Fraunhofer Institut Autonome Intelligente Systeme

Coordination of Decisions in Multi-Agent Systems

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in collaboration with:

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Schedule

1. What is the problem?

2. Non-linear voter models

3. Decisions based on information dissemination

4. Conclusions

Coordination of Decisions

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  dissemination of information: fast, loss-free, error-free
- *bounded rationality:*
  decisions based on incomplete (limited) information

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- *herding behavior:* agents just imitate decisions without complete information about consequences
- our assumption: agent i more likely does what others do
  neighbourhood: spatial effects
  communication: exchange/lifetime of information

The micro-macro link

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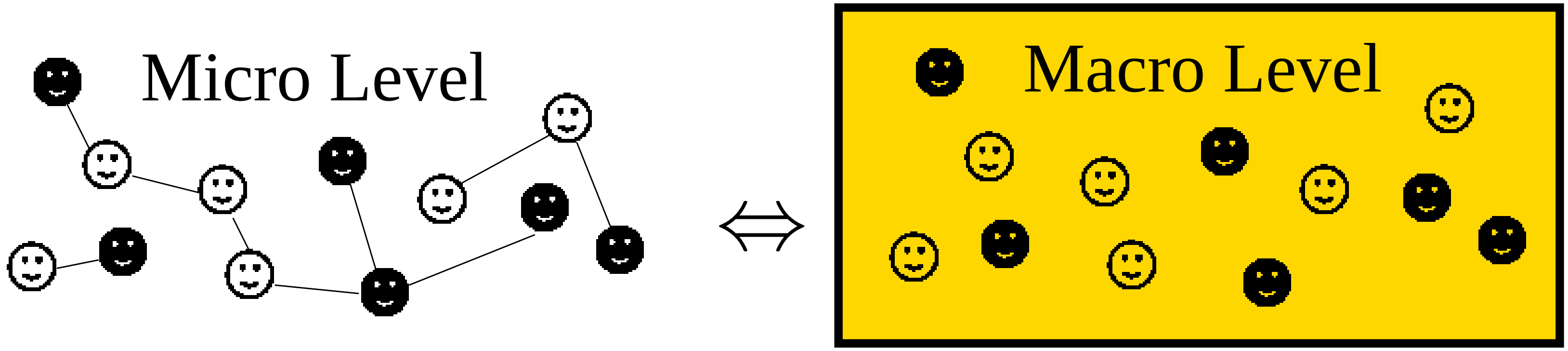

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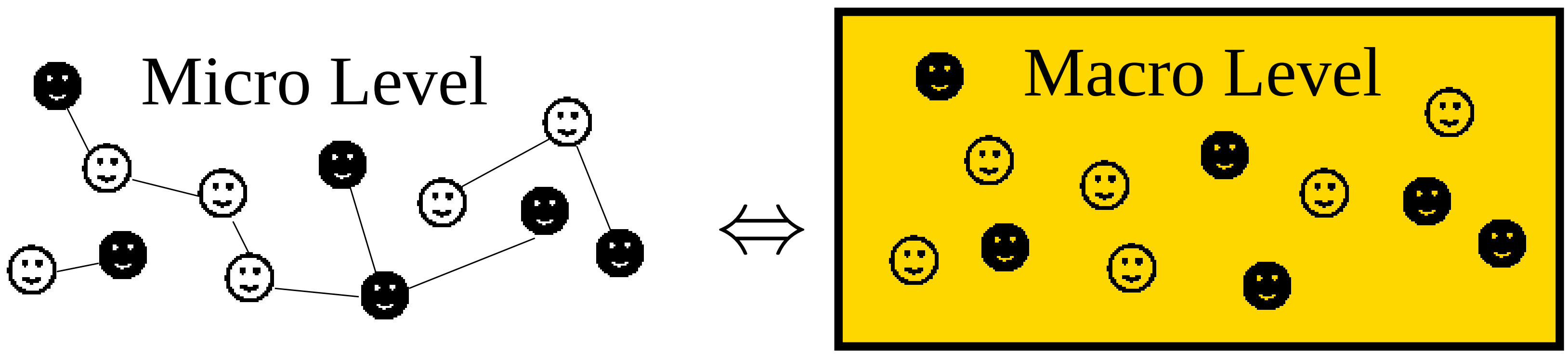

- How are the properties of the agents and their interactions ("microscopic" level) related to the dynamics and the properties of the whole system ("macroscopic" level)?
- **Derivation of analytical results**

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- interdisciplinary enterprise:
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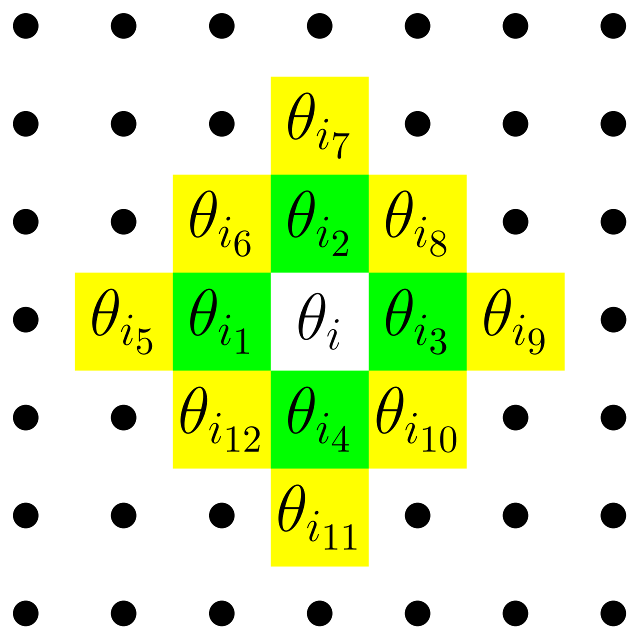
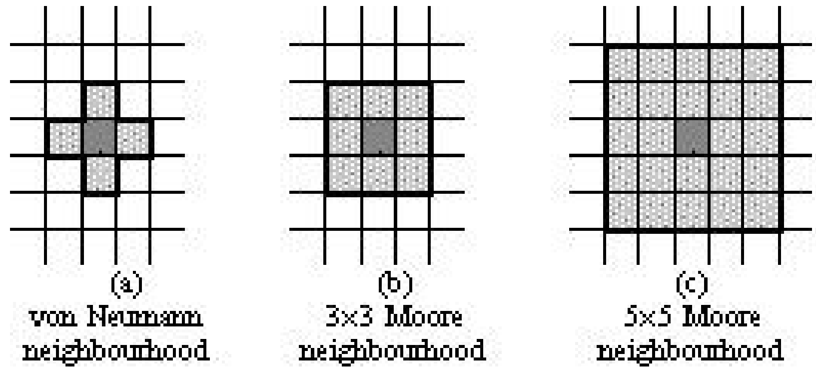
  relation to population biology, ecology
- our interest: investigation of spatial effects
  derivation of macro-dynamics from microscopic interactions

