Artificial Life & Complex Systems

Lecture 8

Artificial Societies

June 1, 2007

Max Lungarella

Contents

- Agent-based systems and modeling
- Artificial society models
  - Schelling’s segregation model
  - Sugarscape

What Are Agent-Based Systems?

- Populations of individual agents (10–10^7)
- Each agent has internal states and rules of behavior; object-oriented implementation OK
- Agents are autonomous or semi-autonomous
- Agents interact with one another and possibly with an environment (local/social interactions)
- An agent's behavior is the result of simple rules based on local interactions with other agents or the environment
- Agents are purposive (self-interested, satisficing globally, utility maximizing locally)
- Aggregate structure (pattern) emerges from agent interactions → swarm intelligence
- Subsequent generations of agents emerge from the interactions of their ancestors

Implementation of Agent-Based Systems

- Each agent is an object
  - Has instance variables (representing internal states)
  - Has methods (representing behavior repertoire)
- The population of agents is also an object
- There is some topology of interaction, e.g. a spatial environment or a social network
- There are objects for data gathering, storage, and display
- Typically programmed either from scratch (C/C++, Java) or using higher-level system (NetLogo, Ascape)

ABM: Application Domains

- Biology
- Computer science
- Engineering
- Optimization
- *Social science*

Social Science

Fundamental question for social science:

"How does the heterogeneous behavior of <u>individual actors</u> or agents generate the <u>global macroscopic regularities</u> of social phenomena?"

For example:

- Group formation, migration, and other population dynamics
- Group activities: warfare and trade
- Transmission of culture and propagation of disease

Traditional Social Simulation Techniques

- Top-down approach
- Based on departmentalization: economics, demographics, political science, epidemiology
- Theoretical basis: game theory, general equilibrium theory
- Mathematical tools: statistical estimating and modeling, differential equations
- Focus: deriving notions of equilibria stability

Traditional Social Simulation Models

- Rational actor: infinite computing capability, infinite lifetime, maximizes a static utility function
- Homogeneous populations and subpopulations
- Inability to model coupling between different social science disciplines (departmentalization)

Artificial Society Model

Example: Ascape

Artificial Society Models

Origin: Thomas Schelling's work (1969+)

Based on multi-agent systems (agent-based modeling)

Main thesis of the approach:

"Fundamental social structures and group behaviors emerge from the interaction of individual agents operating on artificial environments under rules that place only bounded demands on each agent's information and computational capacity." *(Axtell and Epstein, 1996)*

Artificial Society Models: Basic Structure

In general, computer experiments involve <u>three basic ingredients</u>:

1. <u>Agents</u> are the „people“ of artificial societies. Each agents has internal states and behavioral rules. Some states are <u>fixed</u> for the agent‘s life, while others <u>change</u> through interactions with other agents or with the environment. E.g. *fixed* (metabolic rate, sex, vision), *changing* (wealth, cultural identity, health).
2. Life in an artificial society unfolds in an <u>environment</u>. E.g. landscape with renewable resources that agents eat and metabolize. The point is: the environment is a medium separate from the agents, <u>on</u> which the agents operate and <u>with</u> which they interact.
3. Rulezzz

Artificial Society Models: Basic Structure

There are three classes of rules:

a) Agent-agent interaction rules *(e.g. mating rules, combat rules, trade rules)*

b) Agent-environment interaction rules *(e.g. Look around as far as you can, find the site richest in food, go there and eat the food)*

c) Environment-environment interaction rules *(e.g. Rate of resource growths at a site can depend on the rate at neighboring sites)*

Artificial Society Models: Defining Features

- Collective structures are grown from the bottom-up
- Initial population of agent-objects is released into the simulated environment (a lattice of site-objects)
- Organization into recognizable macroscopic social patterns is observed
- The formation of tribes or the emergence of certain stable wealth distributions would be examples

Artificial Societies vs. Traditional Models

Artificial Soc.

- Heterogeneous agent populations
- Space distinct from agent population
- Agent-environment and agent-agent interaction according to simple local rules
- Focus on out-of-equilibrium dynamics
- Collective structures emerge from the bottom-up (e.g. wealth distributions, collective patterns of movement, etc.)

Trad. Models

- Homogenous subgroups (e.g. predator-prey models)
- Typically the spatial component is ignored
- Mathematical social science focuses on equilibria (most analytically tractable configs.)

Artificial Societies vs. Traditional Models

Artificial society-type models aim at:

"The development of a more <u>unified</u> social science, one that embeds evolutionary processes in a computational environment that simulates demographics, the transmission of culture, conflict, economics, disease, …, all from the bottom up."

The goal is to "grow" social structures *in silico* and to demonstrate that certain sets of microspecifications are sufficient to generate the macrophenomena of interest

Generative kind of social science ("synthetic methodology")

Schelling’s Segregation Model

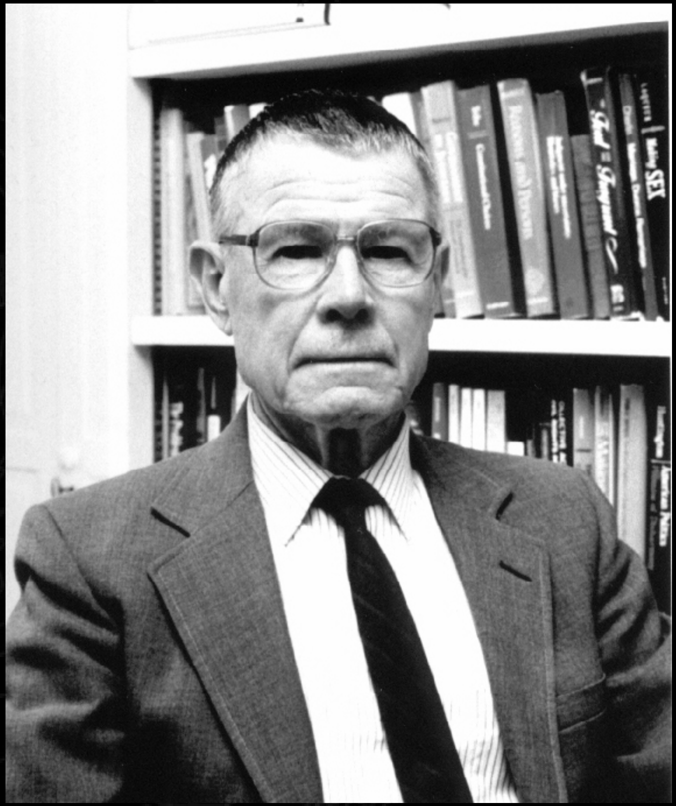
Ethnic neighborhoods

Chinatown, New York City

Little Italy, New York City

Schelling's Segregation Model

- Developed by Thomas C. Schelling (1978)
- One of the first constructive models of a dynamical system capable of self-organization
- Intuitively: simple spatially distributed model of the composition of neighborhoods, <u>in which agents prefer that at least some fraction of their neighbors be of their own "color"</u>
- Striking result: even quite color-blind preferences produce quite segregated neighborhoods



Micromotives and Macrobehavior (1978)

Schelling’s Segregation Model

Neighborhood segregation

Micro-level rules of the game

Stay if at least a third of neighbors are “kin”

< 1/3

Move to random location otherwise

- The board can be interpreted as a city, each square representing a house
- Pennies and dimes can be interpreted as agents representing any two groups in society (two races, two genders, smokers and non-smokers, etc.)
- Neighborhood of agent consist of the squares adjacent to agent’s location (Moore neighborhood)

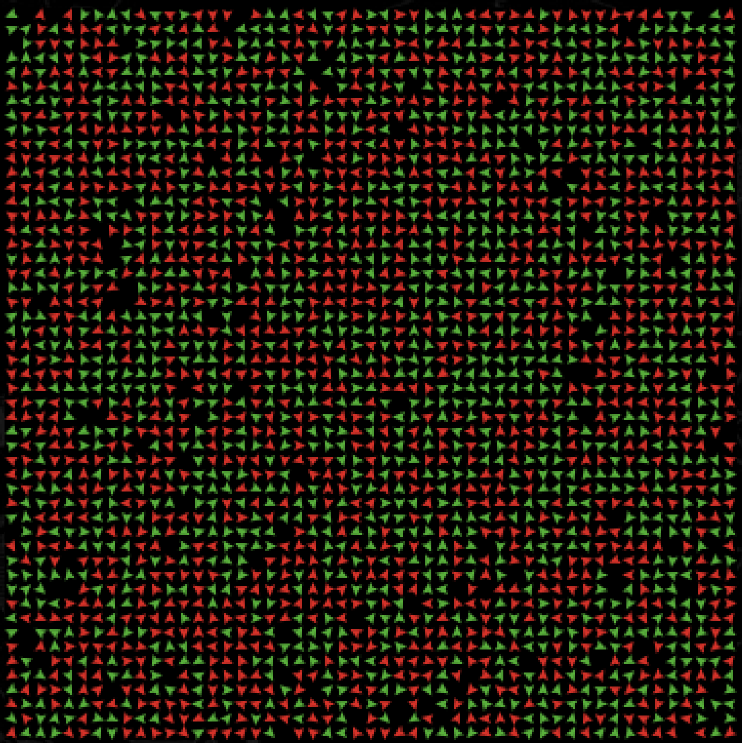
Schelling’s Segregation Model

Time for NetLogo

Schelling's Segregation Model: Results

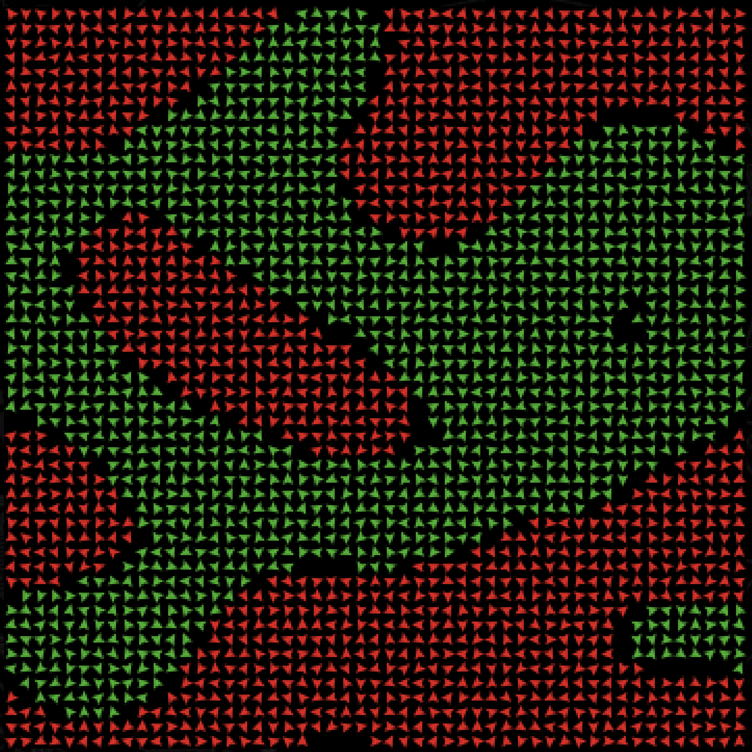
- Schelling found that the board quickly became strongly segregated if the agents' "happiness rules" were specified so that segregation was heavily favored
- Schelling also found that initially integrated boards tipped into full segregation even if the agents' happiness rules expressed only a mild (e.g. 3%) preference for having neighbors of their own type

