Biological perspectives on filamental automata

Alan Gibbons
Dept. of Computer Science, King's College London

Martyn Amos
Dept. of Computing and Mathematics,
Manchester Metropolitan University

Overview

- Introduction
- Biological motivation
- Previous work
- Inducing waves
- Evolving automata
- 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

- 1D strings of identical finite automata (*cells*)
- *Filament state*: string of cell states, read (say) left to right
- Each cell takes input from its neighbours, determining, along with its current state, the cell's next state. Cells update their states synchronously

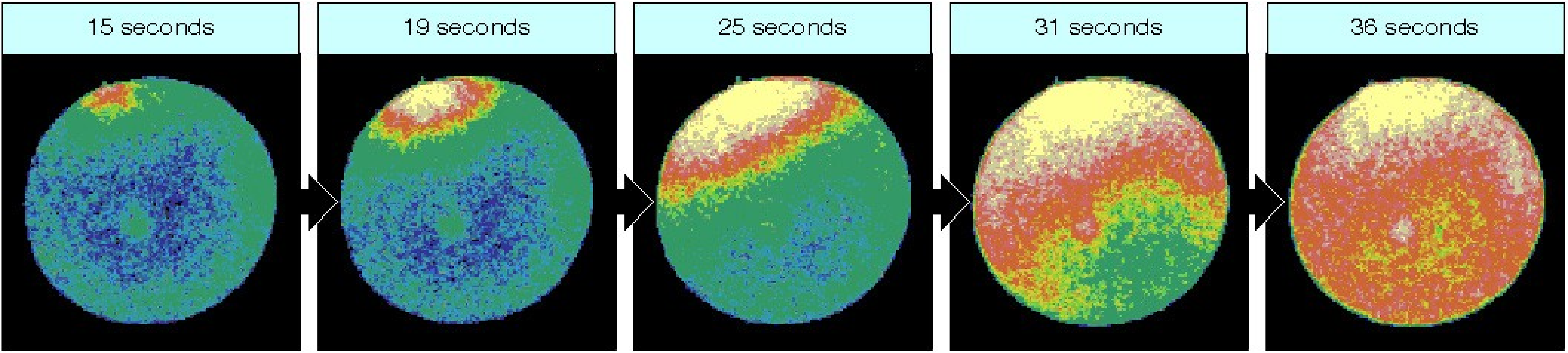
Fundamental question

- We seek the simplest conditions under which cellular behaviour becomes coordinated (evidenced by wave motion along filaments)
- Seeking simplicity through insisting that every cell is an identical FA with the smallest # of states and range of inputs appeals, we believe, to biological plausibility
- For (biological) robustness, we insist on the filaments being self-stabilizing (that is, however the filament state might be corrupted, it will automatically return to regular wave-motion)

