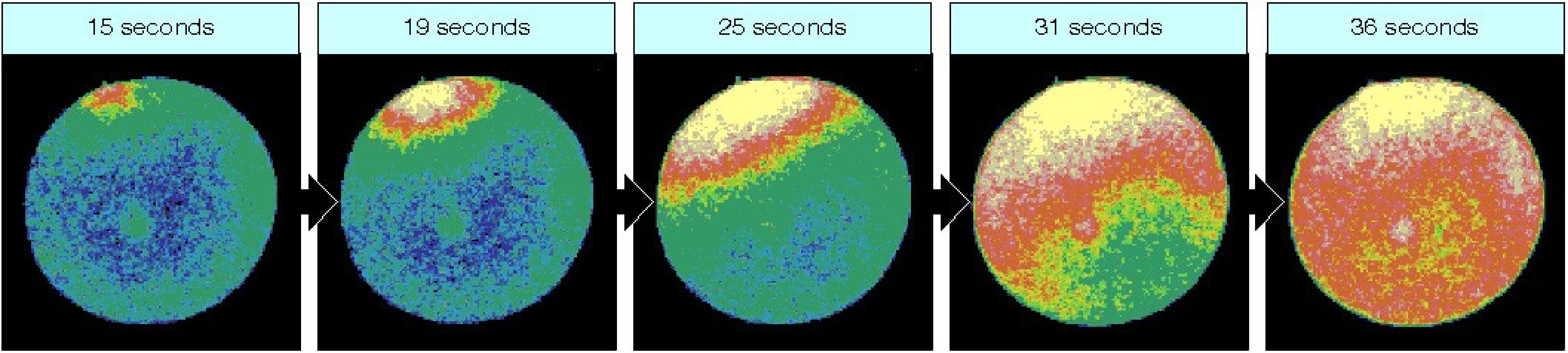
Fundamental question

- Under what conditions might we observe *coordination* of the individual components?
- We restrict our model, partly for reasons of biological plausibility
- Constraints
  - Cells have no more than *three* states
  - Filaments consist of *identical* cells

Biological motivation

- A *huge* number of processes in cells, tissues and organisms are governed by *waves* (chemical concentration, mechanical deformation, electrical signal, etc.)
- Propagating wave-forms are therefore a way of transmitting information within/between cells
- *Coordination* = sustained waves of cellular state changes along a filament