Schelling’s Segregation Model



A perfectly integrated, but improbable, community

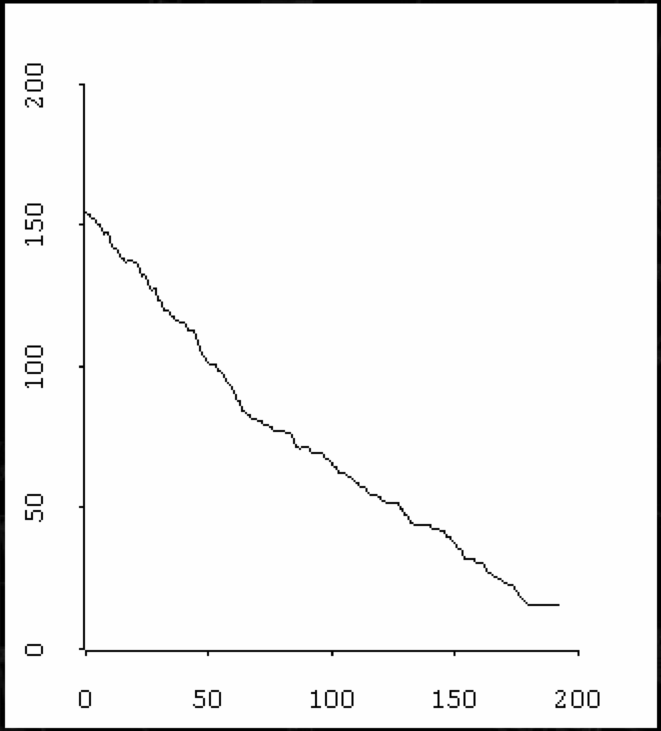
Schelling's Segregation Model



A community after several generations of discontented people moving

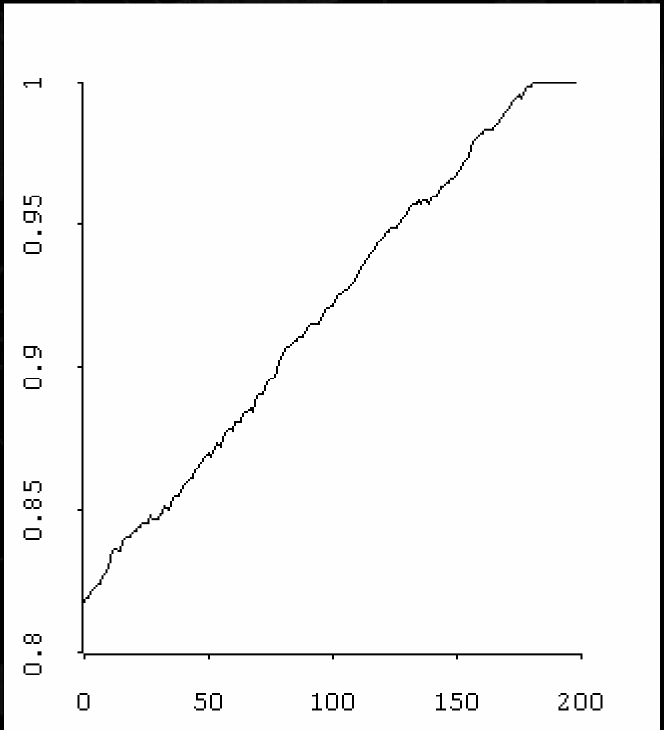
Schelling's Segregation Model

Number of neighborhoods



Time

Happiness



Time

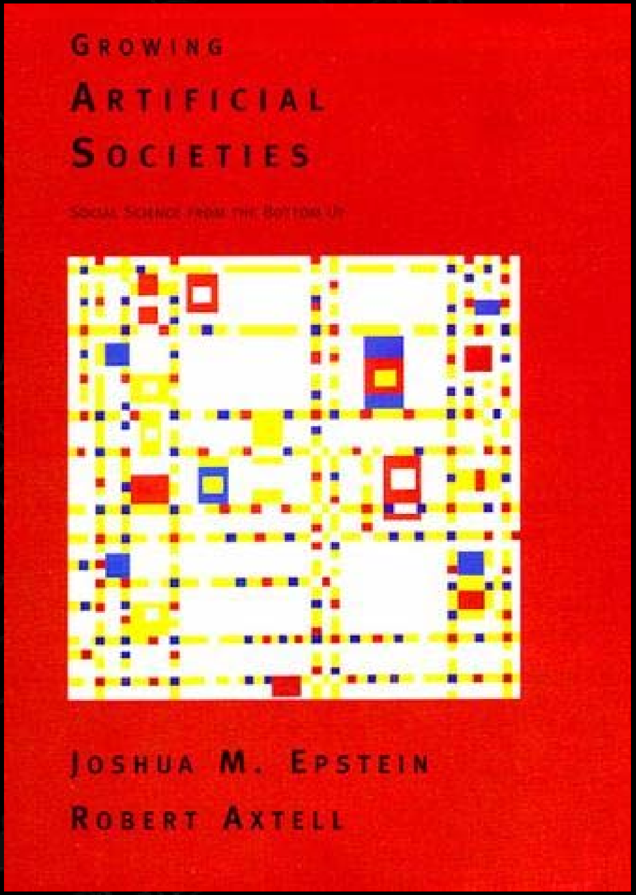
Schelling's Segregation Model

Concepts collected from this example:

- Mild preference to be close to others similar to oneself leads to dramatic segregation
- Conflict between local preferences and global solution: the society as a whole looks segregated but individuals are fairly tolerant!
- Segregation is emergent from the simple local behavioral rule
- Nobody may want a segregated community, but it occurs anyway
- From micromotives to macrobehaviors!

Sugarscape

- Explain social and economic behaviors at large scale through individual behaviors (bottom-up economics)
- 2-D lattice representing an environment in which agents move and act according to rules of behavior
- *Environment:* the set of all lattice points each having a sugar level and capacity (sugarscape wraps around like a torus)
- *Agents:* must eat sugar to survive



CA + Agents = Sugarscape

Sugarscape synthesizes two threads of ALife research:

1) The underlying space (the sugarscape) is a cellular automaton (lattice of sites updated iteratively according to a fixed rule)
2) Populations of adaptive agents live on the CA. The agents interact with on another and they interact with the environment. Inter-agent dynamics affect environmental dynamics, which is fed back to the agent dynamics, and so on.

The agent society and its spatial environment are coupled. In dynamical systems terms (discrete-time dynamical system; A=agent; E=environment):

A[t+1] = f(A[t], E[t])

E[t+1] = g(A[t], E[t])

Other “computational ecologies” will be discussed on June 8/9.

Some Social Behavior Modeled with SScape

Discussed in this lecture:

- Movement and resource gathering
- Pollution
- Sexual reproduction and inheritance
- Cultural transmission
- Trade and economic markets

The Environment

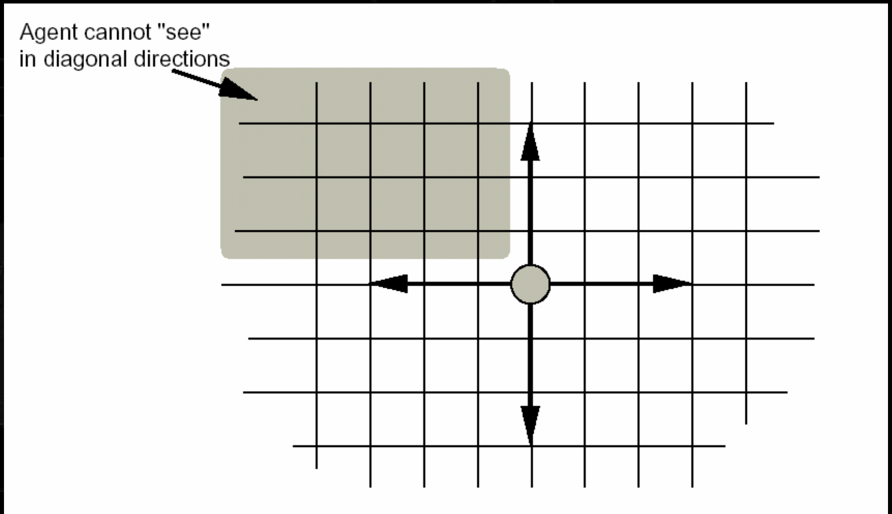
- Primarily passive in expression
- Basic internal state (parameters)
  - (renewable) resource (sugar) level r (variable)
  - resource (sugar) capacity c (fixed)
  - Growback rate α per unit time (fixed)
- Basic rule of behavior
  - Sugar growback **rule** G_a: at each lattice position for each time interval $r_t \leftarrow r_{t-1} + \alpha$ s.t. $r_t <= c$

The Environment (example)

Initial environment: two sugar mountains, two deserts

The Agent

- Active in expression
- Basic internal state (fixed parameters)
  - Vision: random distance *v* it can see (NEWS)
  - Metabolism: random amount of sugar *m* burnt per round

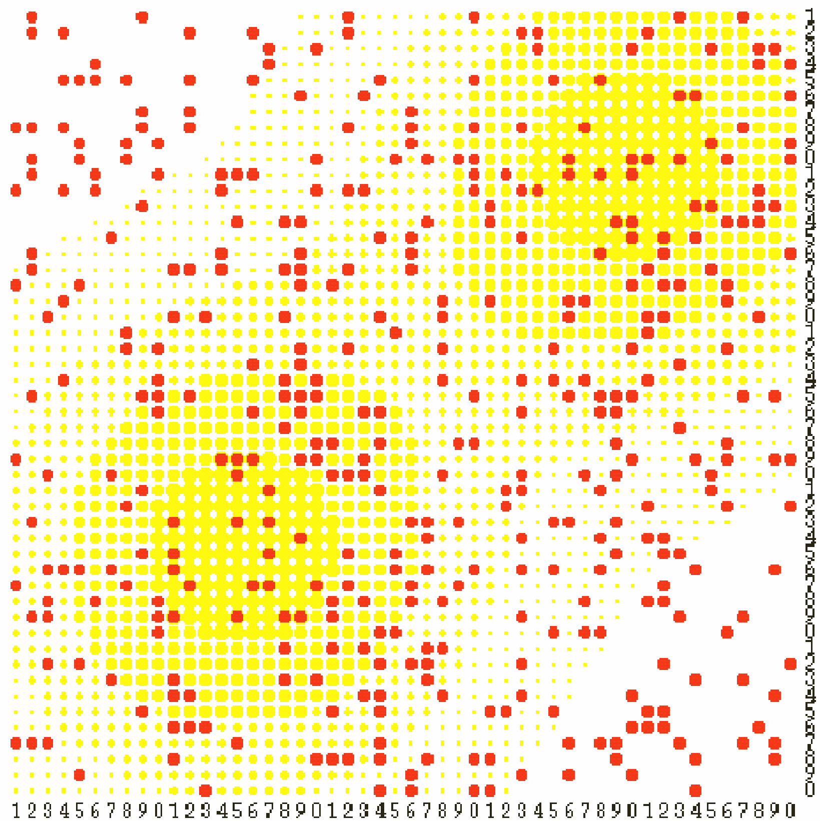


Form of bounded rationality

- Basic internal state (variables)
  - Sugar accumulation (initial endowment): (initial) level *a*
  - Location: random grid position *(x,y)* (two agents are not allowed to occupy the same location)

Agents + Environment

Figure II-2. Sugarscape with Agents



The Agent

- Basic rule of behavior
  - Agent movement (resource gathering) rule *M*:
    - Find the first, closest unoccupied site with max(r) within distance *v* in (NEWS) with random start
    - Move to this site
    - Adjust sugar level (collect all resources at new site): $a \leftarrow a + r - m$
    - If $a <= 0$, agent dies and is removed from sugarscape
- There is no limit to how much sugar an agent can accumulate

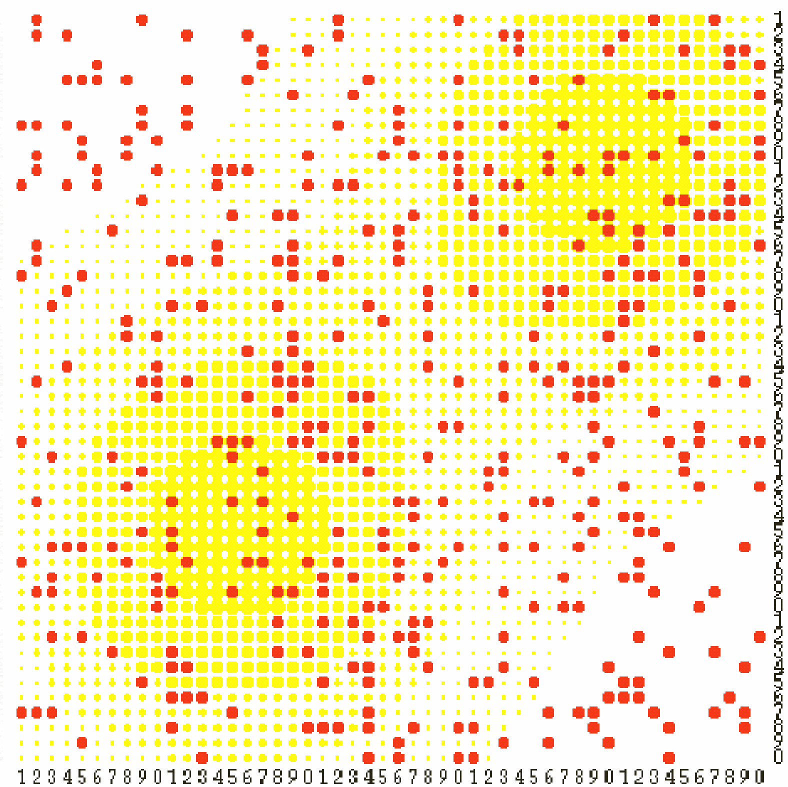
Rule M

From all lattice positions within one‘s vision, find the nearest unoccupied postion of maximum sugar, go there and collect sugar

Sugarscape Example: Rules ($\{G_{inf}\}$,$\{M\}$)

- Basic model with <u>instant growback</u> (sugar grows back to full capacity immediately)
- Random initial heterogeneous distribution of 400 agents with vision ‘v’ in [1,6] and metabolism ‘m’ in [1,4]
- G_{inf}: environment rule
- M: agent rule
- Guess what will happen!
  - Will all agents clump on top of a sugar mountain?
  - Will the movements of the agents persist indefinitely?