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

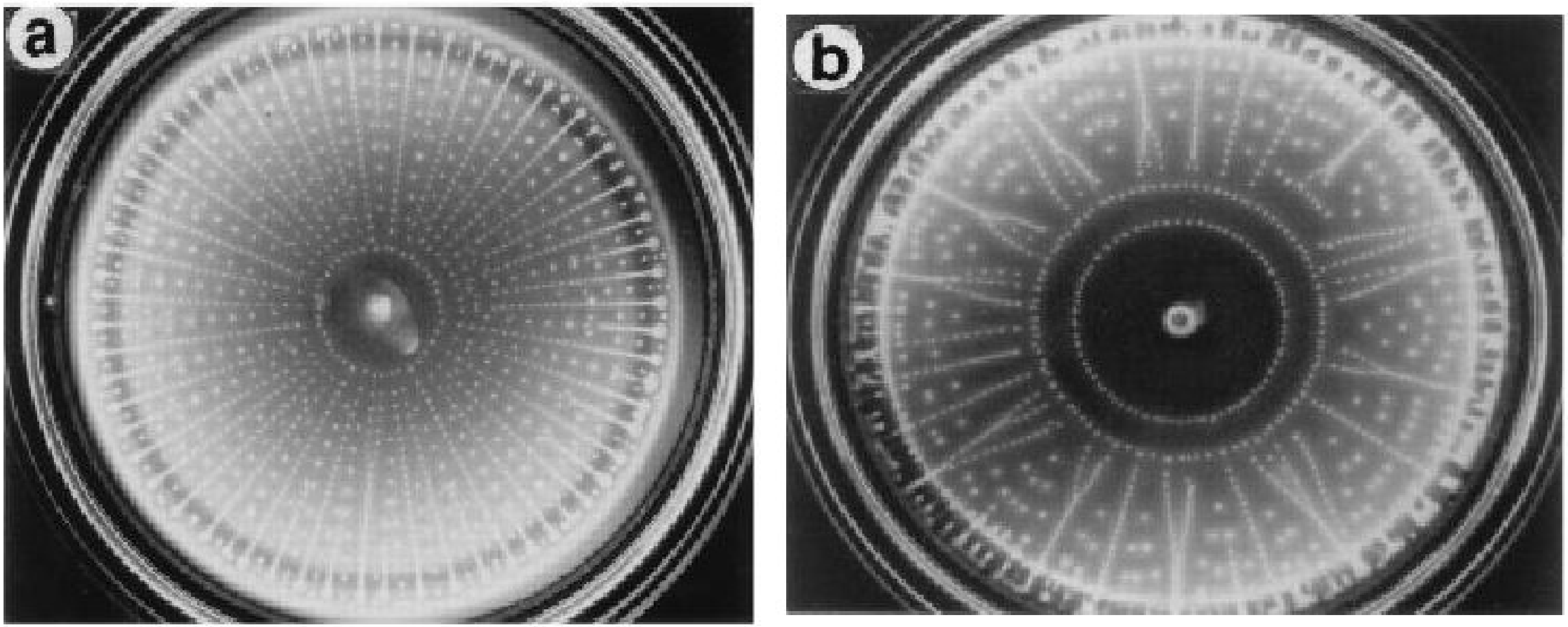
Example - within cell



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

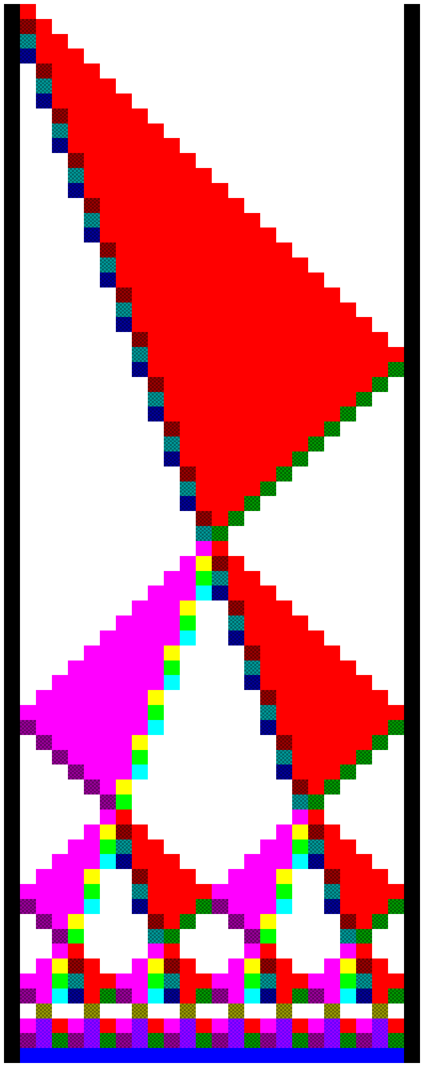


Pattern formation in mobile bacteria.

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

Preliminaries

- Studies of wave motion in CA reveal two types of regular wave pattern:
  - Type A, in which a small cluster of cells change state at each step (the “wave front”)
  - Type B, in which *every* cell changes state at each step