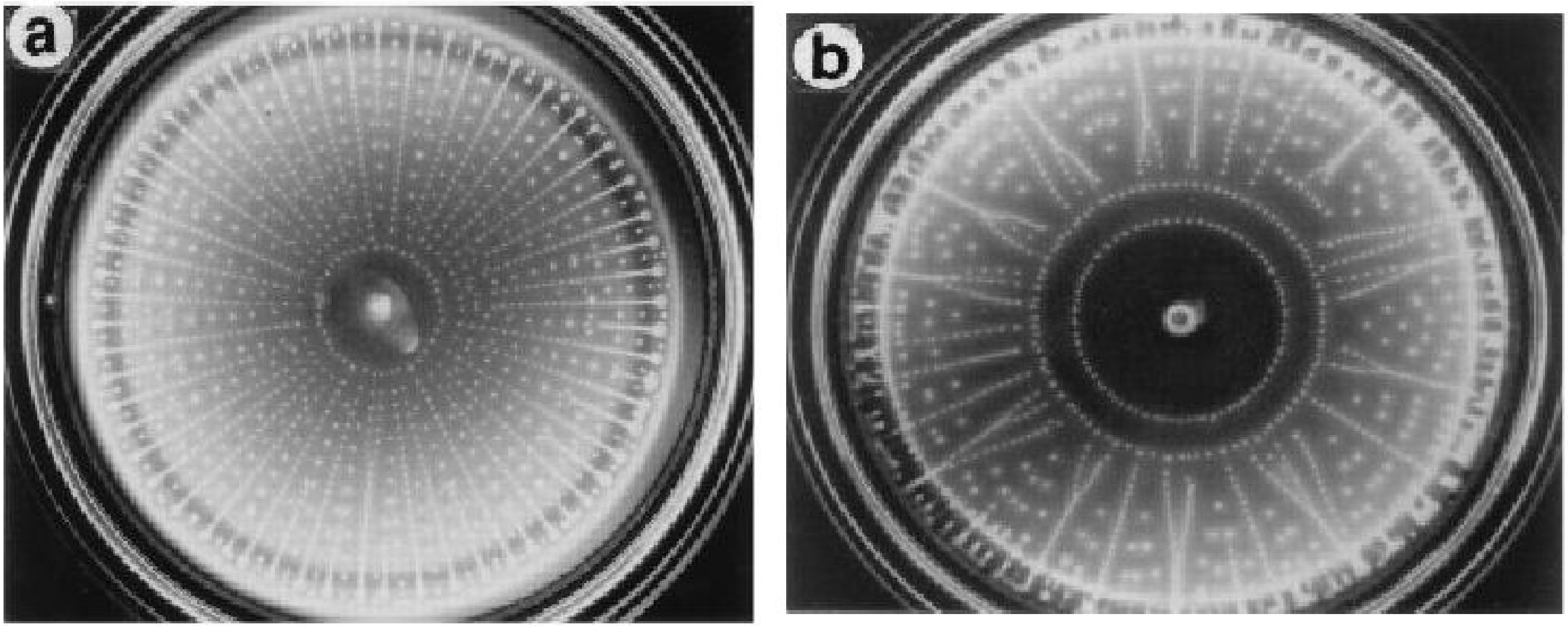
Example - within cell



Calcium wave initiated at fertilization results in egg activation.

Courtesy of Brian E. Staveley, Memorial University of Newfoundland.
http://www.mun.ca/biology/desmid/brian/BIOL3530/DB_Ch12/DBNGerm.html

Example - between cells

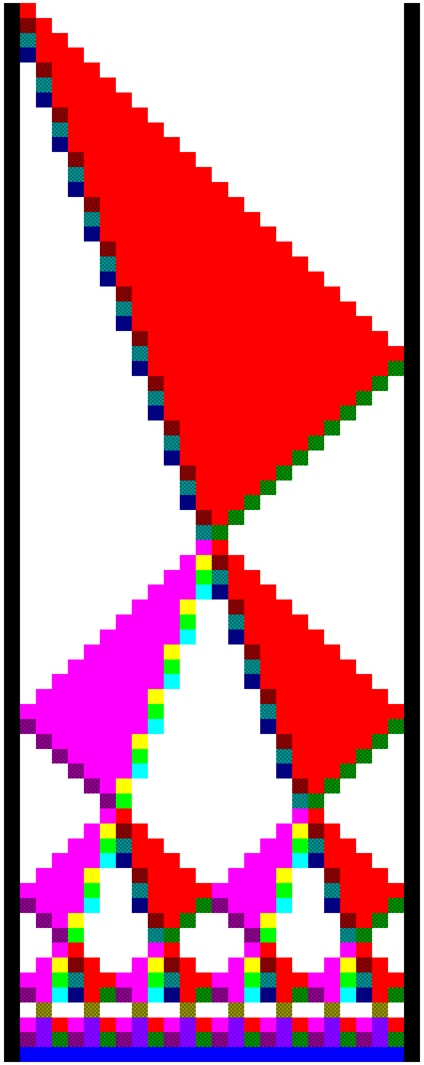


Pattern formation in mobile bacteria.

Courtesy of Howard Berg and Elena Budrene.