Cellular Automaton



- cell i with different states θ_i
- interaction with neighbors j



History: v. Neumann, Ulam (1940s), Conway (1970), Wolfram (1984), ...

Socio/Economy: Sakoda (1949/1971), Schelling (1969), Albin (1975), ...

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- stochastic description: $p_i(\theta_i, t) = \sum_{\underline{\theta}_i'} p(\theta_i, \underline{\theta}_i', t)$,
  local neighborhood: $\underline{\theta}_i = \{\theta_{i_1}, \theta_{i_2}, ..., \theta_{i_{n-1}}\}$

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  transition rates: $w(1-\theta_i|\theta_i,\underline{\theta}_i)$; $w(\theta_i|(1-\theta_i),\underline{\theta}_i)$

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$$\frac{d}{dt}p_i(\theta_i,t)=\sum_{\underline{\theta}'_i}\Big[w(\theta_i|(1-\theta_i),\underline{\theta}'_i)\;p(1-\theta_i,\underline{\theta}'_i,t)$$
$$-\;w(1-\theta_i|\theta_i,\underline{\theta}'_i)\;p(\theta_i,\underline{\theta}'_i,t)\Big]$$

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- solution:
  (1) stochastic computer simulations
  (2) analytical methods

Local Interaction Rules

Local Interaction Rules

- “frequency dependent process”: $\underline{\theta}_i \Rightarrow$ local frequency:

$$z_i^{\sigma} = \frac{1}{n} \sum_{j=0}^{n-1} \delta_{\sigma\theta_{i_j}} \; ; \quad z_i^{(1-\sigma)} = 1 - z_i^{\sigma} \; ; \quad \sigma \in \{0, 1\}$$

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- asymmetric rules: ("Game of Life", n=9)
  "alive": $\theta_i = 1 \Rightarrow$ rule set 1: "alive" if 2 or 3 neighbors alive
  "dead": $\theta_i = 0 \Rightarrow$ rule set 2: "reborn" if 3 neighbors alive

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- symmetric rules: same for $\theta_i \in \{0, 1\}$

z_i^{σ}	$z_i^{(1-\sigma)}$	$w(1-\theta_i \mid \theta_i = \sigma, z_i^{\sigma})$
1	0	ϵ
4/5	1/5	α_1
3/5	2/5	α_2
2/5	3/5	$\alpha_3 = 1-\alpha_2$
1/5	4/5	$\alpha_4 = 1-\alpha_1$

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2/5	3/5	$\alpha_3 = 1-\alpha_2$
1/5	4/5	$\alpha_4 = 1-\alpha_1$

- positive dependence: $0 \leq \alpha_1 \leq \alpha_2 \leq \alpha_3 \leq \alpha_4 \leq 1$
  "majority voting" (frequent opinions survive)
- symmetry between opinions: $\alpha_3 = 1-\alpha_2$ and $\alpha_4 = 1-\alpha_1$
- *linear* voter model: $\alpha \propto z_i^{(1-\sigma)}$
  i.e. $\epsilon = 0$, $\alpha_1 = 0.2$, $\alpha_2 = 0.4$

- negative dependence: $1 \geq \alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \alpha_4 \geq 0$
  “minority voting” (rare opinions survive)

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- “allee effects”: $\alpha_1 \leq \alpha_2$, $\alpha_2 \geq \alpha_3$, $\alpha_3 \leq \alpha_4$, *etc.*
  voting against the trend

Results of Computer Simulations

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- initially $x = 0.5$, random distribution
- **Stochastic CA**