Type A waves and 2-state automata

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

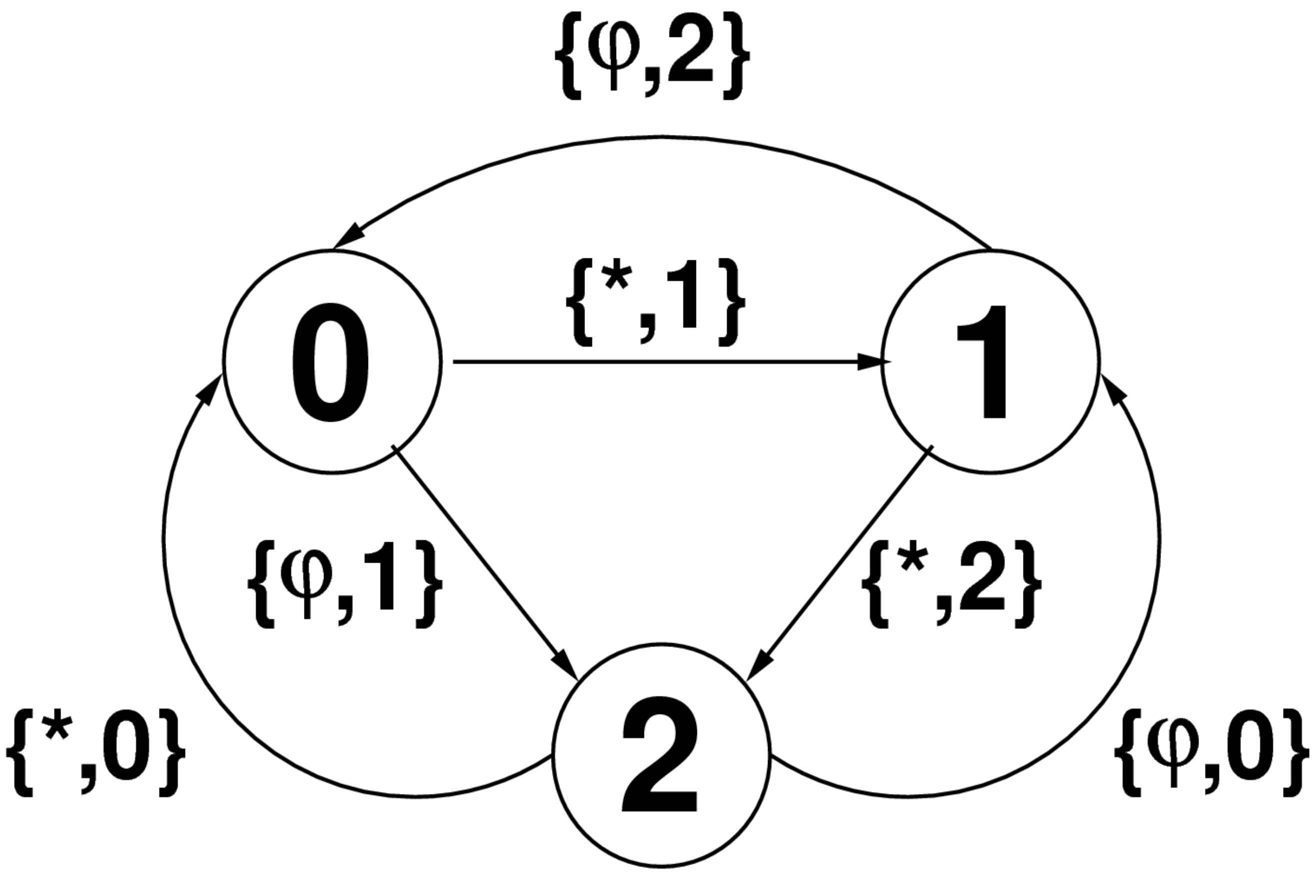
3-state automata

- An exhaustive search of 3-state FA is not practical
- We know of no non-oblivious 3-state FA, taking inputs only from its nearest two neighbours, that induces self-stabilisation in Type A wave in filaments. We believe no such FA exists
- 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

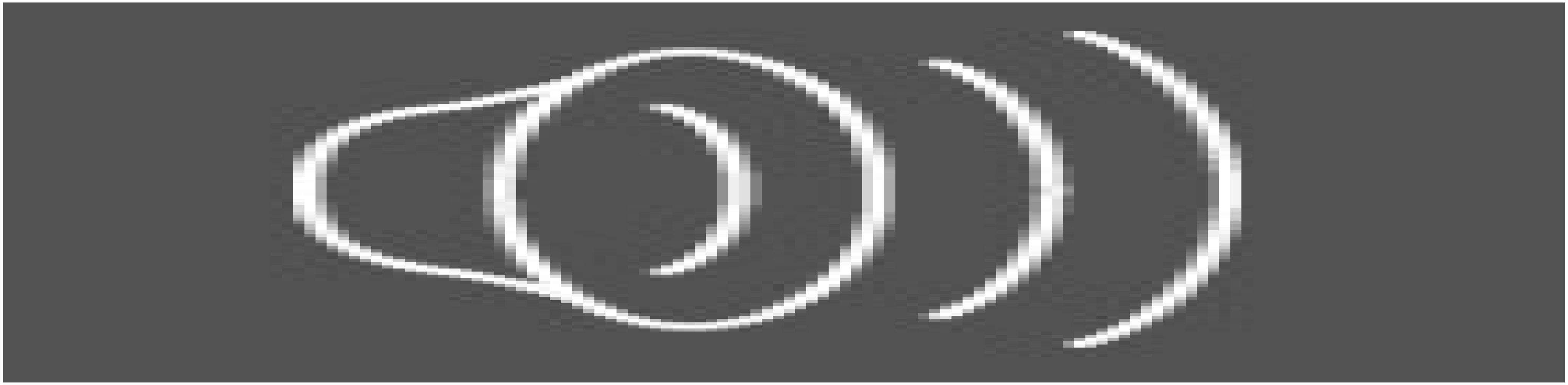
Self-stabilisation in dynamic filament populations