Previous coordination work

- Firing squad synchronization problem (Myhill, 1957)
- Line of identical FSM ("soldiers"), each init. to same state (except "captain" at far left). Input taken from neighbour(s)
- Find a set of rules such that all soldiers enter the unique firing state at the same time
- No 4-state solution exists (Mazoyer, 1988)
- Best-known solution has 6 states



Solution with 15 states, in 3*n* time

Previous coordination work

- Dijkstra (1974-86). *Self-stabilising* rings of automata
- Presented in context of a “token ring” network of computers that eventually settles into a “correct” state
- Algorithmic fault tolerance

Previous coordination work

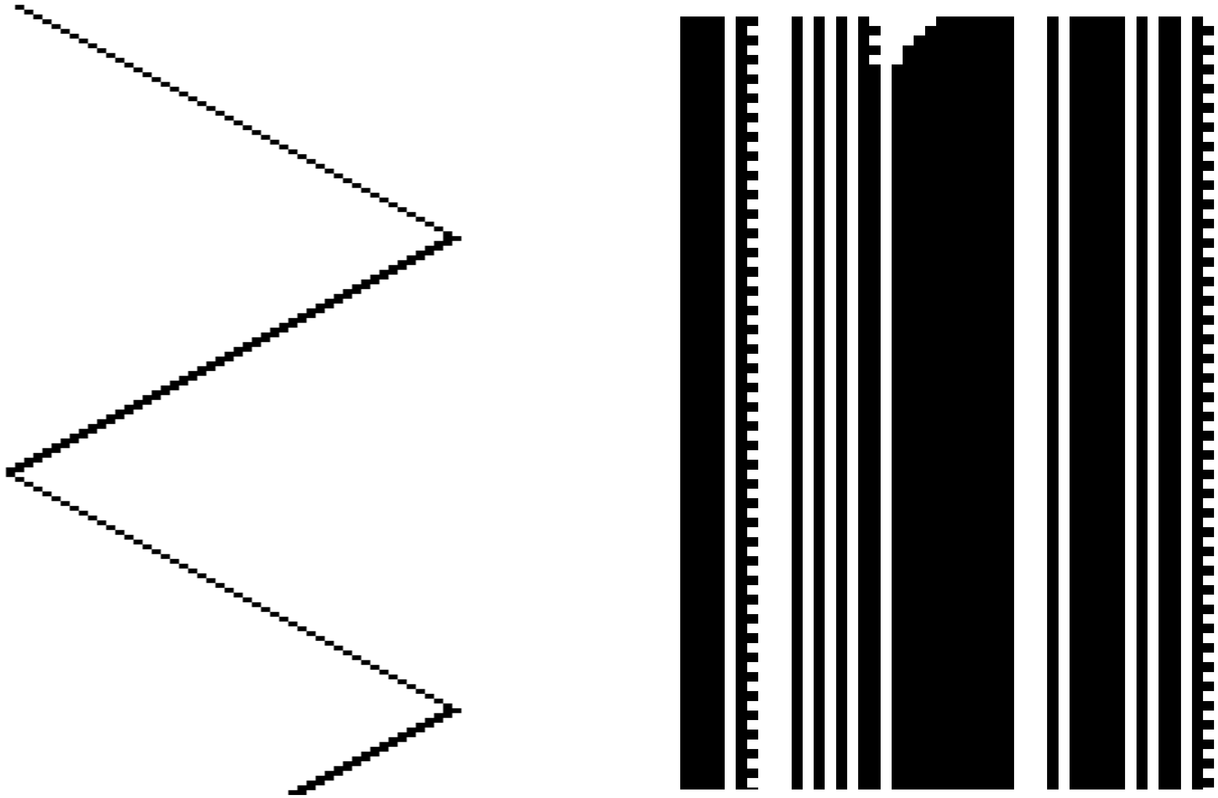
- Das, Crutchfield *et al*. (1995). Evolved synchronised CA
- Issues arising from previous work:
  - Non-uniform automata
  - Large numbers of states
  - Unnatural ring arrangement

Preliminaries

- We study finite automata that induce wave patterns in a filament's state
- There are essentially two types of wave:
  - **Type A: a small # of cells change state at each step (interesting)**
  - Type B: *every* cell changes state at each step (not so interesting)

Type A waves - 2-state automata

- We first undertook an exhaustive search of 2-state automata
- There is no 2-state, non-oblivious FA, *taking input only from its two immediate neighbours,* that generates a Type A wave
- One does exist if we extend the neighbourhood to two cells on each side



Trace of self-stabilising 2-state automaton on (a) filament ($[01^{n\text{-}1}]$), (b) random filament.