Figure II-2. Sugarscape with Agents



Rules ({G_{inf}},{M})

- Most agents stick to the ridges of the terraced landscape. In other words, agents move to next higher “terrace” and never have to move again (creates rings)
- Note: some agents die of starvation (due to high metabolism or low vision)

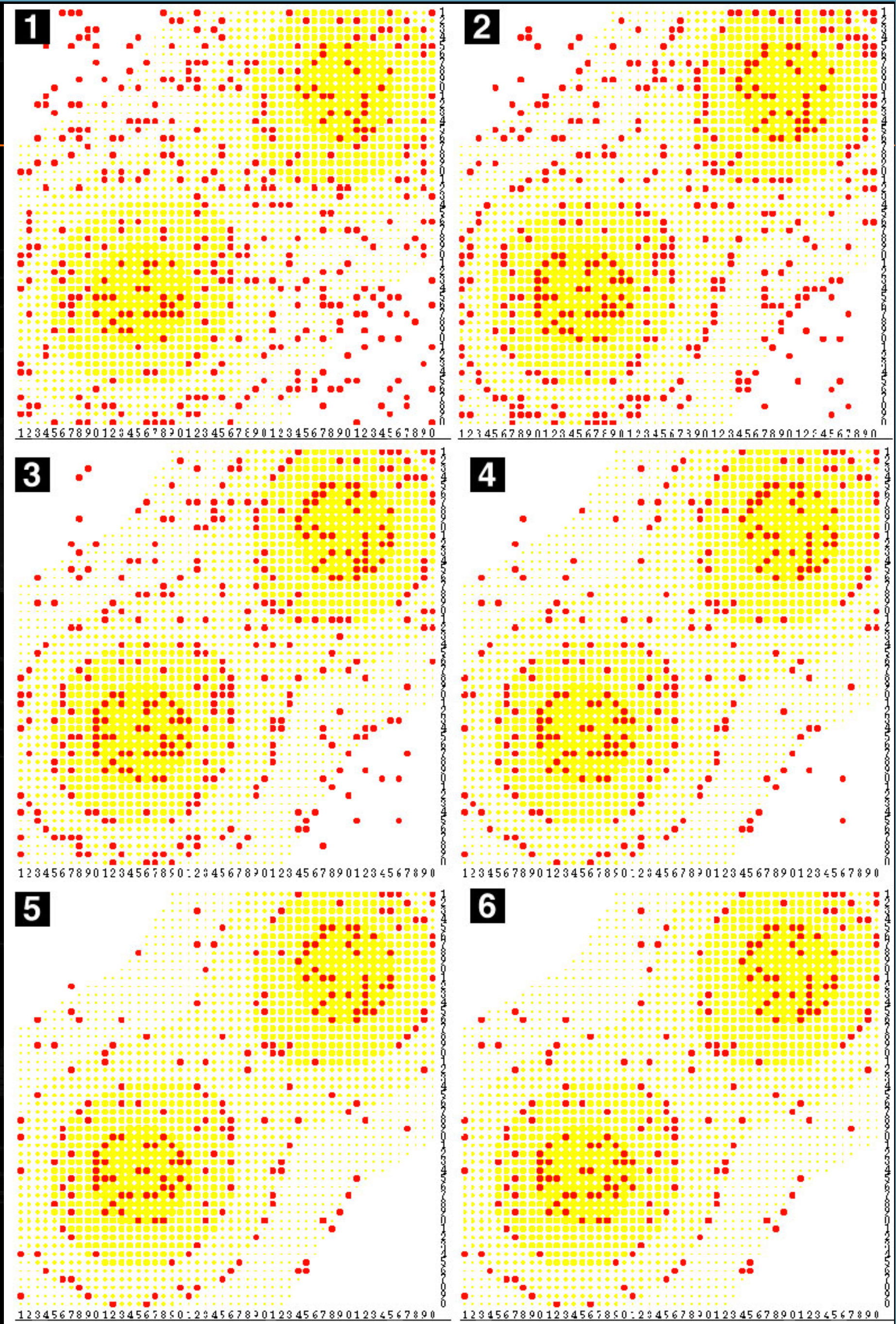


Fig. II-1

Rules ($\{G_{inf}\}$,$\{M\}$)

Explanation of behavior:

- With immediate growback to capacity, the agent's limited vision explains this behavior
- On a ridge an agent can no longer see a better place to go and therefore stays at the same position

What happens if we change G_{inf} to G_1?

Sugarscape Example: Rules ({G_1},{M})

- Basic model with growback of 1 unit/time
- Random initial distribution of 400 agents with vision in [1,6] and metabolism in [1,4]
- What will happen?

Rules ({G_1},{M})

- Agents move to highest "terrace" but have to move around as sugar is consumed
- Emergent characteristics of note:
  - Group formation: two colonies seem to form
  - Isolation of groups
  - Efficient (but decentralized) harvesting mechanism

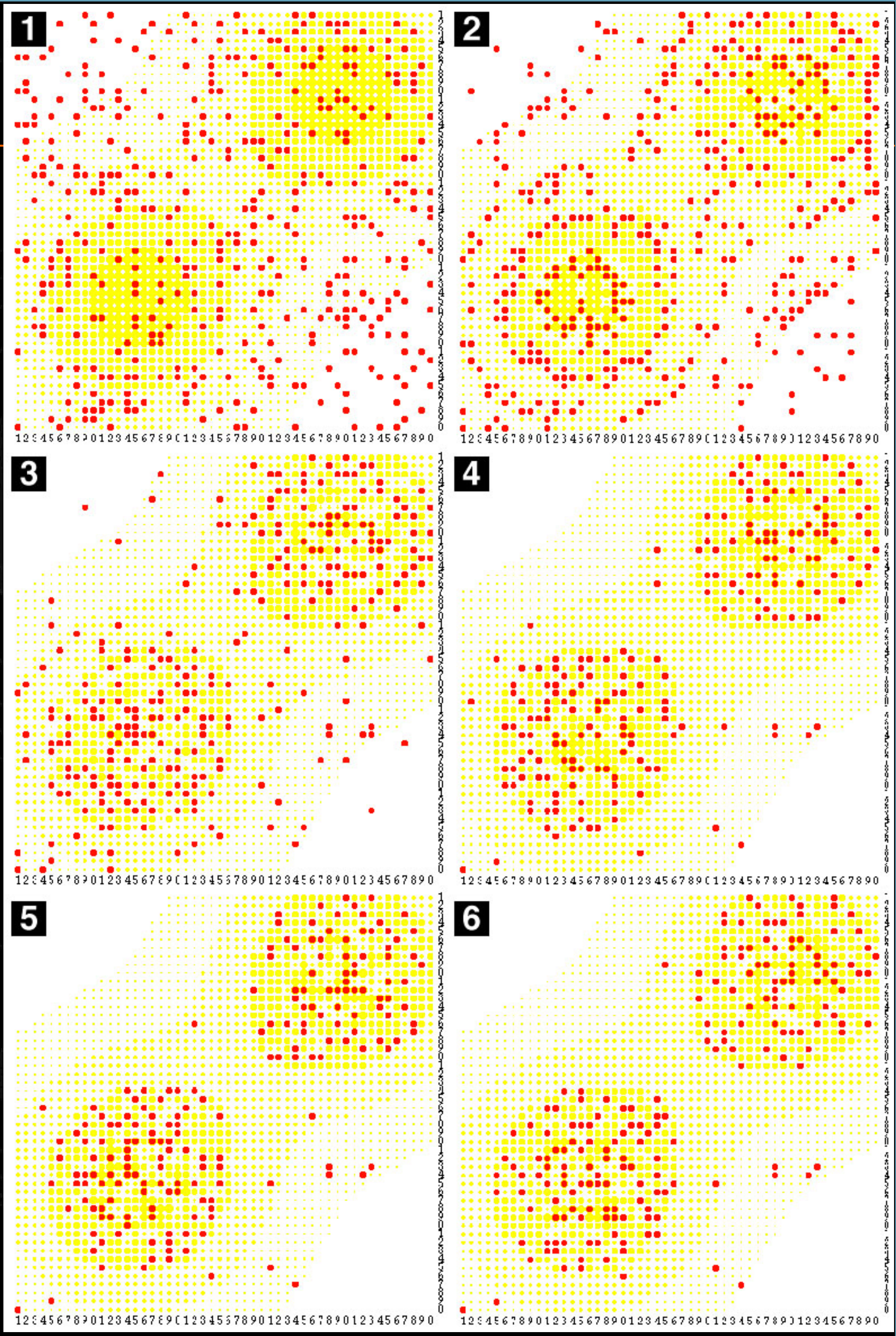
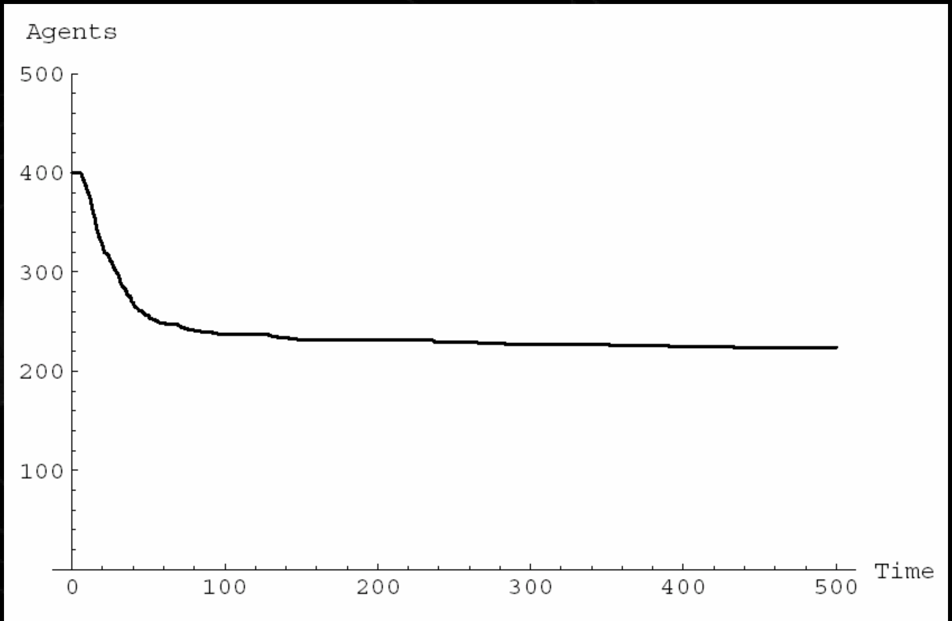
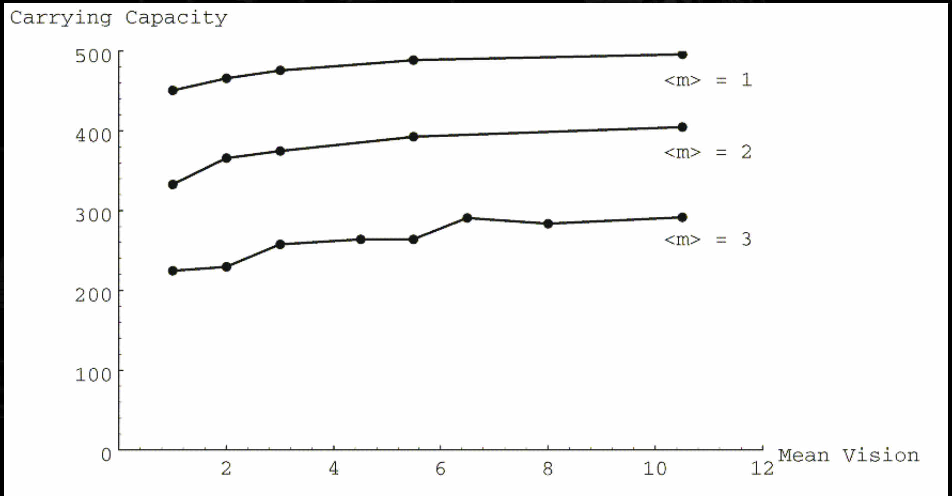


Fig. II-2

Rules ($\{G_1\},\{M\}$)

- Carrying capacity: A given environment will not support an indefinite population of agents
- 400 agents begin the simulation, but a carrying capacity of 224 agents is eventually reached
- Carrying capacity as a function of the genetic composition of the agent. E.g. parameterized by mean metabolism





Wealth and Its Distribution in the Agent Pop.