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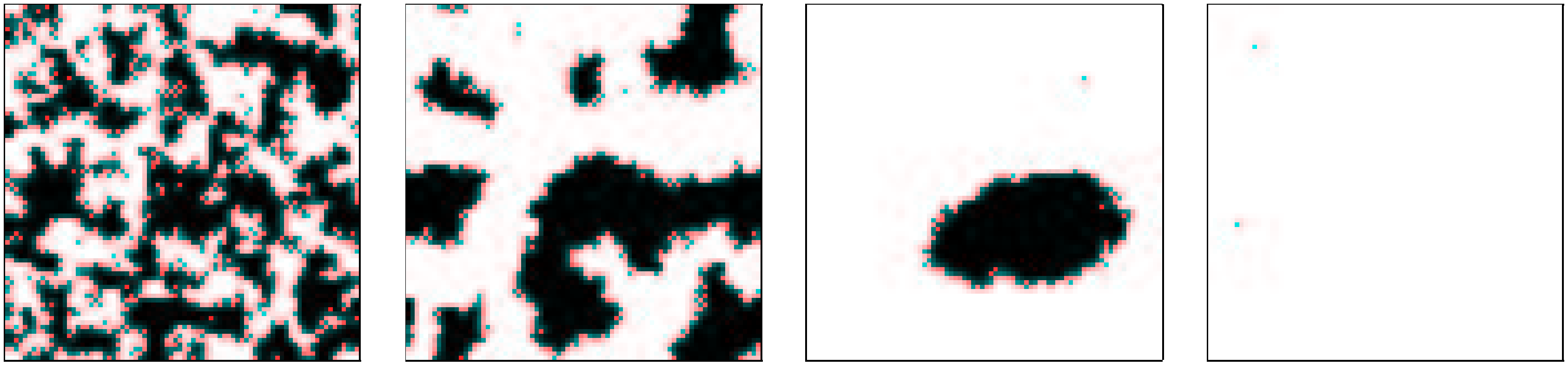
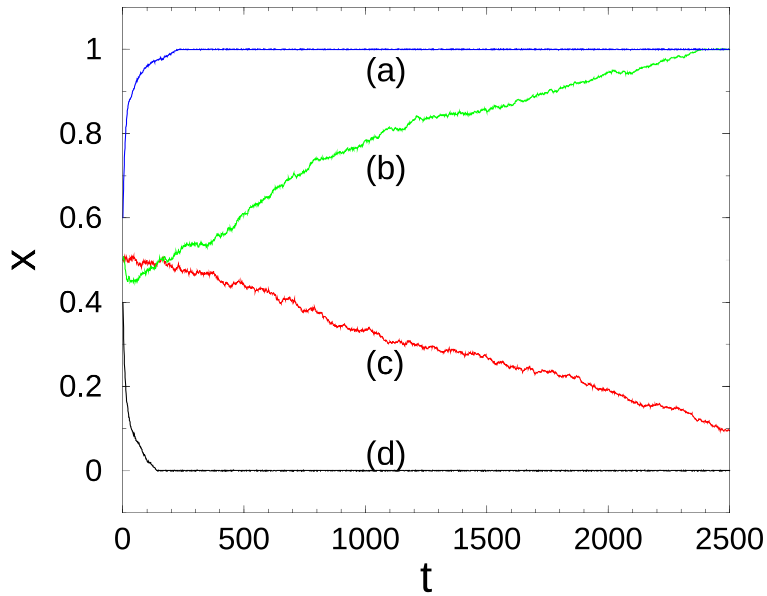
  - Result: coordination of decisions on medium time scales asymptotically: “no opposition”

$\epsilon = 10^{-4}$, $\alpha_1 = 0.1$, $\alpha_2 = 0.3$ $t = 10^1, 10^2, 10^3, 10^4$





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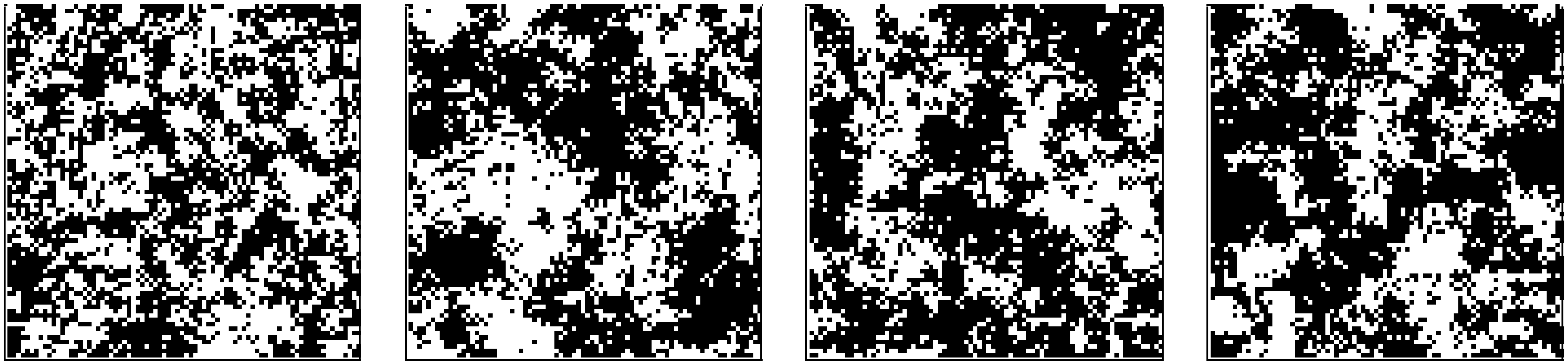
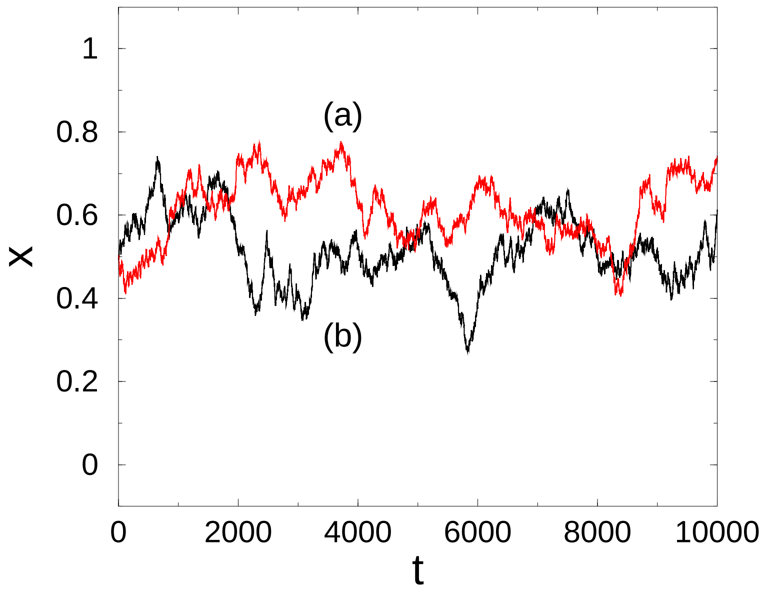
➤ Start Online-Simulation $\epsilon = 10^{-4}$, $\alpha_1 = 0.22$, $\alpha_2 = 0.3$