- We introduce the notion of self-stability of dynamic *populations* of filaments using component FA which are too simple to induce self-stability in *individual* filaments
- Our model is a dynamic population of filaments which grow by the addition of single cells, and in which, at any moment, a fixed proportion exhibit Type A stability and the rest are inert
- We now describe numerical simulation studies

Automaton-I



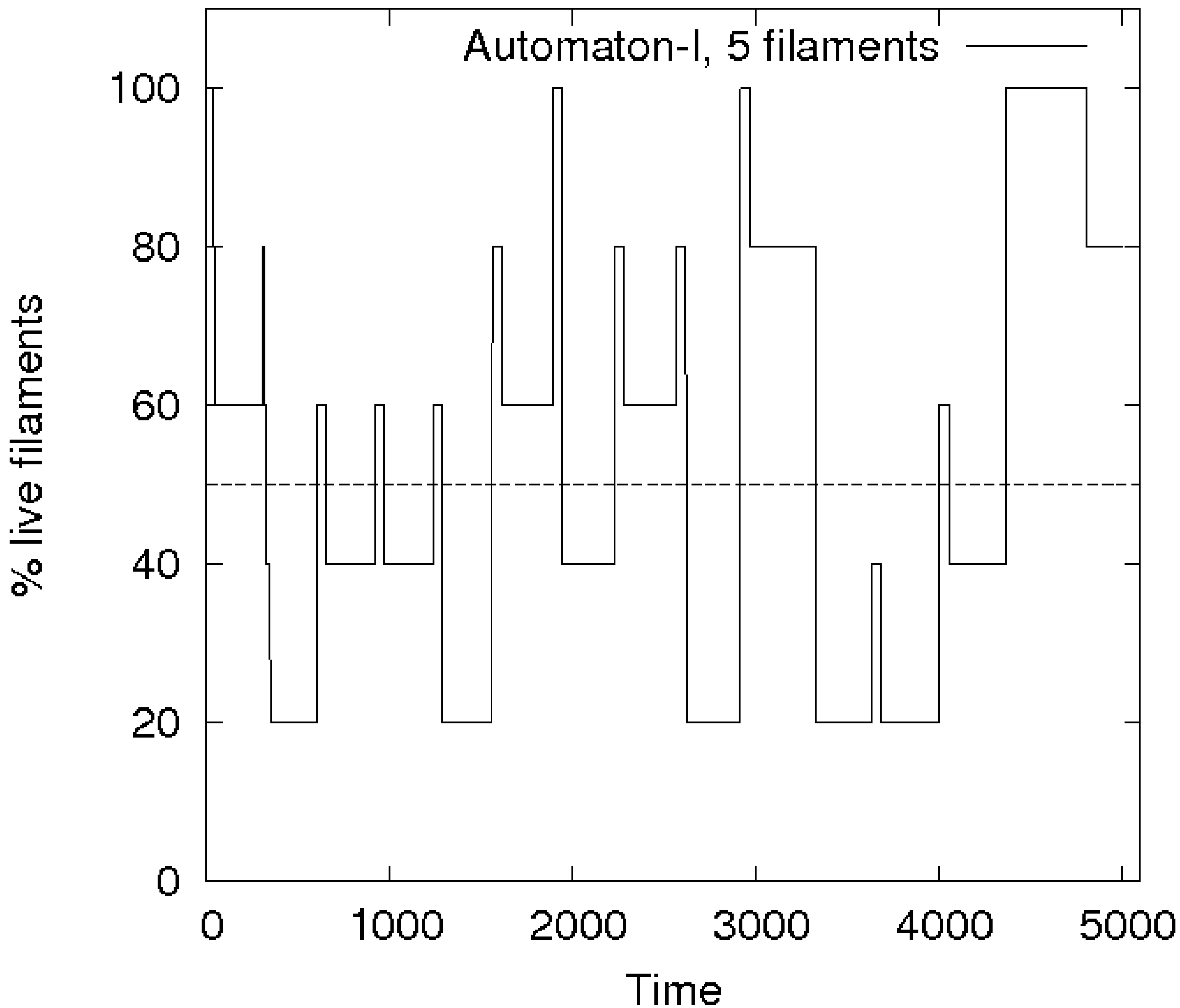