In Sugarscape the agents are accumulating wealth (measured in sugar units) and so there is a wealth distribution

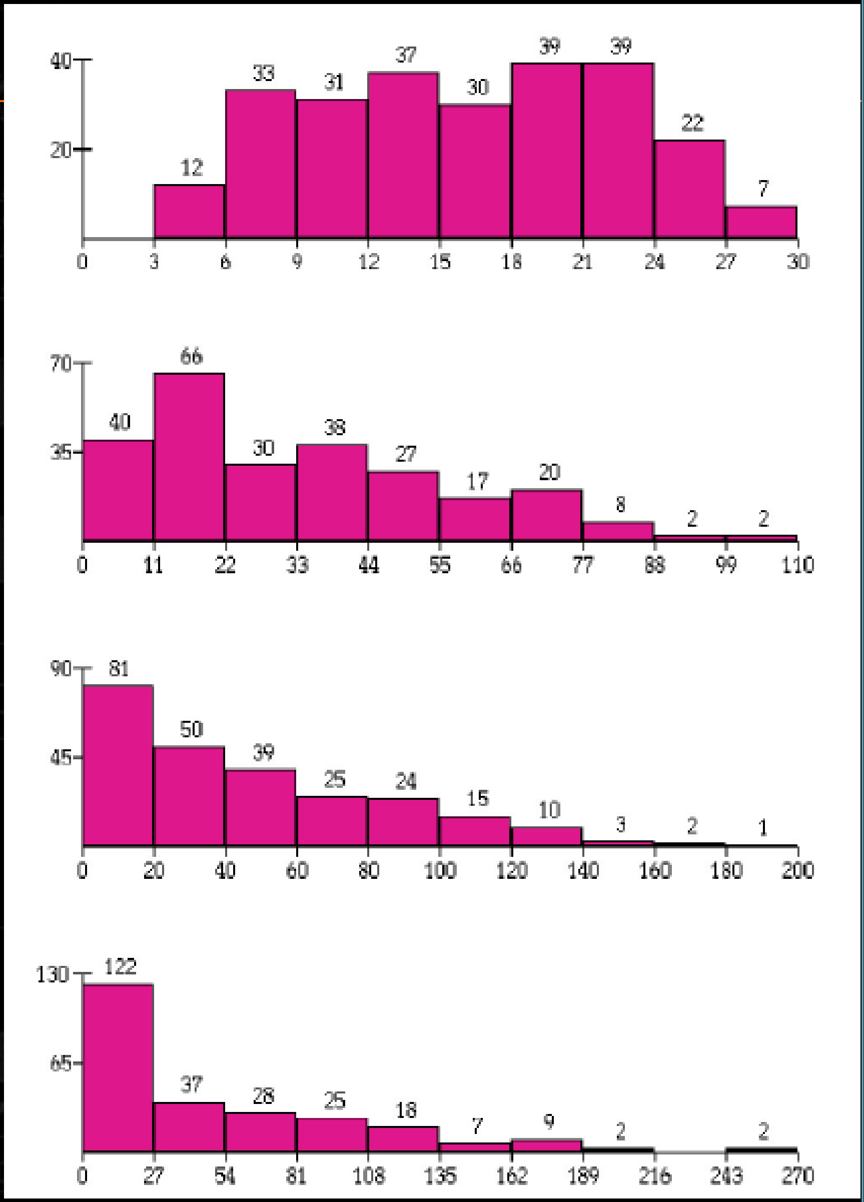
To measure wealth more realistically, agents become mortal (otherwise agents would accumulate wealth for ever!) and an agent replacement rule R[a,b] is introduced:

When an agent dies it is replaced by an agent of age 0 having random genetic attributes, random position on the Sugarscape, random initial endowment, and a maximum age selected from the range [a,b].

Rules ($\{G_1\},\{R_{[60,100]},M\}$)

Characteristics of note:

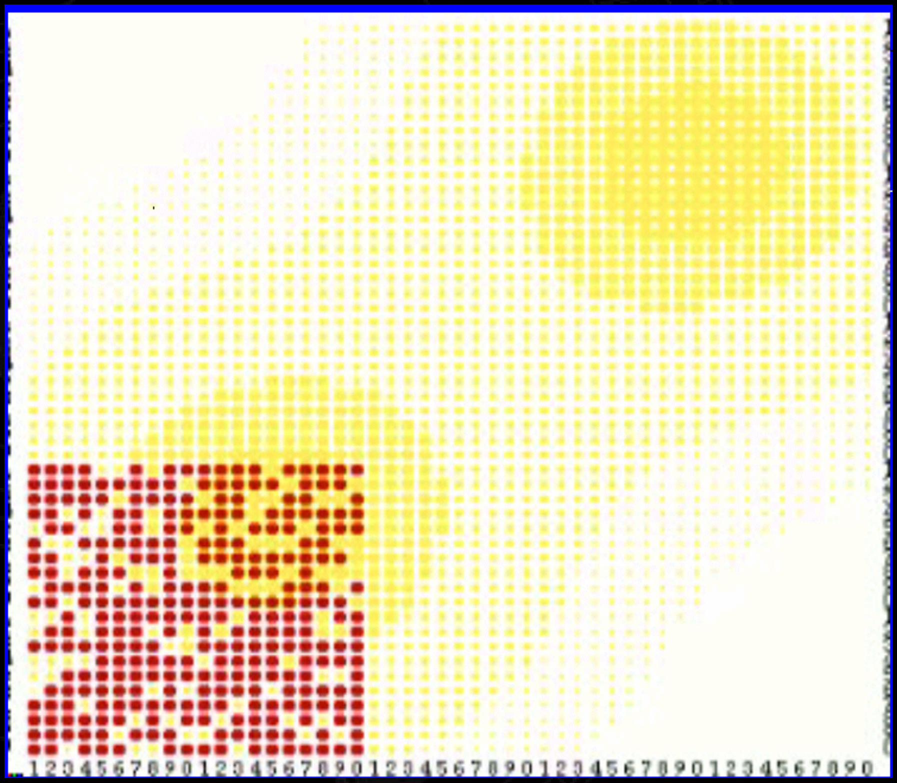
- The skewed distribution of wealth is an emergent structure: a stable macroscopic or aggregate pattern induced by the local interactions of the agents.
- Since it emerged „from bottom-up“, we point to it as an example of self-organization
- Skewed wealth distribution (poorest to richest) called the Pareto law (power law anyone? ☺



X-axis: range of individual wealth (binned)

Migration

- Basic model with growback of 1 unit/time
- Non-random initial distribution of 250 agents with vision in [1,10] and metabolism in [1,4]
- Rules ($\{G_1\}$,$\{M\}$)
- What will happen?



Migration

- Results: coherent waves
- Emergent structures
- Why is this interesting?
- Single agent can only move N,S,E,W. Yet the collective wave is moving NE!
- The whole is indeed more than the sum of its parts!

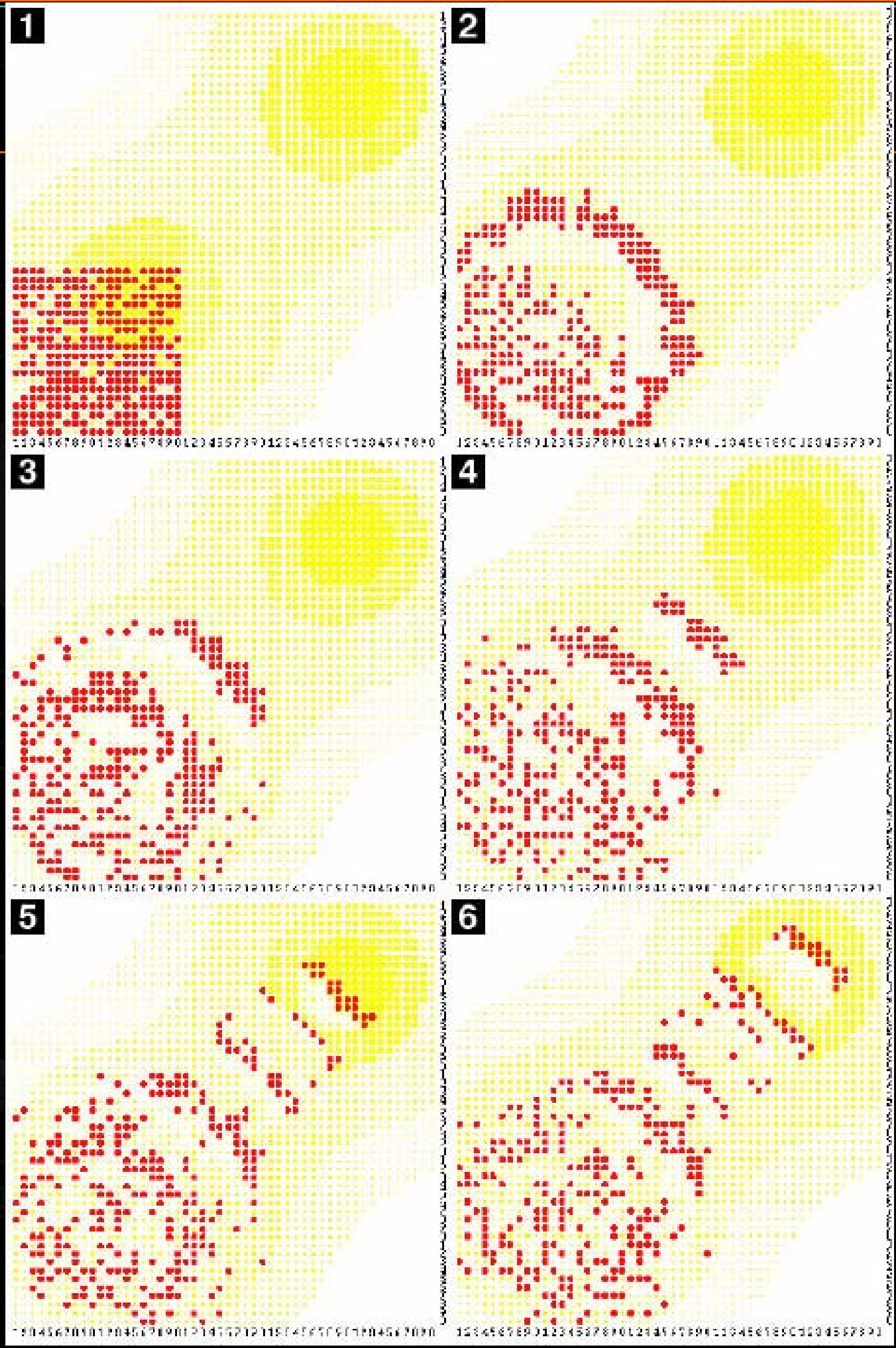


Fig. II-6

Seasonal Migration

- Sugarscape is split into a north and a south by drawing imaginary equator
- For the opening season:
  - Sugar grows back at unit rate in north
  - Sugar grows back at 1/8 unit rate in south
- After 50 time periods, the situation is reversed (seasons change)
- Growback rule $S_{\alpha\beta\gamma}$: Initially it is summer in N and winter in S. Then, every γ time periods the seasons flip. For each site, in summer growback rate is α, in winter growback rate is β

Seasonal Migration: Ascape (II-7)

What do you observe?

Seasonal Migration: Results

- We get migrators and hibernators
- Migrators (bird-like): high vision
- Hibernators (bear-like): low metabolism
- Agents with low vision and high metabolism generally die
- Hibernators do not migrate! South-born and north-born hibernators would rarely meet and hence rarely mate → formation of separate mating pools → in evolutionary time speciation occurs.

Pollution

Two types of pollution:

- **Production pollution** due to the production of sugar (occurs when sugar is gathered): When sugar quantity s is gathered from the sugarscape, an amount of production pollution is generated in quantity αs
- **Consumption pollution** due to the metabolization of sugar by the agents: When sugar amount m is consumed (metabolized), consumption pollution is generated according to βm

Pollution Formation Rule $P_{\alpha\beta}$

The total pollution p^t on a site at time t is the sum of the pollution resulting from production and consumption activities:

$$p^t = p^{t-1} + \alpha\, s + \beta\, m$$

How does this affect the agent's movements?

One solution: Let the pollution devalue – in the agent's eyes – the sites where it is present. Agents do NOT like pollution. Do you?