- Result: coordination of decisions on long time scales
  asymptotically: coexistence, but non-equilibrium

$\epsilon = 10^{-4}$, $\alpha_1 = 0.25$, $\alpha_2 = 0.25$ $t = 10^1, 10^2, 10^3, 10^4$

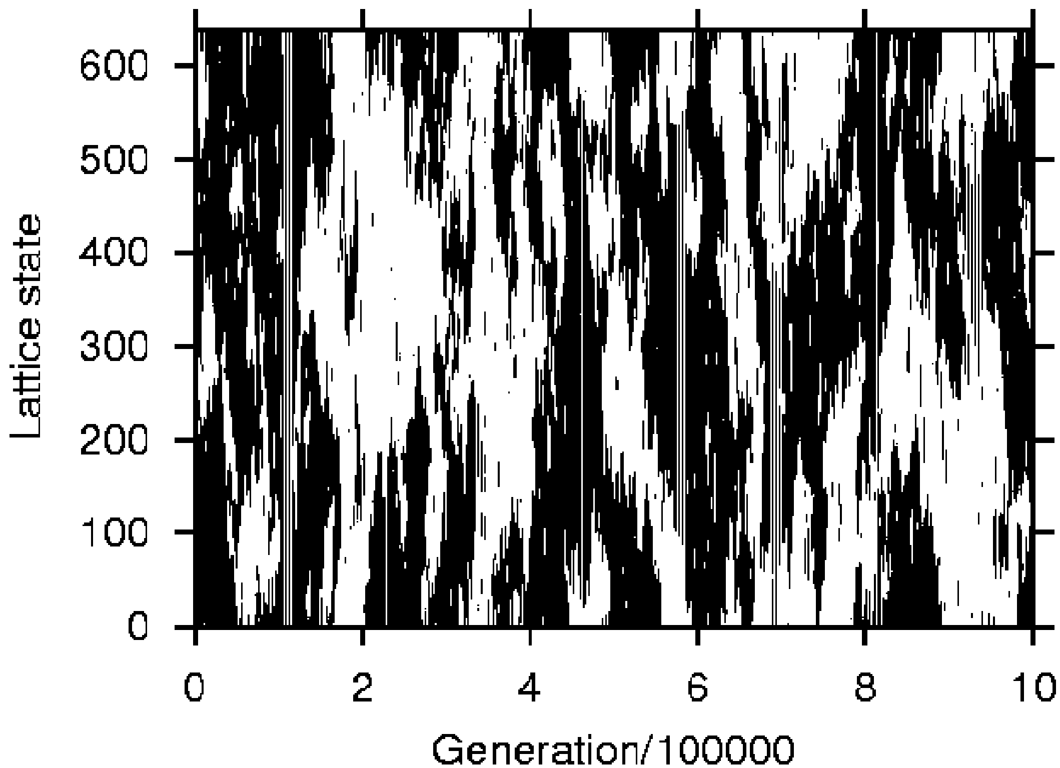




(a) $a_1 = 0.2$, $\alpha_2 = 0.4$ (voter model)

(b) $\alpha_1 = 0.25$, $\alpha_2 = 0.25$

1d CA:



long-term nonstationarity; temporal domination of one opinion

Two tasks:

- 1. define range of parameters for coexistence
- 2. describe spatial correlations between decisions

Macroscopic Equations

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- macroscopic variable: $\langle x(t)\rangle = \dfrac{1}{N}\sum_{i=1}^{N} p_i(\theta_i\!=\!1,t)$

$$\frac{d}{dt}\langle x(t)\rangle = \sum_{\underline{\sigma}'}\Big[w(1|0,\underline{\sigma}')\;\big\langle x_{0,\underline{\sigma}'}(t)\big\rangle - w(0|1,\underline{\sigma}')\;\big\langle x_{1,\underline{\sigma}'}(t)\big\rangle\Big]$$

calculation of $\big\langle x_{\sigma,\underline{\sigma}'}(t)\big\rangle$: consideration of *all* possible $\underline{\sigma}'$ (!)