Animation



Viable populations

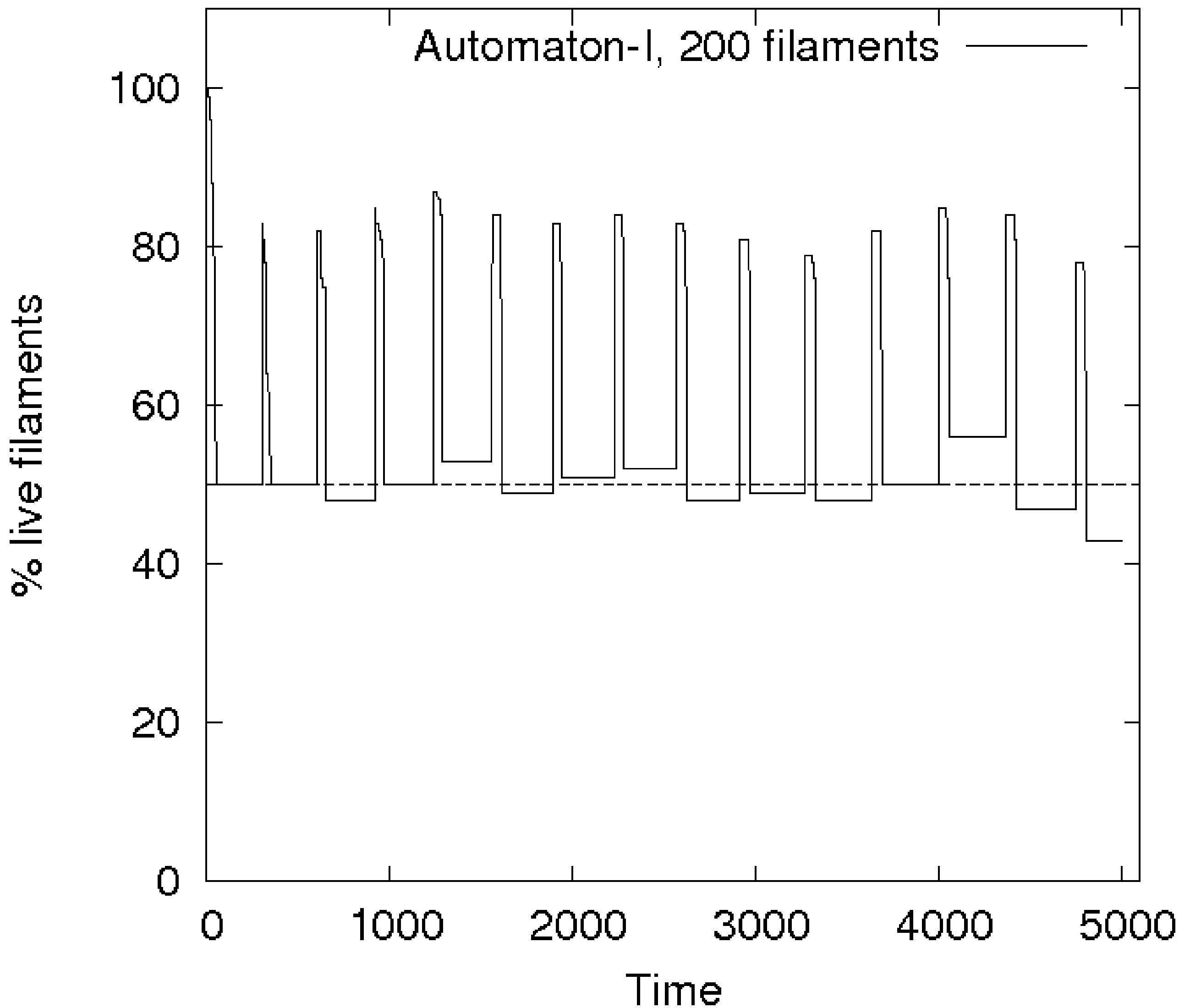
- Illustrating our notions, we consider (here) a population of filaments that individually grow by the regular accretion of single cells
- Our analysis shows that at any given time (for this FA) there should be 50% of the filaments “alive” and the remainder inert
- Turnover in terms of the active population members at any one time - strong biological basis