Agent Movement Rule M, Modified by Pollution

Instead of moving to the site of max. sugar, the agent selects the site with max. sugar/pollution ratio

Mod. Rule M:

- Look out as far as vision permits in the four lattice directions and identify the unoccupied site(s) having the maximum sugar/pollution ratio
- If the maximum sugar to pollution ratio appears on multiple sites, then select the nearest one
- Move to this site
- Collect all the sugar at this new position

Pollution Transport

Final ingredient: there has to be a form of pollution transport, otherwise pollution would simply accumulate without bound at the site of production

Simplest form of transport is <u>diffusion</u>

Pollution Transport

Diffusion on lattice is implemented as a local averaging procedure:

- Each α time periods and at each site, compute the pollution flux: the average pollution level over all von Neumann neighboring sites
- Each site's flux becomes its new pollution level

Which α corresponds to the fastest diffusion possible?

Pollution ($\{G_1, D_1\}, \{M, P_{11}\}$)

Modified **M** rule

At t=50: pollution begins
(P_{11} is turned on)

At t=100: diffusion begins
(D_1 is turned on)

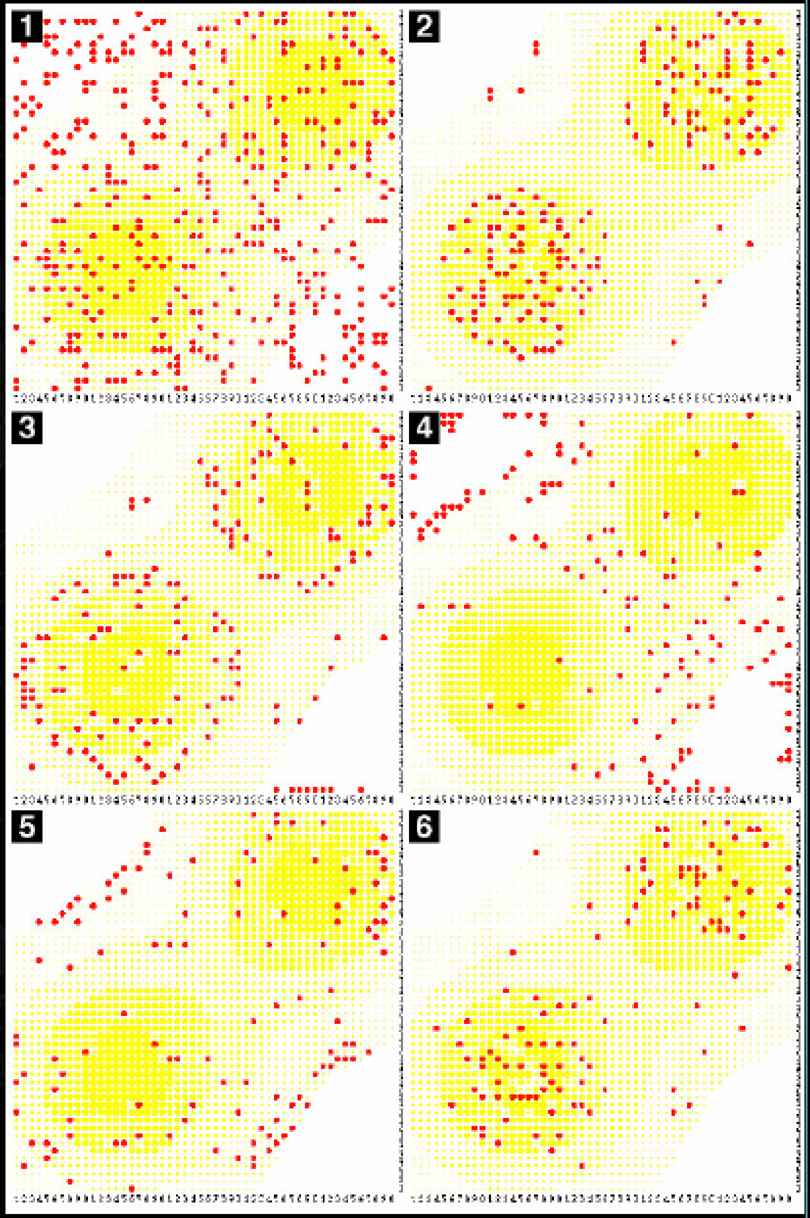


Fig. II-8

Pollution $(\{G_1,D_1\},\{M,P_{11}\})$

Explanation:

- At first agents are hiving the sugar hills, pollution is low
- Then pollution builds up and the agents abondon the polluted zones
- Migration into relatively pristine areas where no pollution has accumulated
- Agents continue to eat from their personal accumulations
- Intense competition → many die of starvation
- Carrying capacity is lower
- When diffusion is turned on, the pollution quickly spreads more or less uniformly around the landscape
- Many agents return back to the regions of highest sugar

Pollution: Interpretation

Pollution = negative externality

What about “positive externalities”?

For example: increasing returns (positive feedback kind of mechanism) leads to spatial clustering – see Silicon Valley

Intermediate Summary

Lessons learned from this example:

- Simple local rules can produce emergent structures (e.g. environmental carrying capacity, migration waves or skewed wealth distributions) – from microrules to macrobehavior
- Sugarscape model can be used as a laboratory in silico to grow macrostructures from the bottom up
- Experiments can lead to hypotheses of social concern that may subsequently be tested statistically against data
- The generative *sufficiency* of simple local rules should come as a surprise!

Increasing the Complexity

In principle the sugarscape model can be made arbitrarily complex

Let‘s look at some examples:

- sexual reproduction
- inheritance
- cultural processes
- combat / warfare

Sexual Reproduction Rules

In order to reproduce agents have to be fertile, that is:

1. They must be old enough
2. They must have a sufficient amount of sugar

Agent sex/mating rule **S**:

a) Select a neighboring agent at random
b) If the neighboring agent is of the opposite sex *and* if both agents are fertile *and* at least one of the agents has an empty neighboring site *then* a child is born
c) Repeat for all neighbors

Sexual Reproduction Rules

- The childs genetic makeup (metabolism, vision, maximum age, etc.) is determined from parental genetics through Mendelian rules
- A newborn is produced by crossover the parents' genetic and cultural characteristics
- Agents are genetically heterogeneous with regard to position and sugar accumulations, but homogeneous with regards to behavioral rules (still **M**)

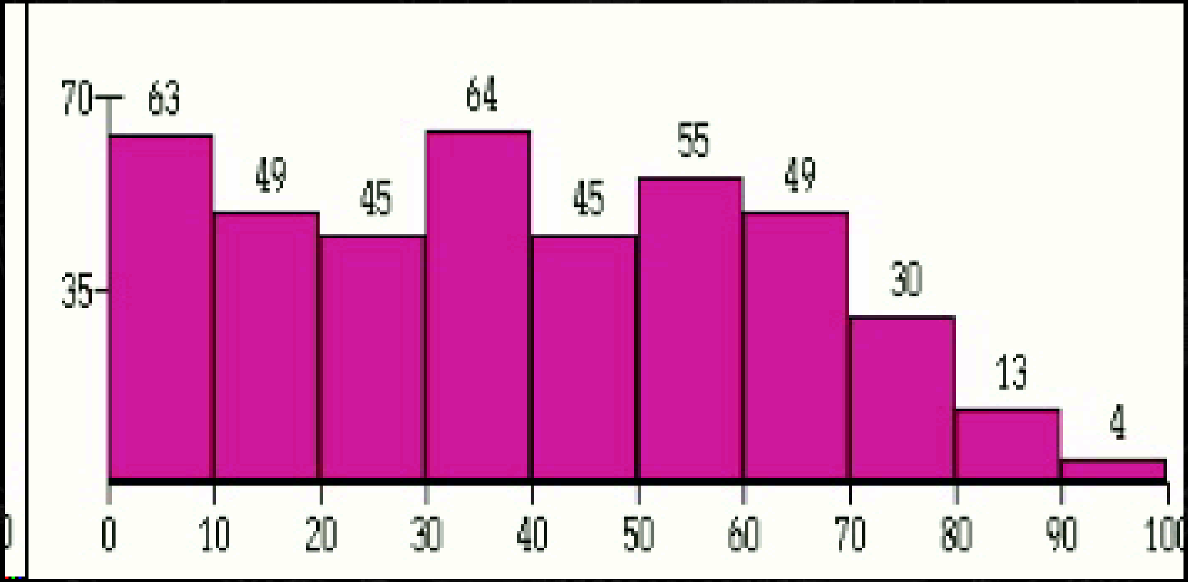
	Metabolism	
Vision	m	M
v	(m, v)	(M, v)
V	(m, V)	(M, V)

Four equally likely genotypes of offspring

Rules ($\{G_1\}$,{S,M})

Ascape!!

Age histogram



Rules $(\{G_1\},\{S,M\})$

Agents with relatively low metabolism and high vision enjoy a selective advantage on the Sugarscape

Agent are colored

a) Blue if vision [1,3], red if vision [4,6]

b) Blue if metabolism [1,2], red if [3,4]

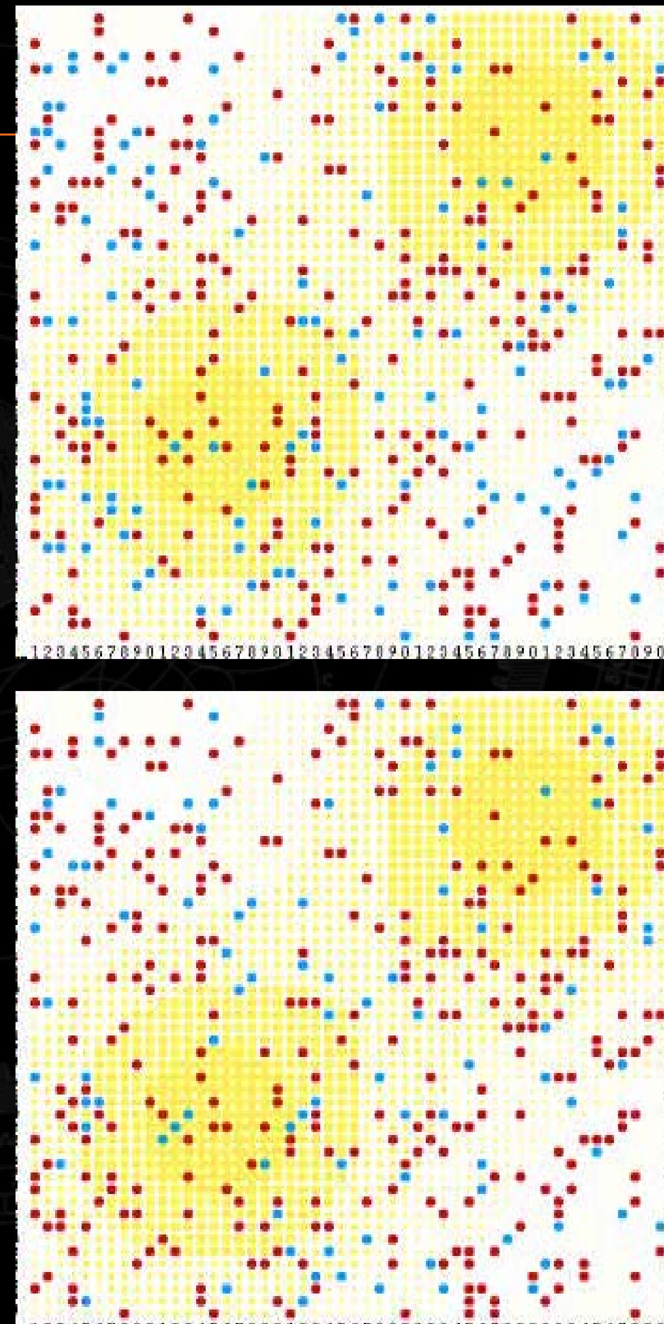
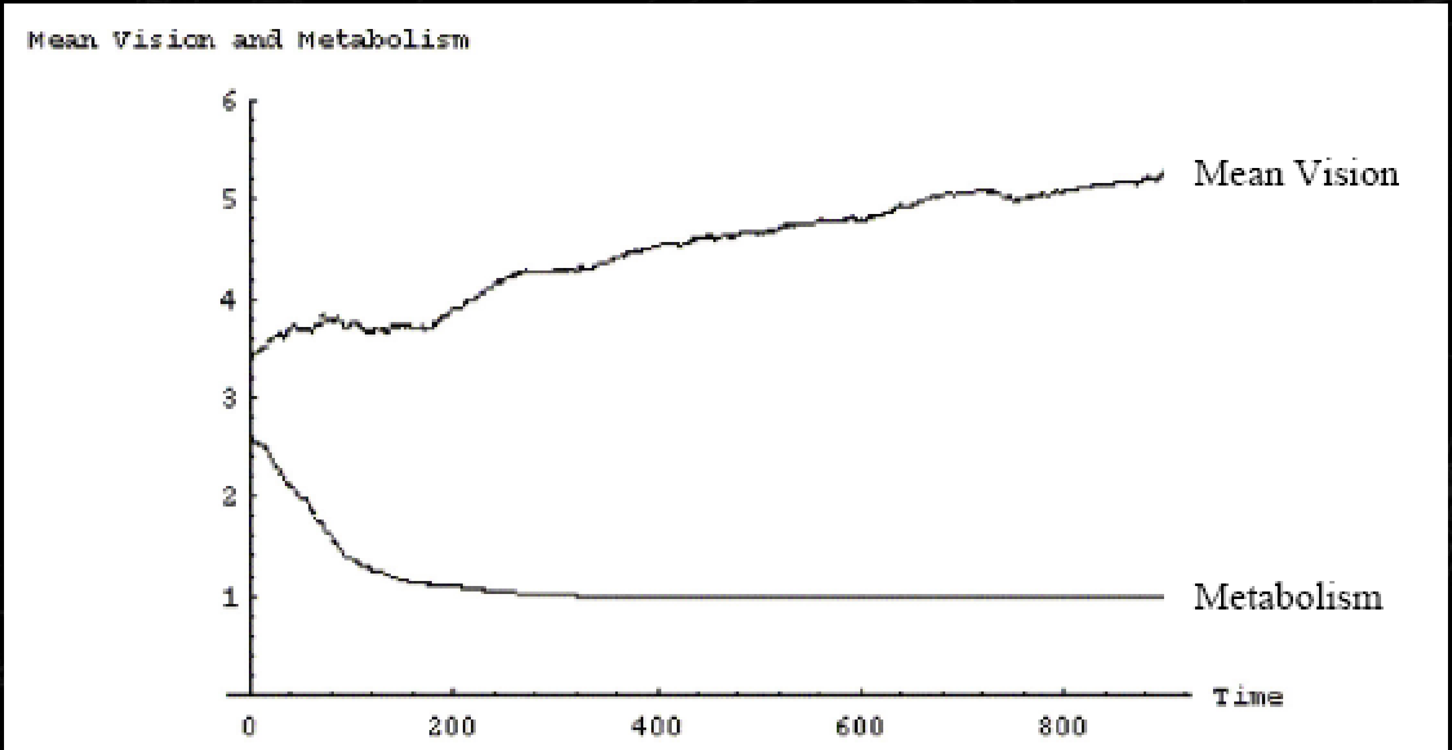