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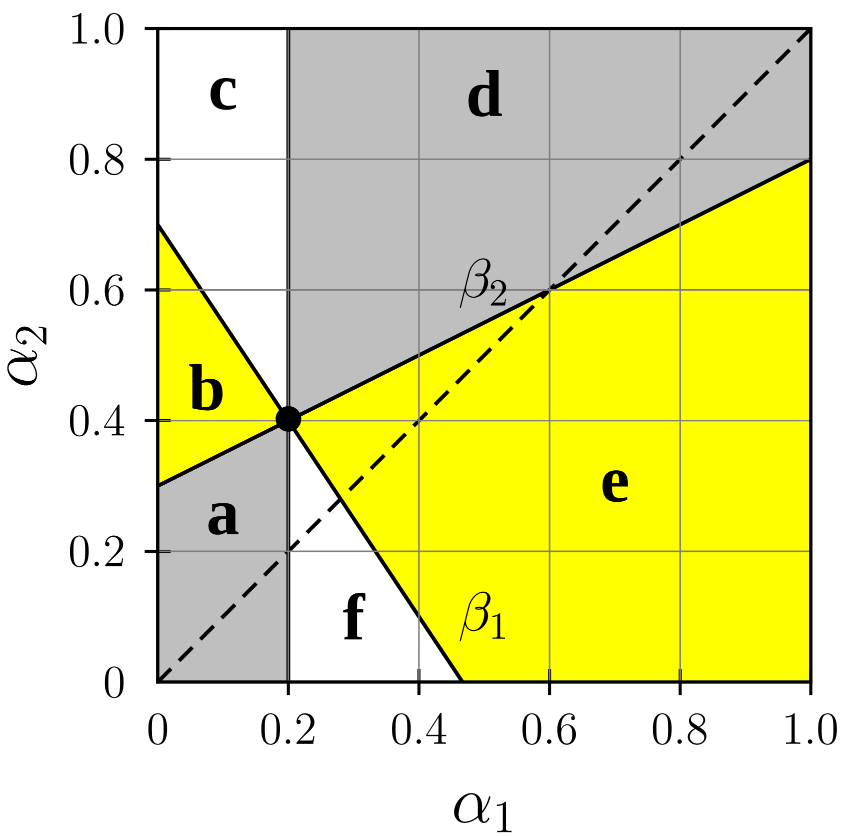
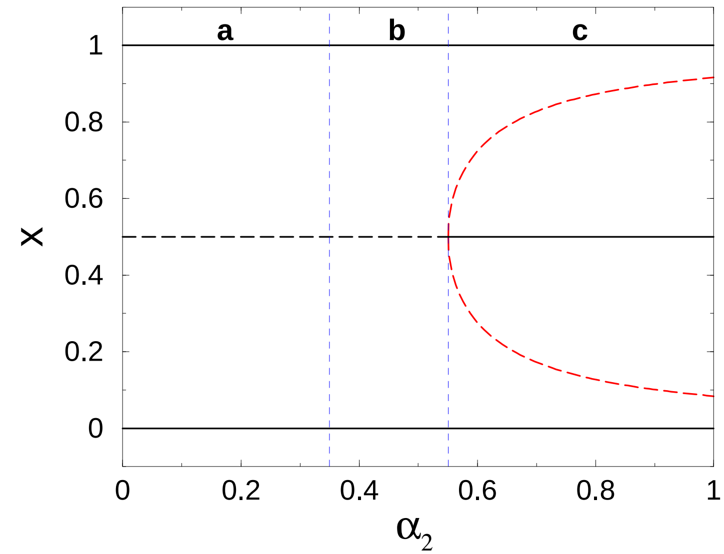
- **1st Approximation:** Mean-field limit
  no spatial correlations

$$\left\langle x_{\underline{\sigma}^0}\right\rangle = \langle x_\sigma\rangle \prod_{j=1}^{m}\left\langle x_{\sigma_j}\right\rangle$$

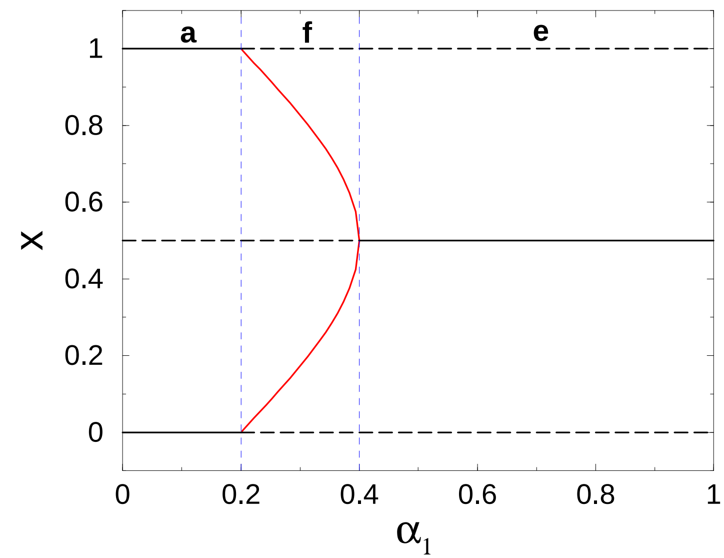


yellow: $x^{(4,5)}$ imaginary
gray: $x^{(4,5)}$ outside (0,1)
(c): $x^{(4,5)}$ unstable

$\alpha_1 = 0.1$



$\alpha_2 = 0.1$



- **2nd Approximation:** pair approximation
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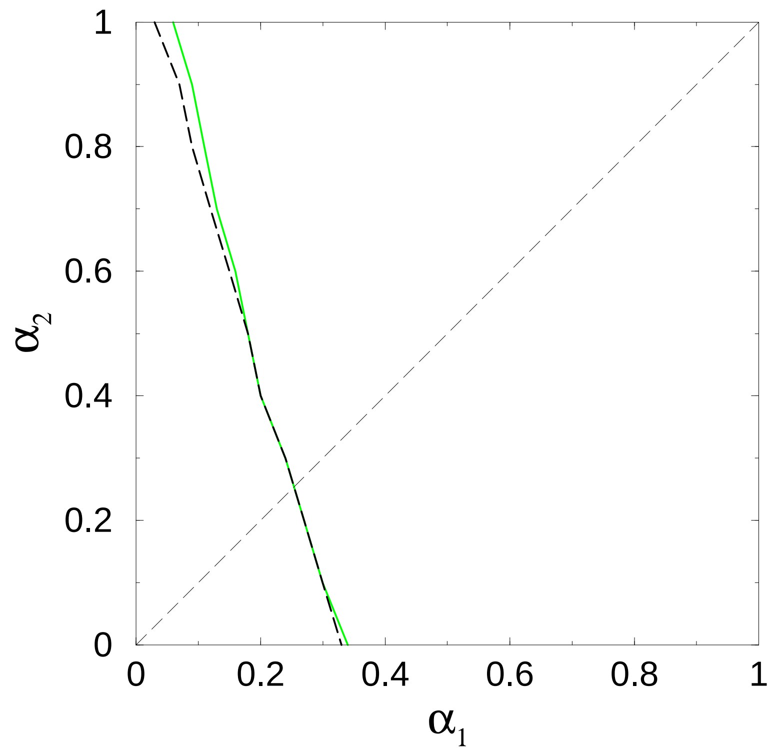
- closed macroscopic dynamics: doublet frequency: $\left\langle x_{\sigma,\sigma'} \right\rangle$
  spatial correlation: $c_{\sigma|\sigma'} := \left\langle x_{\sigma,\sigma'} \right\rangle / \left\langle x_{\sigma'} \right\rangle$