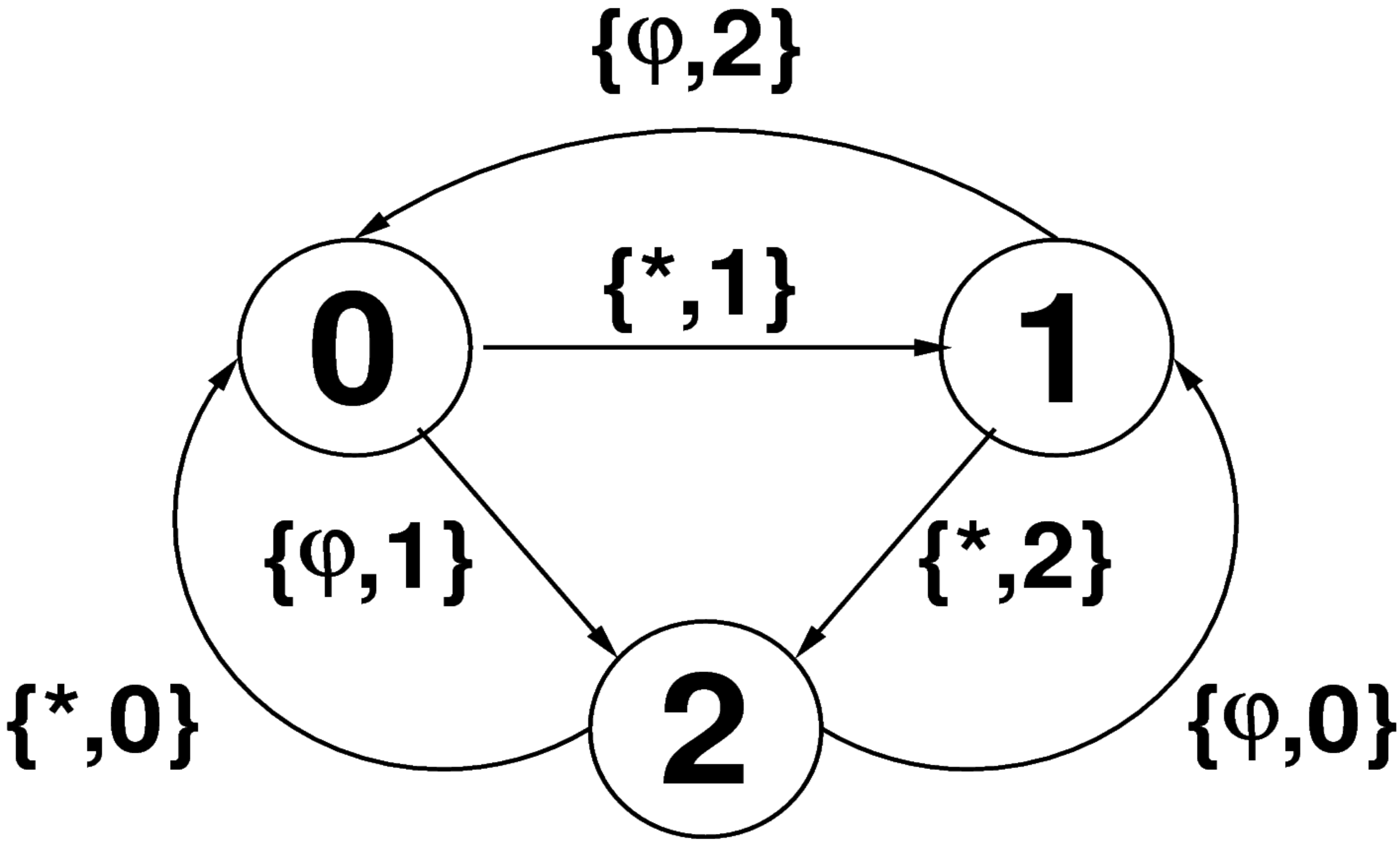
3-state automata

- We know of no non-oblivious 3-state FA, taking inputs only from its nearest two neighbours, that induces *self-stabilising* (i.e. *cyclical, regardless of initial filament state*) Type A waves in filaments
- Dikjstra (1986) describes self-stabilising behaviour for a ring of 3-state machines, but he used three different types of machine
- He believed that there is no such device using just *one* type of automaton

Stability

- However, if we use *populations* of growing filaments, we might induce stable behaviour
- That is, they might exhibit persistent, population-level behaviour that is not observed in all of the individuals, starting from random states

Automaton-I



Traces

Implications

- Automaton-I is not *self-stabilising*. There are initial filament states that do not take us into cyclic behaviour
