# Hierarchical asymmetric cellular automata for multi-scale modelling of ecological and socio-economic systems

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## Introduction

Cellular automata (CA) [Toffoli and Margolus, 1987; Wolfram, 1986] are well known and often used in spatially explicit modelling of ecological systems (see e.g. [Thulke et al., 1999]), environmental systems (see e.g. [Wittmann, 2000]), or socio-economic systems (see e.g. [Wang and Zhang, 2001]). The dynamics of such systems is usually very complex as the underlying processes are based on different scales in time and space. The concept of ordinary CA doesn't support these multi-scale models. We propose a modelling technique that is based on an extension of cellular automata but introduces a formal distinction of these multiple scales, which leads to well-structured and clearly defined models.

## Modelling framework

Our generalisation of CA to **h**ierarchical **a**symmetric **c**ellular **a**utomata (HACA) is characterized as follows:

- The cells of the different spatial scales are hierarchically organized in levels: a cell on one level is defined by an aggregation of cells on the level beyond.
- Each level of cells has its own time scale for state changes in this level. The time scales of different levels are synchronized by a common clock to model temporal dependencies in the dynamics of these levels.
- The state change of cells in one level may depend not only on the cells in this level but also on the state of the neighbouring levels.

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- The structure and the dynamics in one level of cells are based on the extensions proposed for asymmetric cellular automata (ACA) defined in [Sonnenschein and Vogel, 2001]: asymmetric shaped cells, irregular neighbourhood relations, and external influences to cells.

Each level of an HACA can be interpreted as an ACA influenced by external effects determined by the state of the cells in the levels above and below. This supports different views of a system on different levels of granularity. So, the hierarchy of cells can also be interpreted as a further dimension of the model.

The state change of a cell *c* of an automaton (level) *A* of an HACA at time *t+1* depends on:

- the state of the static attributes (constants) of *c*,
- the state of the dynamic attributes (variables) of *c* at time *t*,
- the external influence of environmental values (input parameters) of *A* at time *t*,
- the observable influence of neighbouring cells of *c* on the same level at time *t*,
- the state of the cell embedding *c* on the next level above at time *t*,
- the states of all cells aggregated by *c* from the next level below at time *t*.

Dynamics of the cell's behaviour, i.e. rules for the state change from time *t* to *t+1*, can be defined by an arbitrary computable function on these values, in particular by random functions or fuzzy rules. The behaviour function of cells is fixed for each level. Consequently, all cells on one level behave equally and synchronously, as usual for CA. Cells on different levels on the other hand may follow different rules of behaviour.

## Example

As an example, consider plants which spread by seeds over long distances but also locally by tillers. The dynamics of the vegetative reproduction has to be simulated on a fine-grain scale in time and space, while the production of seeds has to be simulated on a much coarser scale of space and only for some specific time slices in

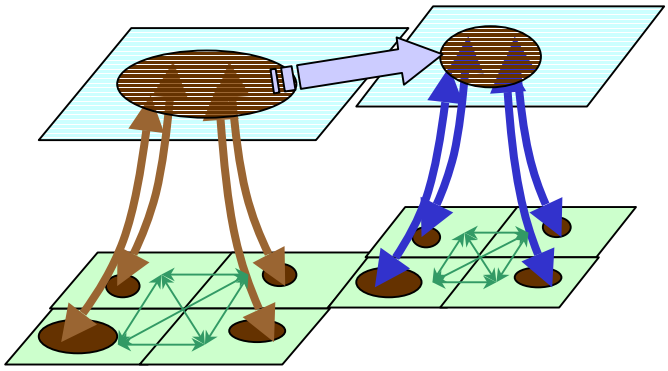

Figure 1

the year. Figure 1 illustrates this by two cells of an upper HACA level which each aggregate four cells of a lower level automaton. The cells on the upper level may model the spread of seeds of plants by wind while the lower level may model the vegetative expansion of local patches of plants. Figure 1 shows the interactions of cells in the same level (seed transportation by wind and tiller growth, resp.) as wells as between levels (emission of seeds) by arrows.

## Outlook

The modelling framework of HACA will be formally defined in the full paper. (A preliminary definition - in German - has been given in [Sonnenschein and Vogel, 2002].) Such a formal definition allows clearly defined semantics of the models, which is - in our opinion - essential for the communication of unambiguous models. The full paper will also include a more comprehensive example for the application of HACA in ecological modelling.

Currently, a C++ programming framework for modelling and simulation with HACA is being implemented, and will be ready for use probably by end of September 2002. Visualisation of single levels of HACA will also be made possible by using the tool I-EpiSim$^2$ [Köster et al., 2002]. Interesting questions for future research can be found in formal analysis of HACA behaviour, visualisation of the dynamic behaviour of HACA in three or rather four dimensions, and in the definition of some standard topologies of HACA for ecological and socio-economic models.

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