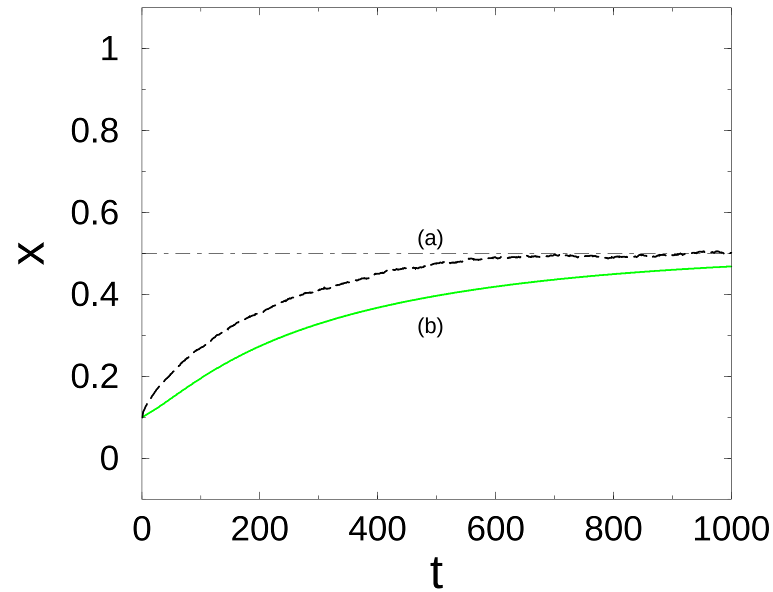
$$\frac{d}{dt}\langle x(t)\rangle = \sum_{\underline{\sigma}'} \Big[\quad w(1|0,\underline{\sigma}')\,(1-\langle x\rangle) \prod_{j=1}^{m} c_{\sigma_j|\sigma} \\ -w(0|1,\underline{\sigma}')\ \langle x\rangle \prod_{j=1}^{m} c_{\sigma_j|(1-\sigma)} \Big]$$

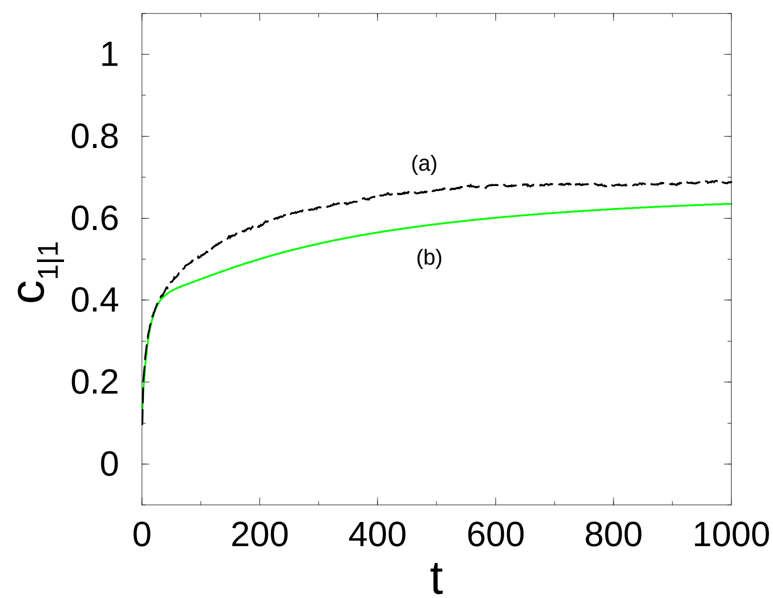
$$\frac{dc_{1|1}}{dt} = -\frac{c_{1|1}}{\langle x\rangle}\frac{d}{dt}\langle x\rangle + \frac{1}{\langle x\rangle}\frac{d}{dt}\langle x_{1,1}\rangle \ ; \qquad \frac{d\,\langle x_{1,1}\rangle}{dt} = \ldots$$

Predictions for Coexistence

Phase Diagram







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- missing: memory effects, dissemination of information

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- Spatio-temporal communication field

$$\frac{\partial}{\partial t} h_\theta(\boldsymbol{r}, t) = \sum_{i=1}^{N} s_i \, \delta_{\theta,\theta_i} \, \delta(\boldsymbol{r} - \boldsymbol{r}_i) - k_\theta h_\theta(\boldsymbol{r}, t) + D_\theta \Delta h_\theta(\boldsymbol{r}, t)$$