- Inspired by our belief that no 3-state self-stabilising automata exists that, taking input only from its two nearest neighbours, induces Type A wave behaviour, we are motivated to study further machines like Automaton-I which clearly induce the same cyclic behaviour for *many* different, but *not all*, initial filament states

Viable populations

- We study filaments that repeatedly “grow” by a single cell after a certain delay ($6n$ iterations, where n is the length of the filament)
- Normal cycle length for Automaton-I is $6n$
- The probability of an arbitrary initial filament becoming normally cyclic is 50% (details in the paper)

Accretion

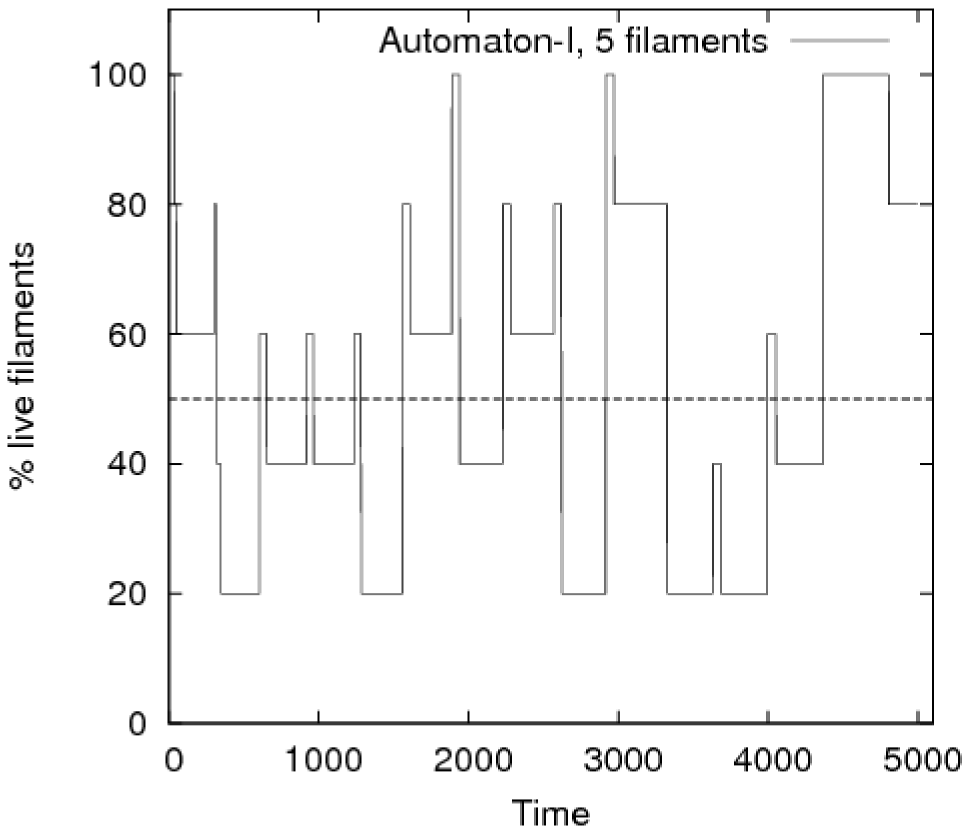
- After a population update by growth ("accretion"), we still expect roughly half of the filaments to be alive, and half to be dead
- At any one time, half of the population is "alive", but, crucially, the individual filaments making up this proportion constantly change
- Turnover in terms of the active population members at any one time - strong biological basis