Fig. III-2

Rules ({G_1},{S,M})



Mean Vision and Metabolism
6
5
4
3
2
1
0
200
400
600
800
Time
Mean Vision
Metabolism

Rules ($\{G_1\},\{S,M\}$)

- A fitness function was nowhere explicitly defined
- Merely rules of reproduction were stated
- Fitness is and emergent property of the sugarscape
- It emerges from agent-environment and agent-agent interactions
- Fitter agents could bring about their own extinction (overgrazing + explosive reproduction → characterized by large oscillations in the population dynamics)
- Mass extinctions may be endogenous; agent-based modeling suggest that internal dynamics alone is sufficient to generate cataclysmic event

Rules ($\{G_1\},\{S,M\}$)

Examples 5a-5c: NetLogo + Ascape III-2

Population <u>oscillations</u> can be produced by

a) Changes in infertility age

b) Changes in individual sugar endowment

Inheritance of Wealth

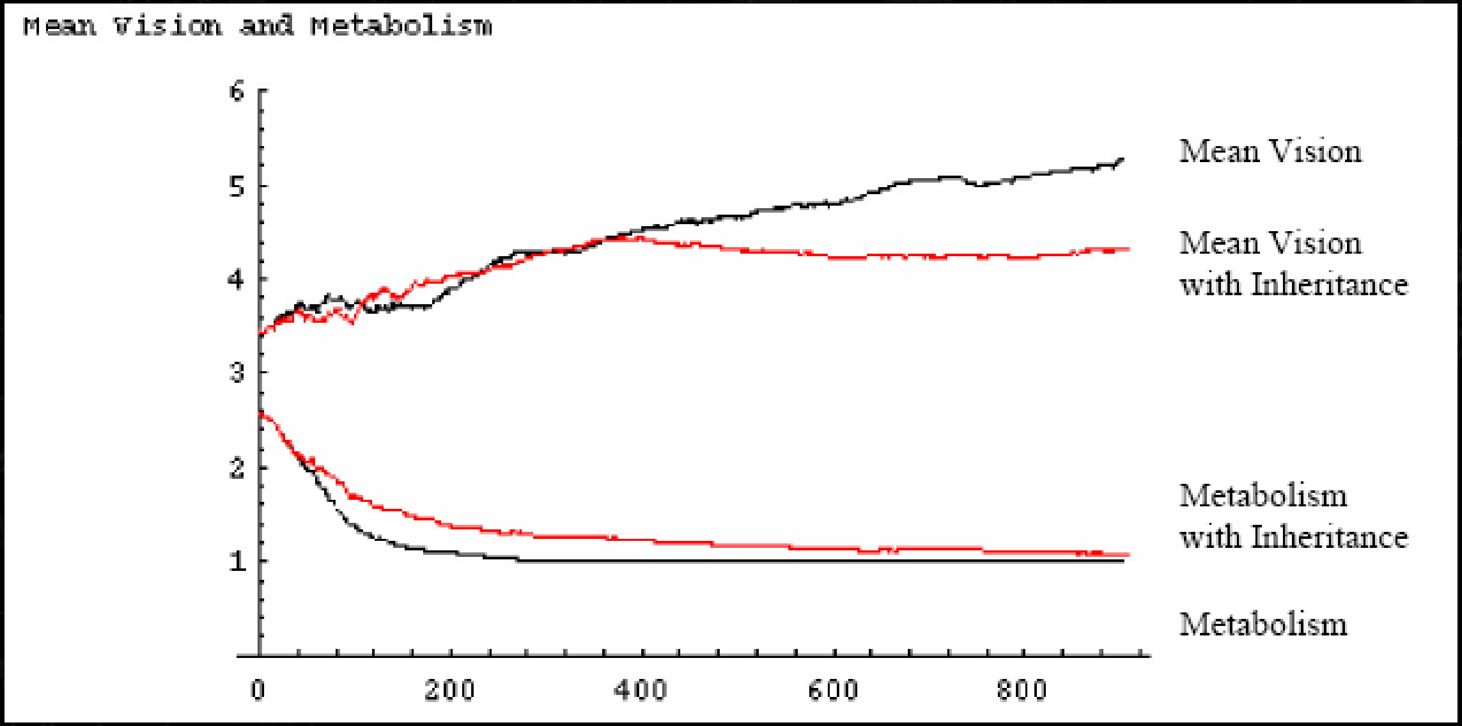
What is the effect inheritance?

Agents are allowed to pass their accumulated holdings of sugar (wealth) on to their offspring when they die

In artificial societies biology and economics can be studied *together*

Inheritance of Wealth (Rule ({G_1},{S,M,I})

Agent inheritance rule I: When an agent dies its wealth is equally divided among all its living children



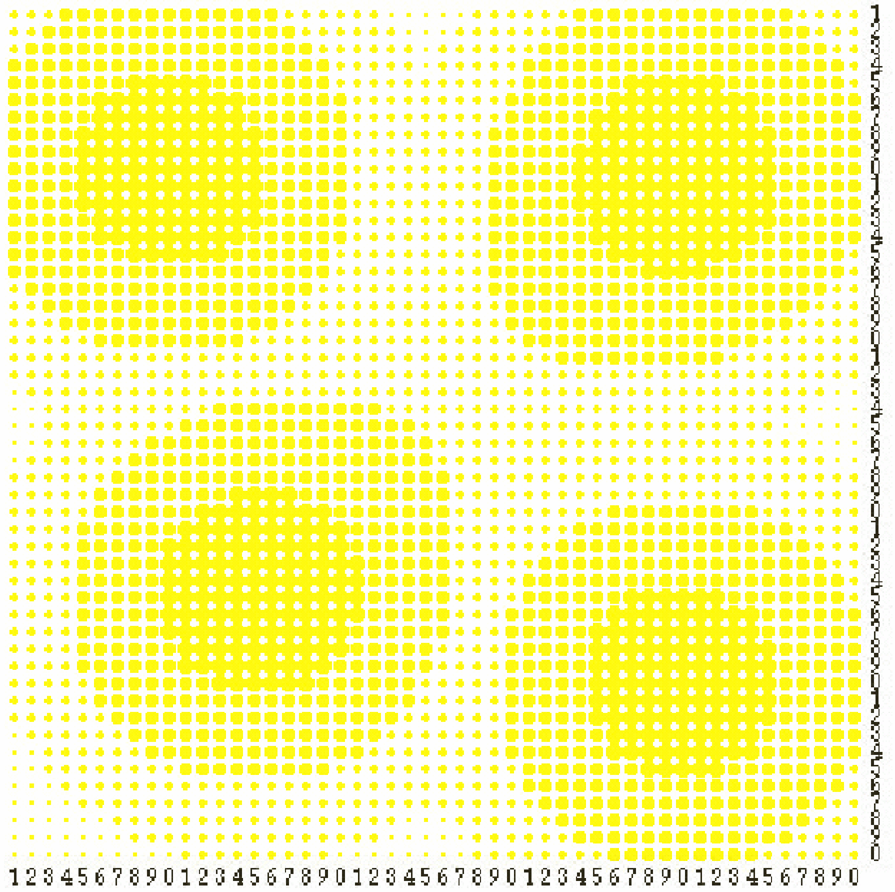
Inheritance of Wealth: Results

- Inheritance retards selection! Agents who might otherwise have been “weeded out” are given am advantage through inheritance (social rule influences biological evolution)
- Interestingly, no effect on metabolism
- Moreover: “Social Darwinists oppose wealth transfers to the poor on the ground that the undiluted operation of selective pressures is ‘best for the species.’ Conventiently, the fail to mention that intergenerational transfers of wealth from the rich to their offspring dilute those very pressures.” *(Axtell and Epstein, 1996)*

Trade Comes to the Sugarscape

Additional commodity: *spice*

- At each grid point there are now two values: for sugar and for spice (two hills for each)
- Each agent requires sugar as well as spice for its metabolism
- Agents die if either their sugar or their space drops to zero



Trade Comes to the Sugarscape

We need a way for the agents to compare their needs for the two goods

A „rational“ agent with large accumulation of sugar and low accumulation of spice should pursue sites with more spice

One way to capture this is to have agents computing how „close“ they are to starving death

They then attempt to gather relatively more the the good whose absence most jeopardizes their survival

The Agent Welfare Function

Imagine an agent with <u>metabolism</u> (m_1,m_2) and <u>accumulation</u> (w_1,w_2) computing the „amount of time until death given no further gathering"

Time-to-death: $\tau_1 = w_1/m_1$ and $\tau_2 = w_2/m_2$

Hence τ_1/τ_2 is a measure of the relative importance of finding sugar or spice

The agent's welfare function is defined as:

$W(w_1,w_2) = w_1^{m1/(m1+m2)} * w_2^{m2/(m1+m2)}$

Cobb-Douglas utility function

The Agent Welfare Function

- The welfare function is state-dependent insofar as the arguments (w_1,w_2) denote accumulated quantities of the two commodities, not instantaneous comsumption
- If agents age and accumulate wealth (w increases!), they will view the same source site differently

The Agent Welfare Function

Let *s* denote a site and with x_1^s and x_2^s the sugar and spice levels at that site

Formally, the agents perform an optimization calculation over the sites in their vision-parameterized neighborhood $N_{n,}$ according to

$$\max W(w_1 + x_1^s, w_2 + x_2^s) \quad \text{over all } s \text{ in } N_n$$

Agent selects site producing maximum welfare

Multicommodity Agent Movement Rule M

- Look out as far as vision permits in each of the four lattice directions: NEWS
- Considering only unoccupied lattice positions, find the nearest position producing <u>maximum welfare</u>
- Move to the new position
- Collect all the resources at that location

Rule ({G_1},{M}): Results

- Migration
- Carrying capacity is lower: there are two ways to die (by running out of either resource)

Rules of Trade

- Trade requires a rule system for the exchange of sugar and spice between agents
- When will they trade?
- How much will they trade?
- At what price will exchange occur?

Rules of Trade

Neoclassical theory of general equilibrium describes how a single centralized market run by a so-called auctioneer can arrive at an equilibrium price vector for the entire economy.