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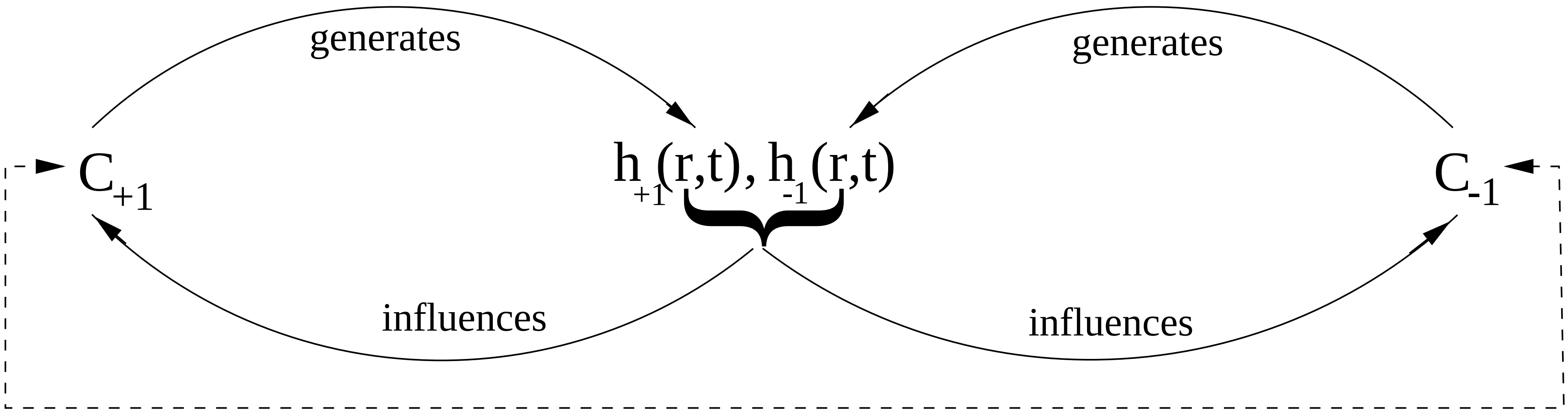
- existence of *memory*
  exchange of information with *finite* velocity

non-linear feedback:



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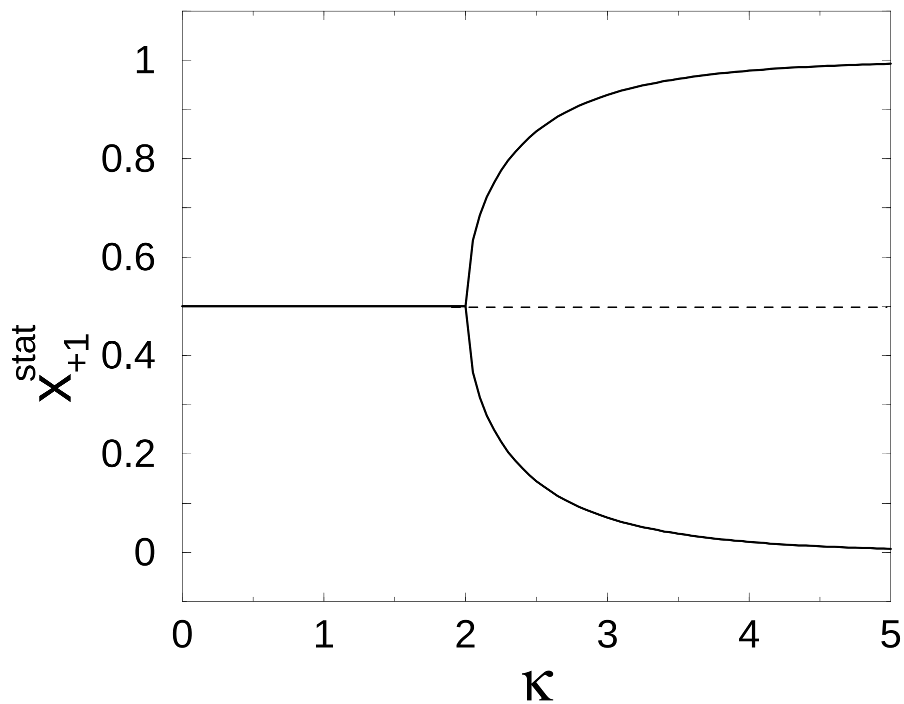
- subpopulations: $x_\theta(t) = N_\theta(t)/N$
- stationary states: $\dot{x}_\theta = 0$, $\dot{h}_\theta = 0$
  with $s_{+1} = s_{-1} \equiv s$, $k_{+1} = k_{-1} \equiv k$

$$(1 - x_{+1})\;\exp\left[\kappa\, x_{+1}\right] = x_{+1}\;\exp\left[\kappa\,(1 - x_{+1})\right]$$

  - bifurcation parameter: $\kappa = \dfrac{2s\,N}{A\,k\,T}$

Bifurcation diagram:

