Urdar - an artificial ecology platform

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Abstract

Cross-feeding interactions are a common feature of many microbial systems, such as colonies of *E. coli* grown on a single limiting resource. We have studied this phenomenon in Gerlee and Lundh (2010) from an abstract point of view by considering artificial organisms which metabolise binary strings from a shared environment. The organisms are represented as simple cellular automaton rules and the analog of energy in the system is an approximation of the Shannon entropy of the binary strings. Only organisms which increase the entropy of the transformed strings are allowed to replicate. This system exhibits a large degree of species diversity, which increases when the flow of binary strings into the system is reduced.

Introduction

The origin of biodiversity has been a long standing problem in ecology and the evolution and maintenance of diversity was long difficult to account for, especially in the light of the proposed competitive exclusion principle which states that several species competing for the same resources cannot co-exist. Related to these issues is the question of how species diversity influences ecosystem productivity (Waide et al., 1999). Several experiments and theoretical models have been devised to resolve this issue, but many of the results have been inconclusive and even contradictory.

One of the simplest ecological system where diversity emerges, and is stably maintained, is in populations of *E. coli* growing in a homogeneous environment limited by a single resource, usually glucose. The diversity is facilitated by cross-feeding (syntrophy), where one strain partially degrades the limiting resource into a secondary metabolite which is then utilised by a second strain. This phenomenon was first observed by Helling et al. (1987).

In Gerlee and Lundh (2010), we present a more general model of the evolution of cross-feeding, which is not aimed at modelling a specific biological system, but rather extracts and models the general principles governing systems where cross-feeding might emerge. In order do this, we have devised a novel Artificial Life system, named *Urdar*[1] in which the fitness of an organisms is defined in a more general sense and where interactions between organisms are at the core of the model. The fitness of the organisms in this model is directly related to their ability to extract energy from a common environment, and is thus closely connected to the fundamental concept of energy which drives many ecological interactions.

[1]Urdarbrunnr is one of the three wells that lie beneath the world

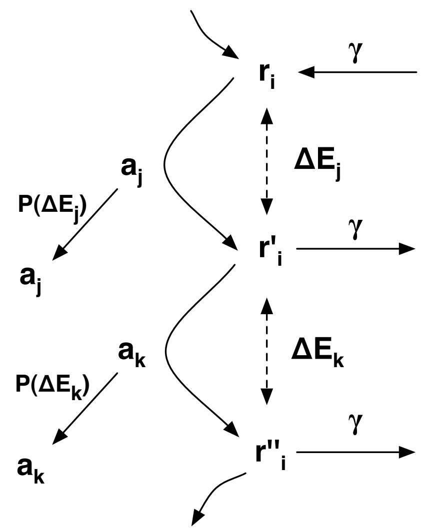

Figure 1: A schematic view of the model. The agents a in the model digest binary strings r by applying CA-rules, transforming r to r'. To each such metabolic step we can associate a difference in energy ΔE (visualised with dotted lines). The reproduction of each agent depends on how much it can decrease the energy of the binary string and occurs with probability $P(\Delta E)$ (represented by the arrows on the left hand side). The binary strings exist in a common pool which they enter (and leave) at a rate γ, as shown by the arrows on the right hand side.

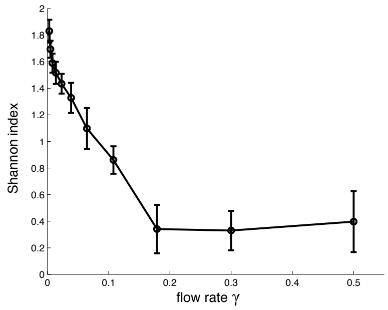

Figure 2: The Shannon diversity index of the species distribution as a function of the flow rate γ. Each data point was averaged over 20 simulations and the error bars represent one standard deviation.

The Model

In order give a short description[2] let us give its main features. The dynamics, depicted schematically in figure 1, during one update can be described in the following way:

1. Each agent in the population picks randomly a resource string r_j from the resource pool R and transform it accordingly to its CA-rule and then puts the transformed string back into the resource pool.

2. The efficiency of the "metabolic process" just occurred is evaluated by measuring the energy difference ΔE of the string before and after the "digestion/transformation". This is done by drawing a random number x uniformly between 0 and 1, and if $P(\Delta E) > x$ the agent reproduces, replacing a randomly picked agent with a copy of itself.

3. With probability μ the offspring will be mutated uniformly to another CA-rule.

4. In order to keep energy flowing into the system, after all agents have been updated, a fraction γ of the strings are replaced with high energy binary strings.

Results

The main result indicates that the diversity increases as the resource level in the system drops, and this trend was investigated systematically by measuring the time average of the Shannon index shown in figure 2 and reveals that the diversity is a decreasing function of the flow and exhibits an approximately linear decrease with the flow rate γ, except for a saturation for high values of γ.

We have also studied the total population's productivity. See figure 3. A still open question for future studies is how

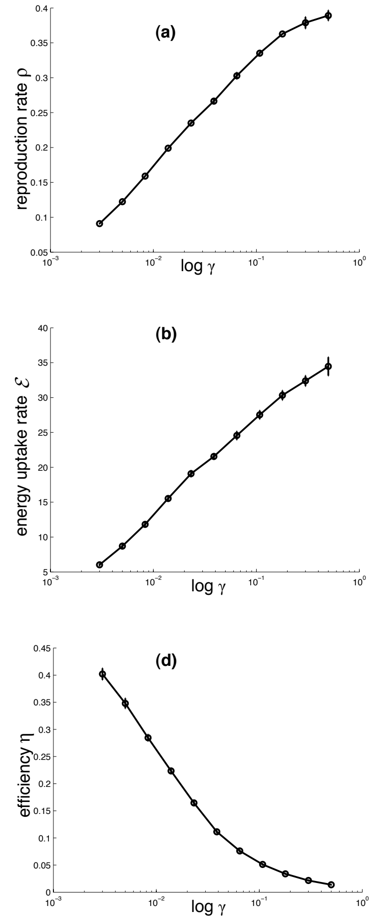

Figure 3: Three different measures related to productivity in the system. (a) shows the reproduction rate ρ, i.e. the number of divisions per update which corresponds to biomass growth, (b) shows the energy uptake rate $\mathcal{E}$, i,e. the energy difference between outflow and inflow, and (d) shows the efficiency of the energy uptake η.

good these population-productivity is compared to the optimal productivity, i.e. how good is the through evolution obtained population with respect to the total energy extraction.

References

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Waide, R., Willig, M., Steiner, C., G., M., Gough, L., Dodson, S., Juday, G., and Parmenter, R. (1999). The relationship between productivity and species richness. *Annu. Rev. Ecol. Syst.*, 30:257–300.

tree Yggdrasil in Norse mythology. The name means well of fate.

[2] An online version of the platform is available at: http://www.math.chalmers.se/~torbjrn/Urdar/urdar.html