Results



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

Results

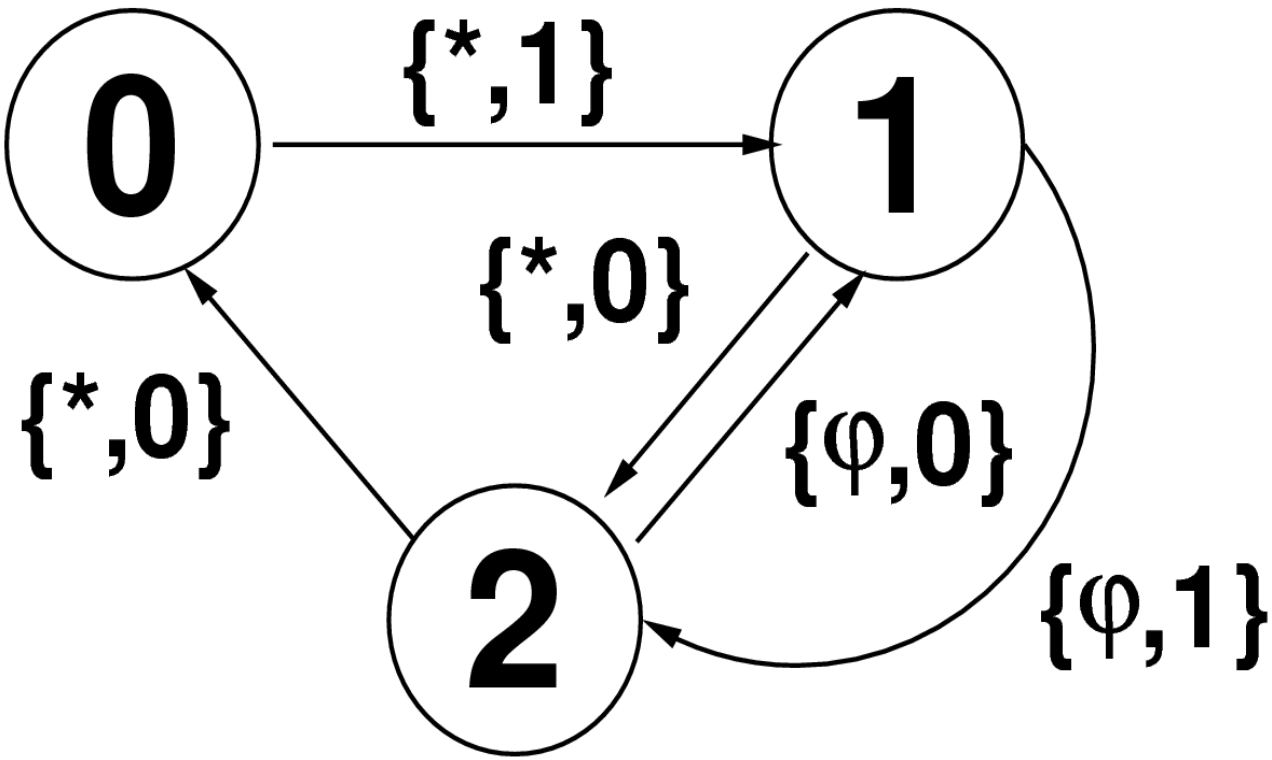


Automaton-I, 200 filaments
% live filaments
Time
0
20
40
60
80
100
0
1000
2000
3000
4000
5000

Evolving automata

- We demonstrate that FA leading to viable populations can be evolved via a genetic algorithm
- Starting with a random population of 3-state FA, we evolved the population using a fitness function that (essentially) measures the lifetime of filaments