Two problems:

1. An auctioneer announcing prices to the entire economy is quite unrealistic
2. No individual or institution could ever possess either complete knowledge of agent preferences an endowments or sufficient computational power to determine the appropriate prices

Rules of Trade: Kreps' Model

"… We can imagine consumers wandering around a large market square, with all their possessions on their backs. They have chance meetings with each other, and when two consumers meet, they examine what each has to offer, to see if they can arrange a mutually agreeable trade… If an exchange is made, the two swap goods and wander around in search of more advantageous trades made at chance meetings."

Trade in Sugarscape

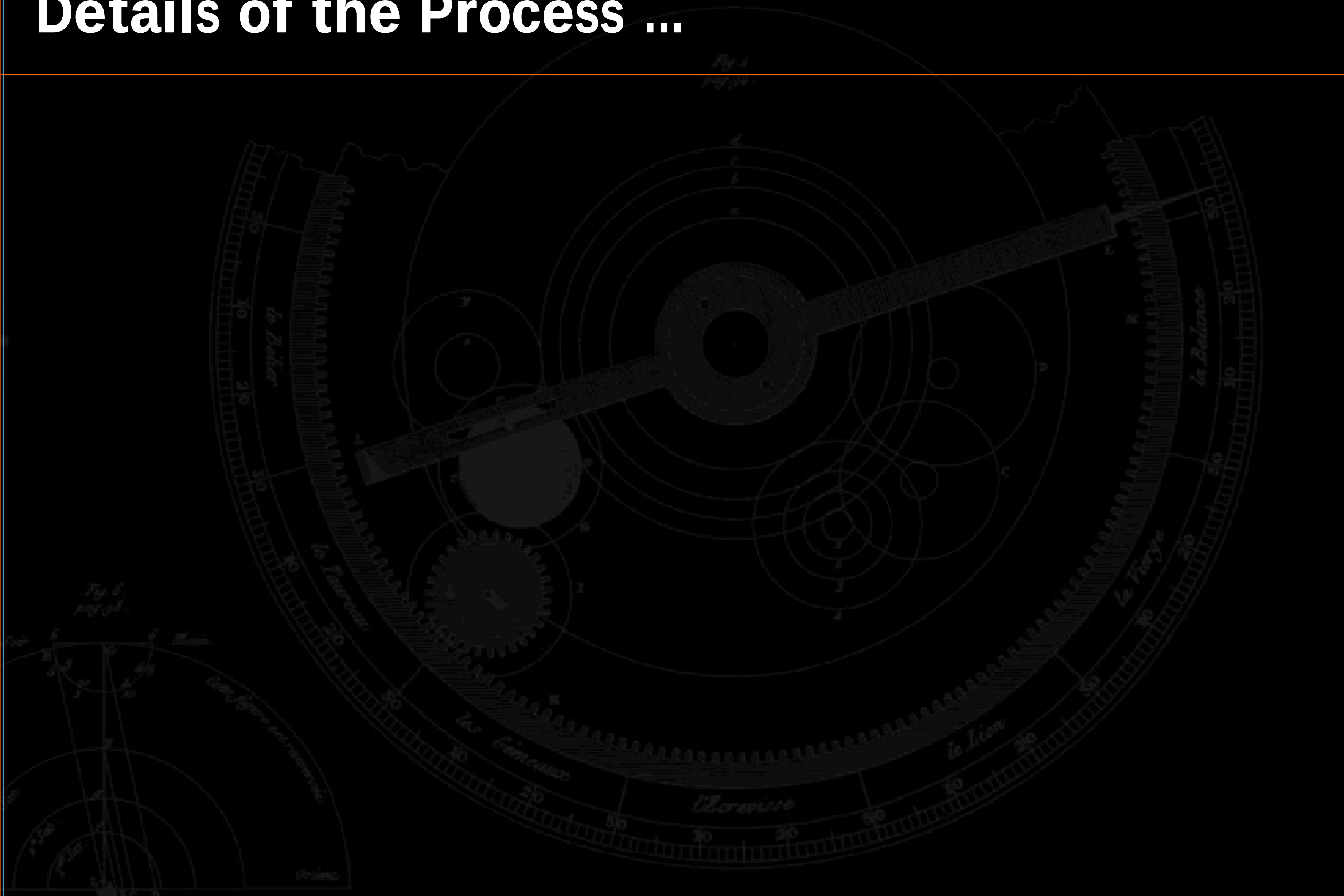
- Implemented along the line of Kreps
- Trade is a welfare-improving bilateral barter between agents
- No use of an auctioneer
- Agents move around following M
- Agents have the permission to trade with the agents they land next to (von Neumann neighbors)

Trade in Sugarscape

- When an agent-neighbor pair interacts to trade, each agent starts to compute its internal valuations of sugar and spice
- Then a bargaining process is conducted and a price is agreed
- Finally an exchange of goods between agents occurs if both agents are made better off by the exchange

This three step process is repeated until no further gains from trade are possible (details follow)

Details of the Process …



Internal Valuations

According to microeconomic theory, an agent's internal valuations of economic commodities are given by its so-called marginal rate of substitution (MRS)

The MRS is the least-favorable rate at which an agent is willing to exchange units of one good or service for units of another

For example: if $MRS_{XY} = 2$ then the consumer will give up 2 units of Y to obtain 1 additional unit of X

Here: An agent's MRS of spice for sugar is the amount of spice the agent considers to be as valuable as one unit of sugar, that is, the value of sugar in units of spice

Invent a welfare function of the agents able to control trading between two agent in a „rational“ way!

The Agent Welfare Function

We define:

$$MRS \equiv \frac{dw_2}{dw_1} = \frac{\frac{\partial W(w_1, w_2)}{\partial w_1}}{\frac{\partial W(w_1, w_2)}{\partial w_2}}$$

dw_1: unit sugar, dw_2: unit spice

Note: here MRS measures the relative internal scarcity of the two resources

If *MRS < 1*: the agent thinks of itself as being relatively poor in spice (internal valutation 1)

If *MRS > 1*: the agent thinks of itself as being relatively poor in sugar (internal valutation 2)

The Agent Welfare Function

One can show that:

$MRS = m_1 w_2 / m_2 w_1 = \tau_2 / \tau_1$

Which is ...

The ratio of time-to-death (makes sense and it's easy to compute!)

Exchange Direction

When two agents (A and B) encounter one another (when agents are neighbors) the *MRS* of each agent is computed

These internal valuations are shared knowledge; that is, the agents truthfully reveal their preferences to one another

If $MRS_A > MRS_B$: agent A considers sugar to be relatively more valuable than does agent B, and so A is a sugar buyer and a spice seller while agent B is the opposite

	$MRS_A > MRS_B$		$MRS_A < MRS_B$	
Action	A	B	A	B
Buys	sugar	spice	spice	sugar
Sells	spice	sugar	sugar	spice

The Bargaining Rule: Price of Exchange

MRS determines the direction in which resources will be exchanged

The price is the ratio of the spice and sugar quantities exchanged

The price must, of necessity, fall in the range of $[MRS_A, MRS_B]$ and is determined according to the bargaining rule:

$$p(MRS_A, MRS_B) = \sqrt{MRS_A, MRS_B}$$

Agent Trade Rule T

- Agent and neighbor compute their *MRS*; if these are equal then end (no trade), else continue
- The direction of exchange is as follows: spice flows from the agent with the higher *MRS* to the agent with the lower *MRS* while sugar goes in the opposite direction
- Calculate price *p* according to *bargaining rule*
- Quantities to be exchanged:
  - $p > 1$: p units of spice for 1 unit of sugar
  - $p < 1$: 1/p units of sugar for 1 unit of spice
- If trade increases welfare of both agents AND the agents' MRSs do not cross over then the trade is made

Markets of Bilateral Traders

Note: There is no auctioneer (and other types of nonlocal information)

Question: Can the population of spatially distributed agents reproduce anything like an equilibrium price through local interactions alone?

Markets of Bilateral Traders: Test

- Population of 200 immortal agents
- Welfare function on
- Migration and Trade
- Uniform distributions of metabolisms for sugar and spice ([1,5])
- Randomly distributed endowment ([25,50])
- Vision [1,5]

Markets of Bilateral Traders

Two neoclassical assumptions:

- Infinitely lived agents
- Fixed preferences

Markets of Bilateral Traders: Rule ({G_1},{M,T})

Economic equilibrium emerges from the bottom up

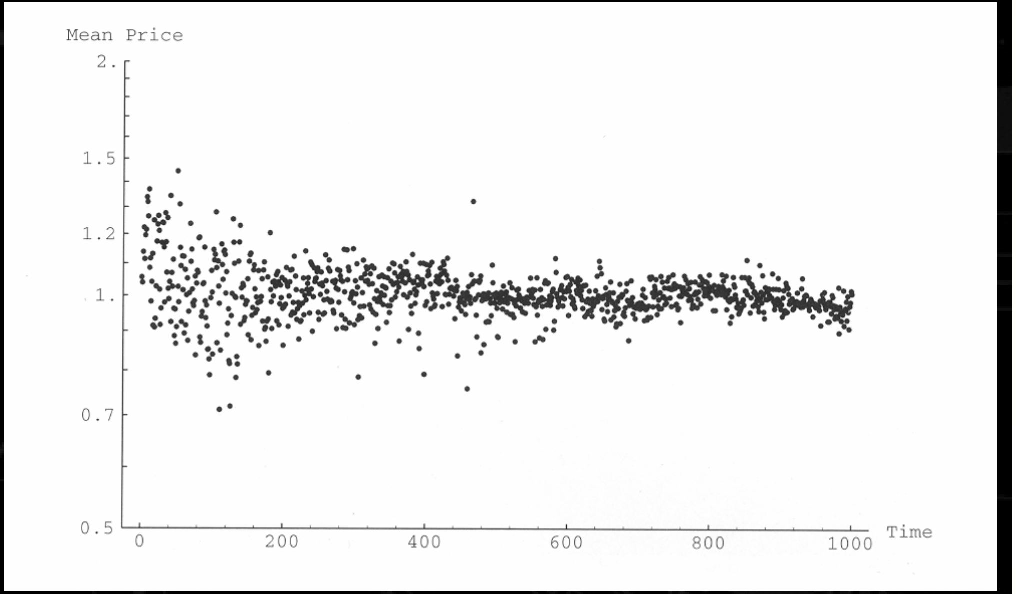
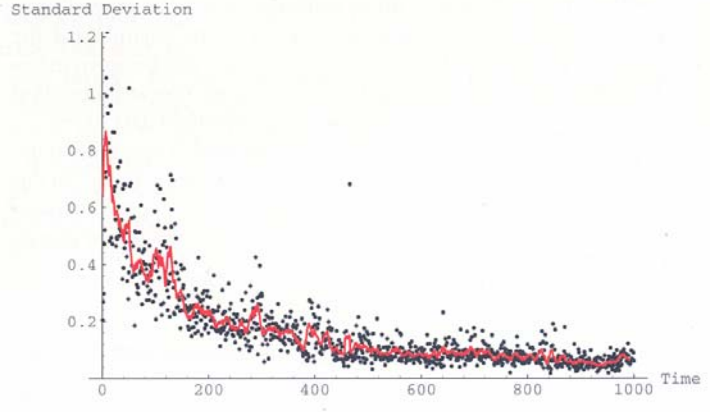


Figure IV-5. Typical Time Series for the Standard Deviation in the Logarithm of Average Trade Price under Rule System ({$\mathbf{G}_1$}, {**M**, **T**})



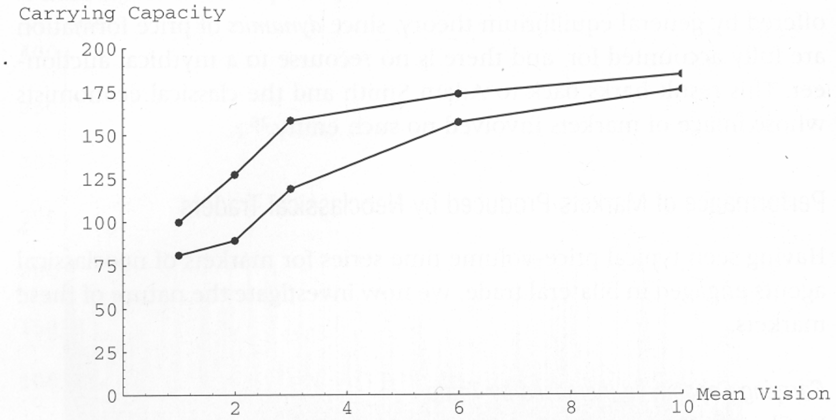
Markets of Bilateral Traders: Rule ({G_1},{M,T})

Beneficial effect on carrying capacity

Why?

