Stomatal Networks & Cellular Computation

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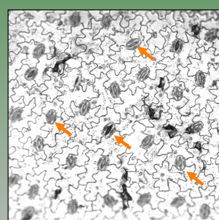
Stomatal Networks

- Stomata, the "cells" of the network, are tiny pores on the surface of a leaf that control the exchange of CO_2 and H_2O between the inside of the leaf and the atmosphere. They do this by adjusting the pore aperture.
- Aperture size varies in response to light, CO_2, humidity, and water stress.
- These "cells" can also interact locally via hydraulic forces with neighboring "cells."
- The image shows a stomatal network on the surface of a *Vicia faba* leaf. Stomata (examples marked by red arrows) shown are approximately 30 μm long.

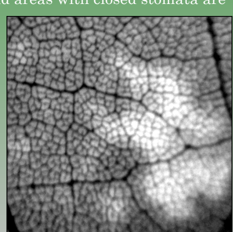


Problem Solving

- A plant solves the following problem: how open or closed should its stomata be?
- When plants open their stomata, CO_2 diffuses into the leaf where it is used in photosynthesis—a good thing; however, with the stomata open, water escapes to the atmosphere—a bad thing.
- Therefore, a plant putatively adjusts its apertures so that it maximizes CO_2 uptake for a given amount of water loss—constrained optimization problem.

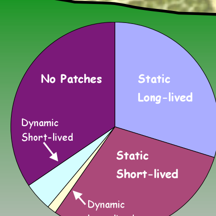
Patchiness

- Even when environmental conditions are temporally constant and spatially uniform, groups of tens to thousands of stomata can behave differently from stomata in adjacent areas—stomatal patchiness.
- Stomatal patchiness can be dynamic, with complicated and apparently unpredictable spatial and temporal variations appearing over the surface of the leaf.
- The image shows a 512 by 512 grayscale image of chlorophyll fluorescence containing ~10^5 stomata; areas with open stomata are dark and areas with closed stomata are bright.



Sensitive dependence on microscopic conditions

- Stomatal responses to environmental perturbations (e.g. abrupt humidity change) can be placed into one of five categories as shown in the pie chart.
- Despite having the same macroscopic conditions, which of the responses will occur in any one of the experiments is never predictable.
- This suggests that stomatal dynamics is sensitive to microscopic conditions—a situation that is reminiscent of space-time systems with self-organizing dynamics.
- The pie chart shows the proportion of each response for 76 experiments with the same macroscopic initial conditions and the same humidity perturbation.



Questions

- In addition to the qualitative characteristics shared by stomatal networks and some cellular computers shown to the side, what quantitative features do they have in common?

- If they are qualitatively and quantitatively similar, are cellular computers, therefore, good models for stomatal networks?

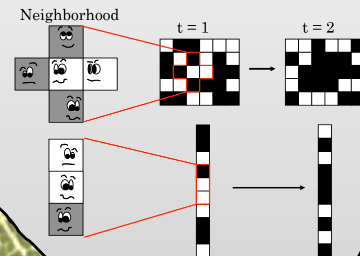
Statistic	Stomata	1-D CA	2-D CAs			
Fourier Spectrum Power Law Exponent	1.94 ± 0.06 (R^2=0.99)	1.98 ± 0.02 (R^2=0.99)	1.99 ± 0.11 (R^2=0.99)	2.16 ± 0.12 (R^2=0.99)	1.91 ± 0.12 (R^2=0.99)	1.84 ± 0.17 (R^2=0.99)
Hurst Statistic Power Law Exponent	0.60 ± 0.03 (R^2=0.94)	0.82 ± 0.06 (R^2=0.94)	0.54 ± 0.002 (R^2=0.99)	0.60 ± 0.005 (R^2=0.96)	0.44 ± 0.005 (R^2=0.96)	0.35 ± 0.008 (R^2=0.96)
Event Waiting-Time Distribution Power Law Exponent	1.15 ± 0.21 (R^2=0.93)	1.77 ± 0.23 (R^2=0.91)	2.22 ± 0.14 (R^2=0.96)	1.96 ± 0.11 (R^2=0.97)	2.73 ± 0.24 (R^2=0.92)	2.35 ± 0.19 (R^2=0.93)

Summary

Qualitative and quantitative features of stomatal patches are essentially indistinguishable from those found in locally connected cellular computers that perform global computational tasks. The reason so many plant species exhibit stomatal patchiness may be that, through their stomata, plants are performing a sophisticated kind of problem solving that is similar to emergent computation. Unambiguous resolution of this conjecture awaits the development of sharper tools than now exist for quantifying computation, especially as it exists in natural systems.

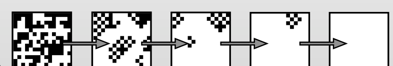
Cellular Computer Networks

- "Cells" of the network are usually arranged in a 1-or 2-dimensional lattice.
- Each "cell" is characterized by a deterministic transition rule. The transition rule can be a differential equation or a look-up table. In either case, the transition rule incorporates the state of the "cell's" neighborhood.
- The size of a "cell's" neighborhood is different for different systems. For example, a neural network is extensively connected, with each "cell" receiving input from many other "cells" at one time, whereas a cellular automaton (CA) is locally connected, with each "cell" receiving input from only its immediate neighbors at one time.
- The image below shows one time step for a 2-dimensional and a 1-dimensional CA. The neighborhood of the 2-dimensional CA is 5 cells and the neighborhood of the 1-dimensional CA is 3 cells.



Problem Solving

- There are a variety of global computational tasks that a cellular computing network can perform. One instructive example is the density classification task.
- Given an initial distribution of binary states, one solution to the density classification task is a steady state corresponding to the state that comprised the majority of the initial distribution.
- A time lapse of a 2-dimensional CA solving the density classification problem is shown below. The initial conditions are 49% black and 51% white. It arrives at the correct solution.



Patchiness

- It has been shown that, in some CA that perform emergent computation, the global task is accomplished by "patches of information" coherently propagating over large distances. In these example systems (in which information is processed strictly locally), global computation is achieved because distant regions of the system can communicate via coherent patch propagation.

Sensitive dependence on microscopic conditions

- In general, the further the initial density is from 0.5 the easier the density classification task. For densities close to 0.5, the task is more difficult.
- Although the macroscopic initial density may be exactly the same, different microscopic configurations can lead to very different, unpredictable, behaviors—ranging from quickly achieving a steady state to taking an inordinately long time.
- The two 1-dimensional CA simulations shown started with exactly the same number of black and white cells, but the positions of 2 cells were swapped.