Numerical simulations

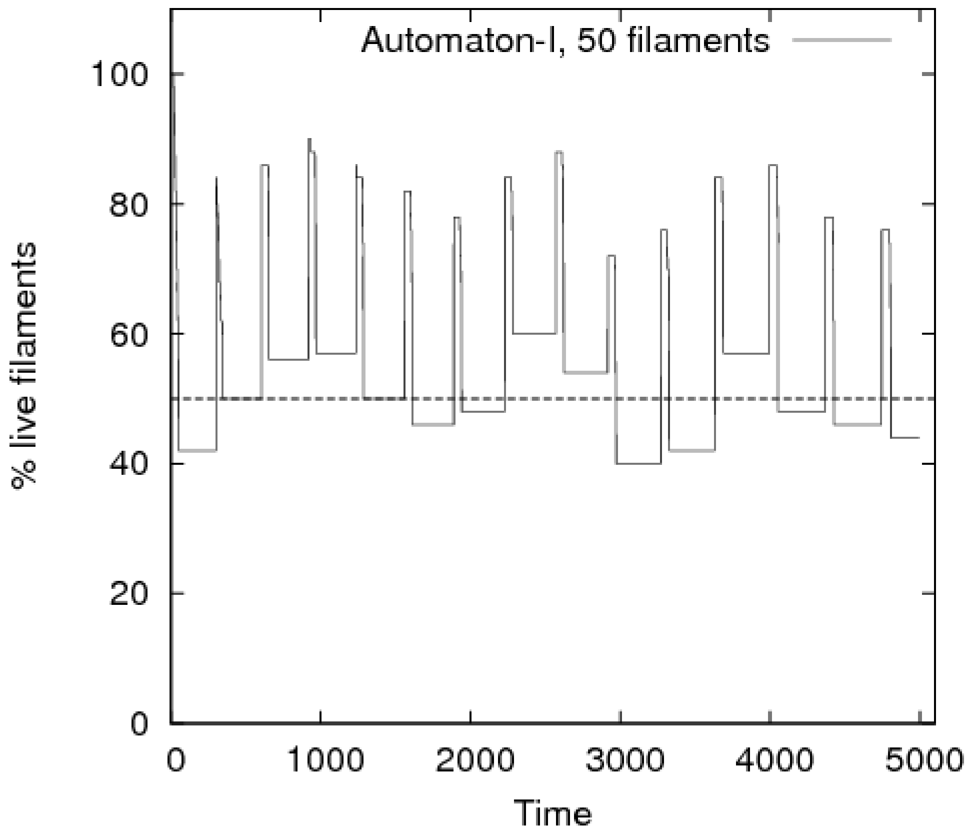
Population of *m* (5..200) filaments of length *n* was created. The state of each filament was initially randomised, and then each was simulated for 5000 iterations

- Crucially, filaments were allowed to periodically grow; after a set interval (6*n*), the right end of each filament was extended by the addition of a randomly-initialised "cell"