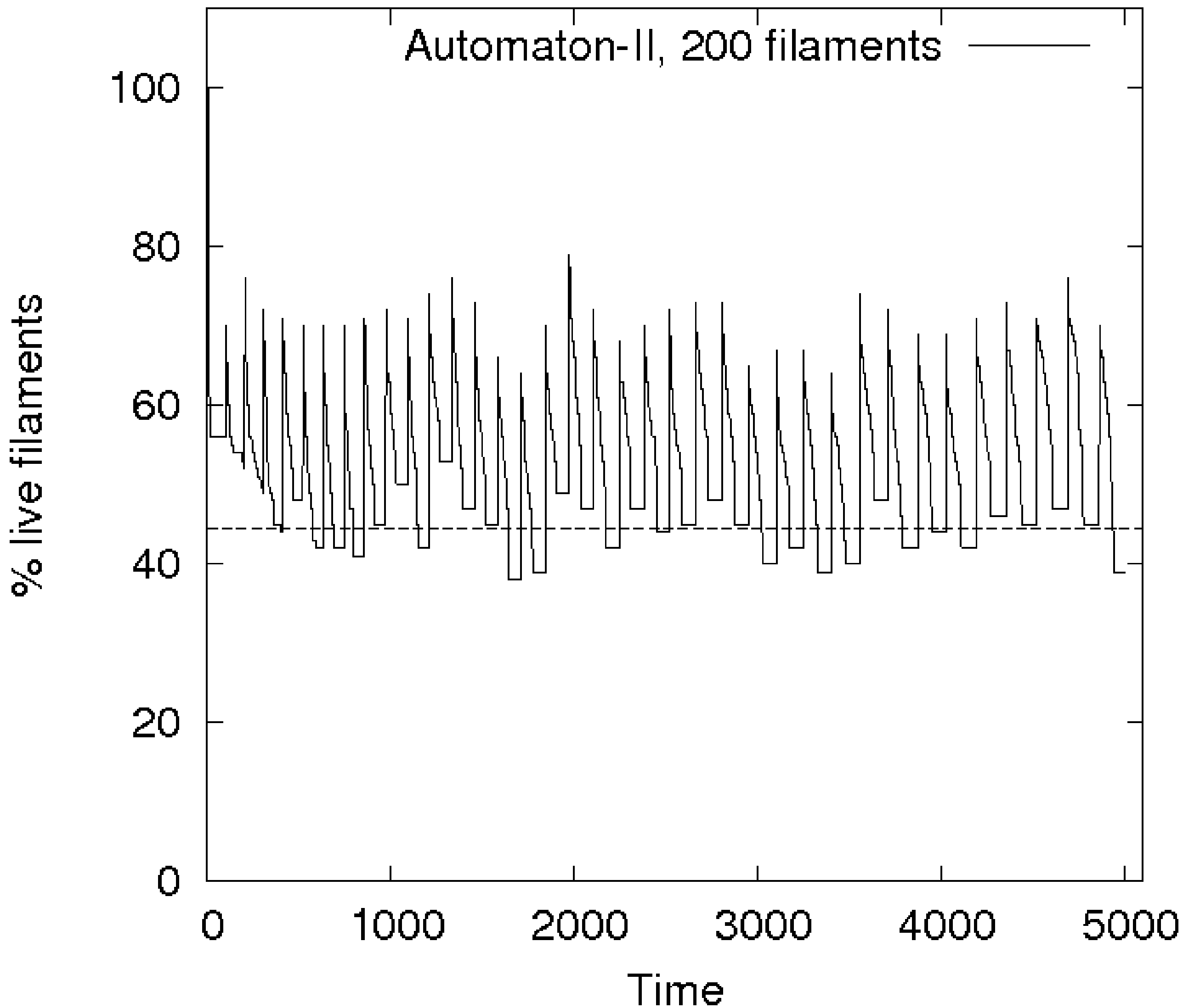
Automaton-II



Analysis

- Our analysis shows that this automaton should yield a viable population for which the proportion of live filaments is 4/9 (44.4%)
- We ran the same set of simulations as for the previous automaton

Results



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

Conclusions

- In terms of the number of states and range of input, we have described the simplest FA that, for individual 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. For Type B waves, there is a self-stabilising filament using any number of states > 1
- We then introduced the notion of viable *populations* of filaments, which exhibit self-stability under growth induced by automata that are not powerful enough to induce stable behaviour in individual filaments

Future work

- Concerning viable populations, we wish to run a variety of (biologically plausible) simulations that allow coalescence and/or self-division of individual filaments
- One interesting possibility, for example, is to allow for joining/division around a “thermally stable” filament length
- We do not yet fully understand which 3-state FA lead to viable populations
- We need to identify real biological phenomena for which this work would be a plausible model
- What biological implications might follow?

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  (plug)

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