Agent 1 has an abundance of sugar but is close to death by spice deprivation; agent 2 has a surfeit of spice but is on the verge of death through sugar deprivation. An exchange of agent’s 1 sugar for agent’s 2 spice will keep both alive!

Figure IV-6. Carrying Capacity as a Function of Mean Agent Vision, with and without Trade, under Rule System ({$\mathbf{G}_1$}, {**M**, **T**})



pletely decentralized trade. It is of a profoundly different character than the Walrasian general equilibrium.

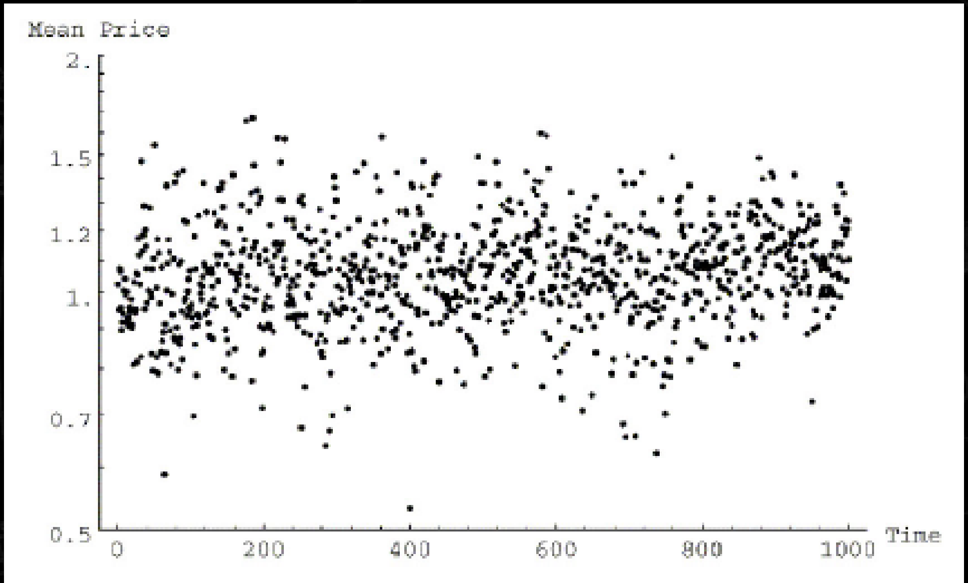
Effect of the Distribution of Vision on Price

One can get larger amounts of price variance by making market "thinner"

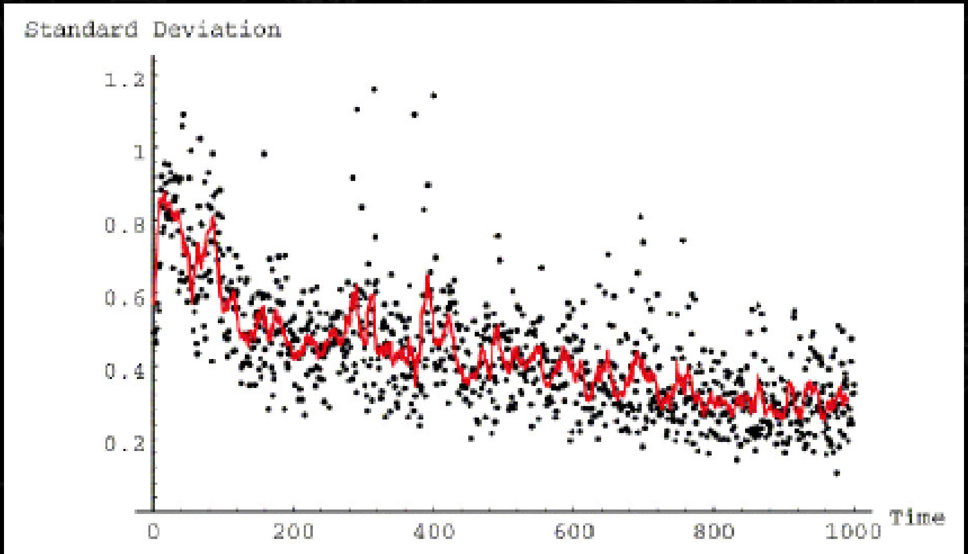
For example: if agent interactions are restricted, then less trade occurs, price convergence slows, and the distribution of MRS is broader

One way to produce a thin market is by limiting the vision of the agents

Vision = 1



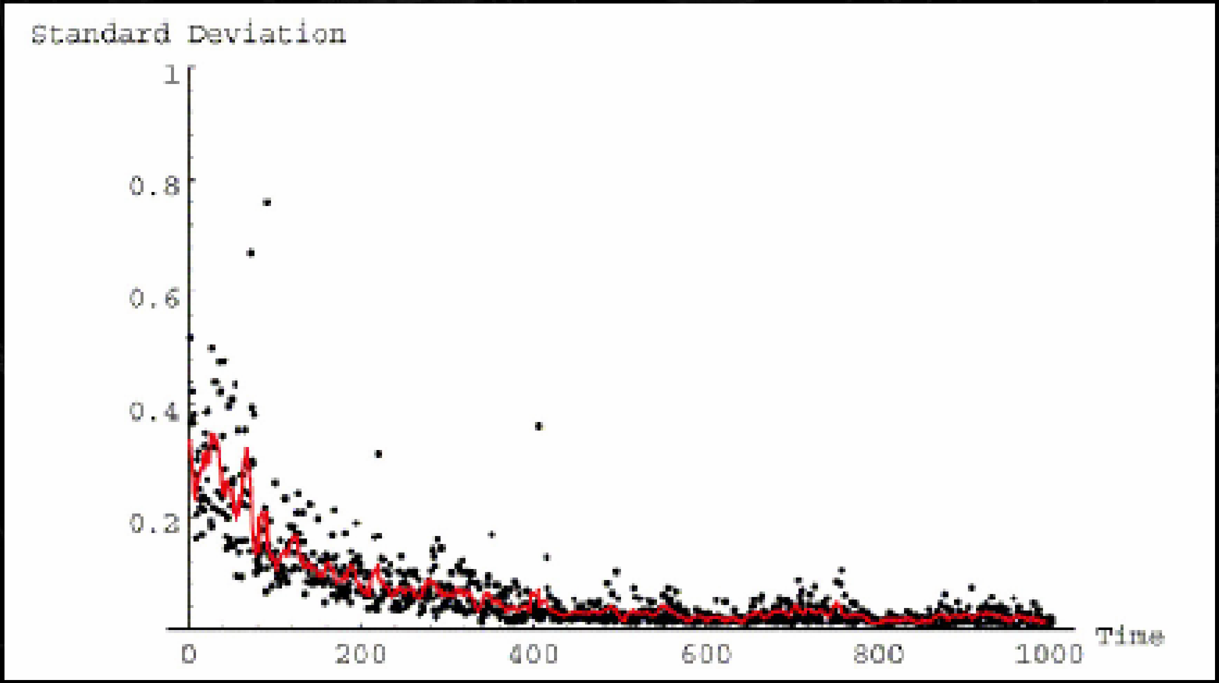
Mean Price
2.
1.5
1.2
1.
0.7
0.5
0
200
400
600
800
1000
Time



Standard Deviation
1.2
1
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
Time

Vision [1,15]

Creates market with much less price variance. Due to higher vision, there is much more intense interaction (more perfect mixing) of the agent population and therefore equilibrium is approached quickly. Information-rich environment. E.g. financial markets.



Enter Mortal Agents (Vision in [1,5])

- Age in [60,100]: Variance does <u>not</u> decrease over time!
- Where trade price is concerned, this economy is far-from-equilibrium

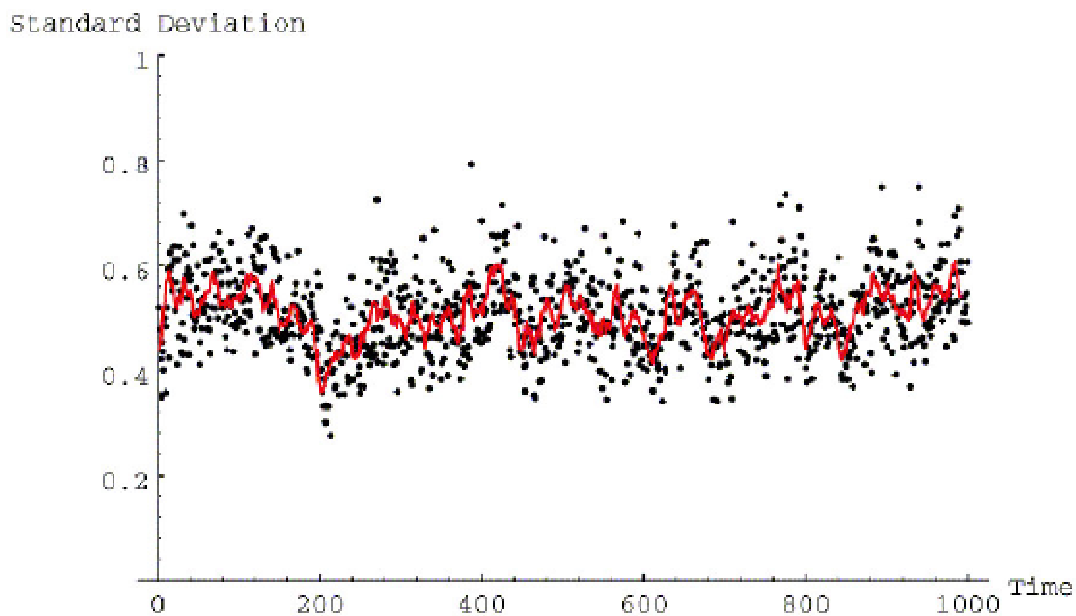


Figure 15: *Typical time series for the standard deviation in the logarithm of average trade price under rule system ({G1}, {M, $R_{[60,100]}$, T) (with vision randomly distributed between 1 and 5).*

Enter Mortal Agents (Vision in [1,5])

Age in [960,1000]: Variance does decrease over time!

The longer the lifetime the more the economy approaches equilibrium → assumptions for near-equilibrium economy are not always justified!

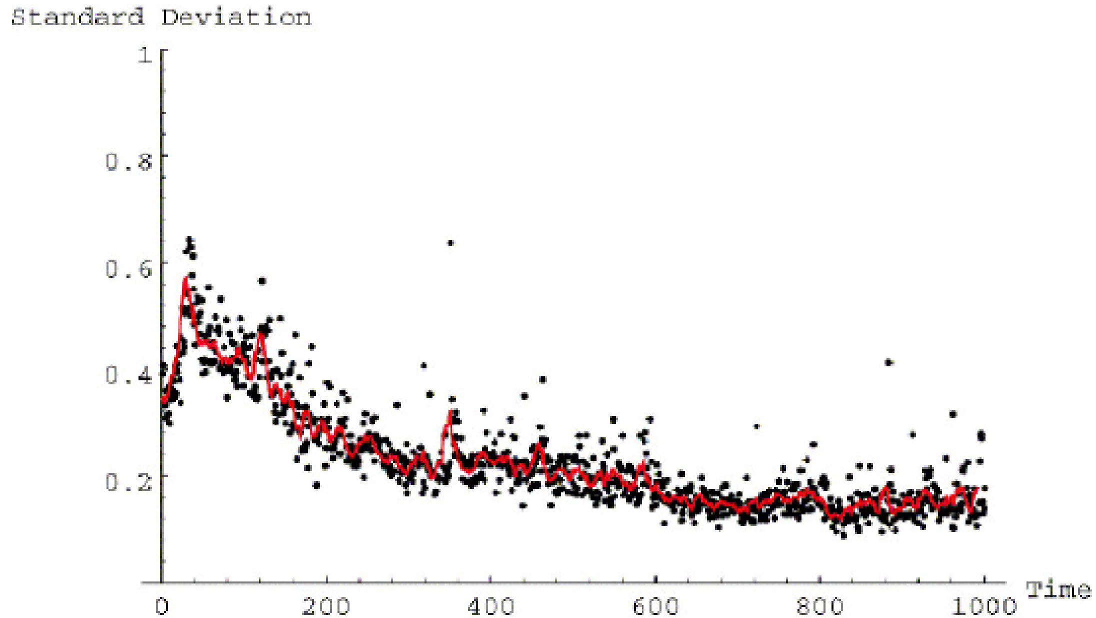


Figure 16: *Typical time series for the standard deviation in the logarithm of average trade price under rule system ({G1}, {M, $R_{[960,1000]}$, T).*