Results

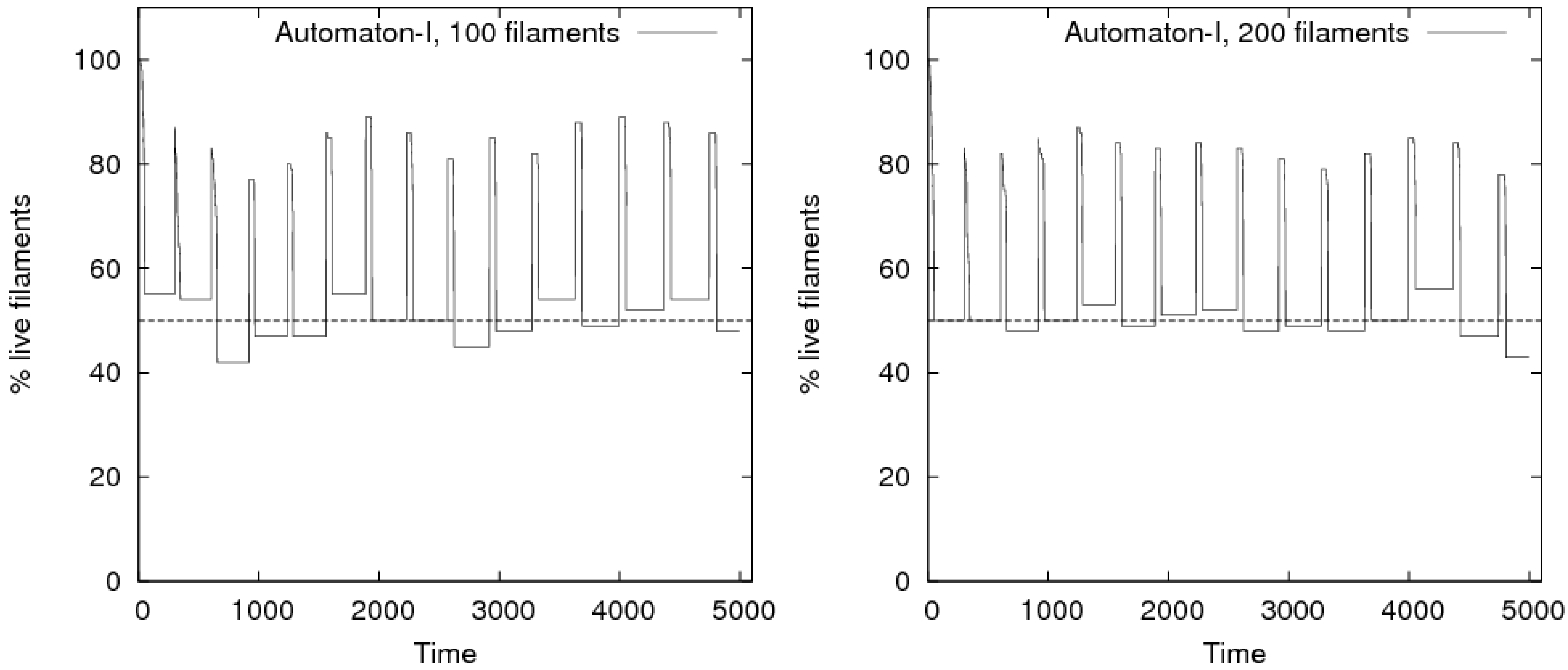


Automaton-I, 5 filaments
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
Time
% live filaments



Automaton-I, 50 filaments
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
Time
% live filaments

Results



Automaton-I, 100 filaments
% live filaments
Time
0
20
40
60
80
100
0
1000
2000
3000
4000
5000
Automaton-I, 200 filaments
% live filaments
Time

Conclusions

- In terms of the number of states and range of input, we have described the simplest FA that, for filaments, induce regular cyclic behaviour
- For Type A waves, we described a self-stabilising 2-state machine; we no of no other machine with the same characteristics that is as simple
- We then introduced the notion of viable populations of filaments, which exhibit stable characteristics under growth induced by automata that are not powerful enough to induce stable behaviour in individual filaments

Future work

- Consider effect of allowing filaments to join together, in pairwise fashion, rather than simply being extended by a single cell at a time
- Biological implications (if any)?
- Asynchronous updates? Noise?