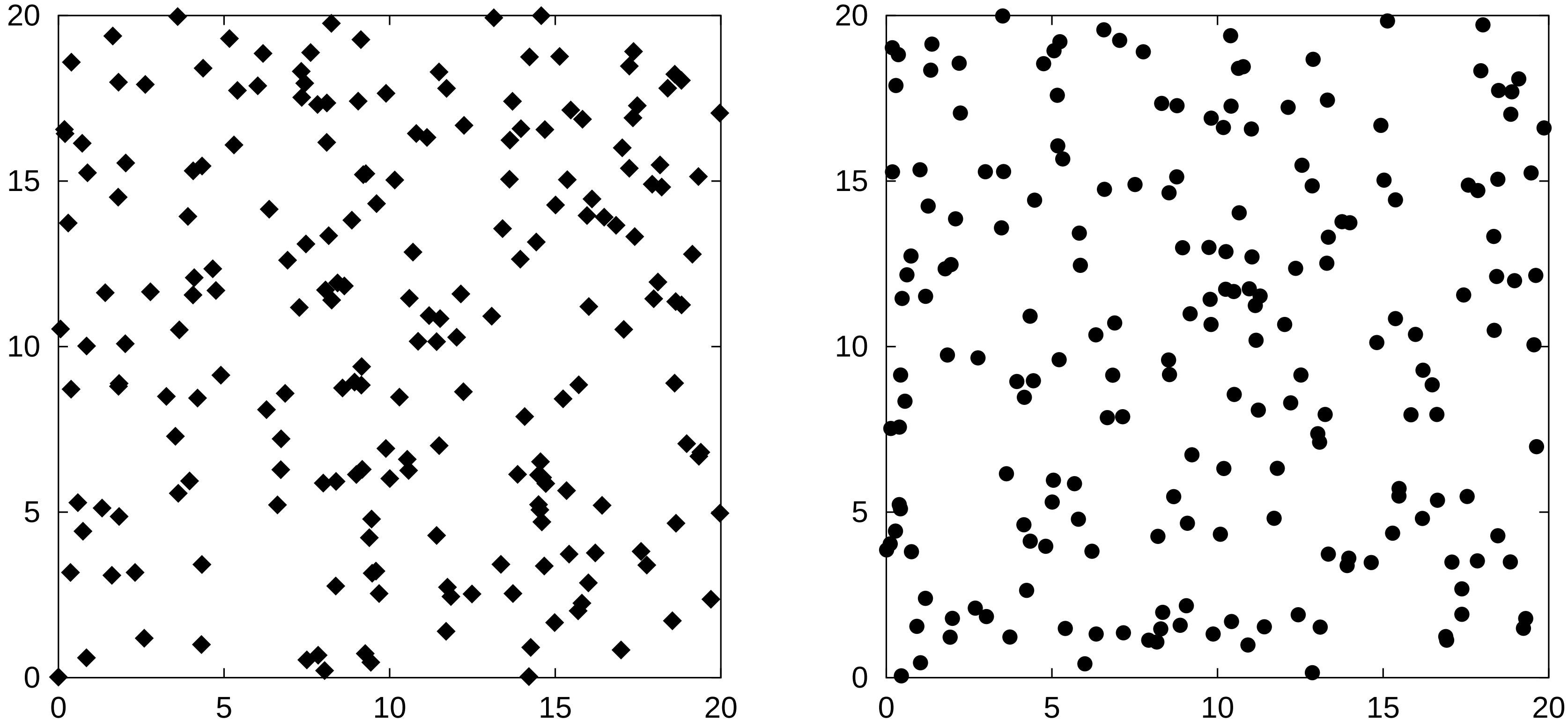


$$\kappa = \frac{2s\,N}{A\,k\,T} = 2 \Rightarrow \text{critical population size: } N^c = \frac{k\,A\,T}{s}$$

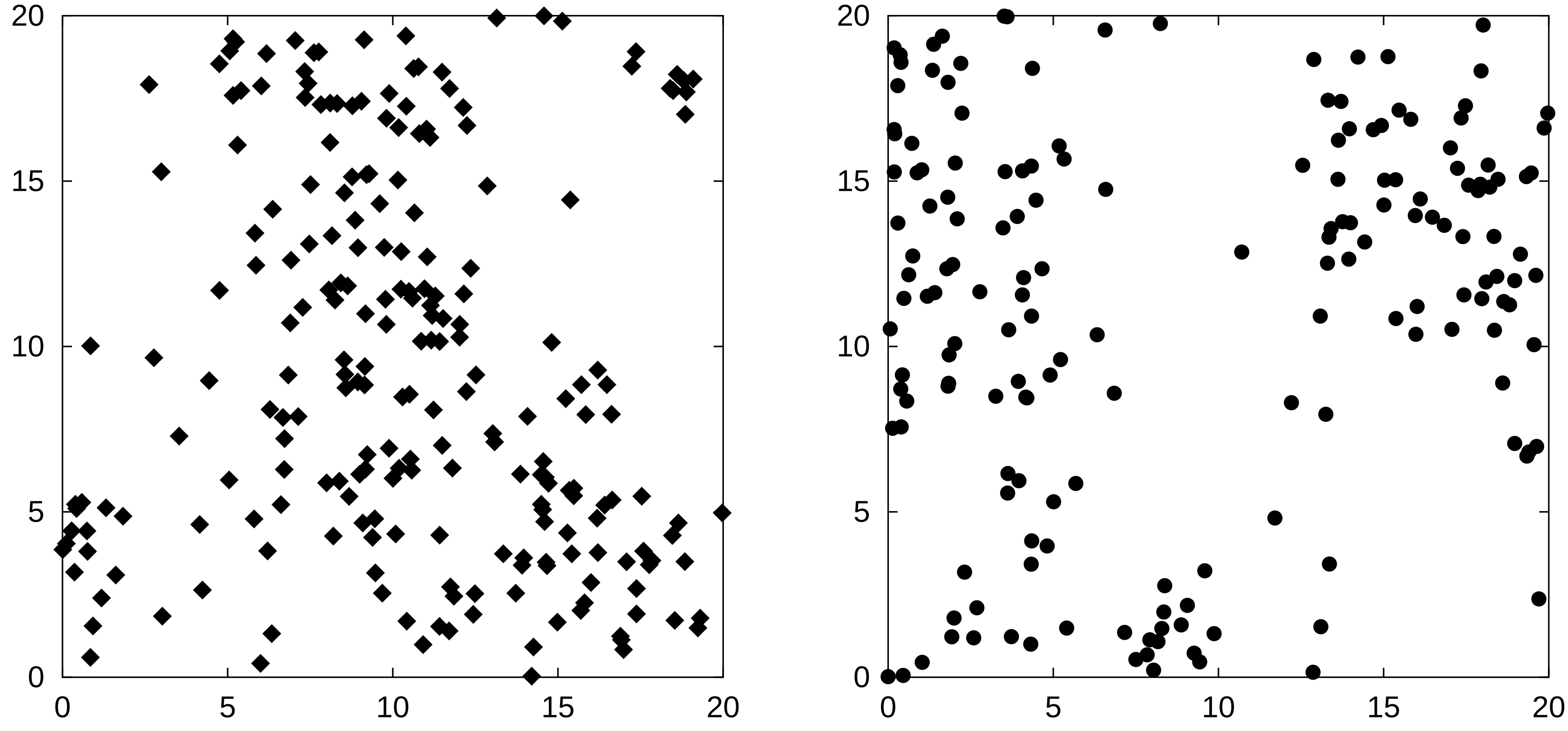
Emergence of minority and majority

Spatial Influences on Decisions

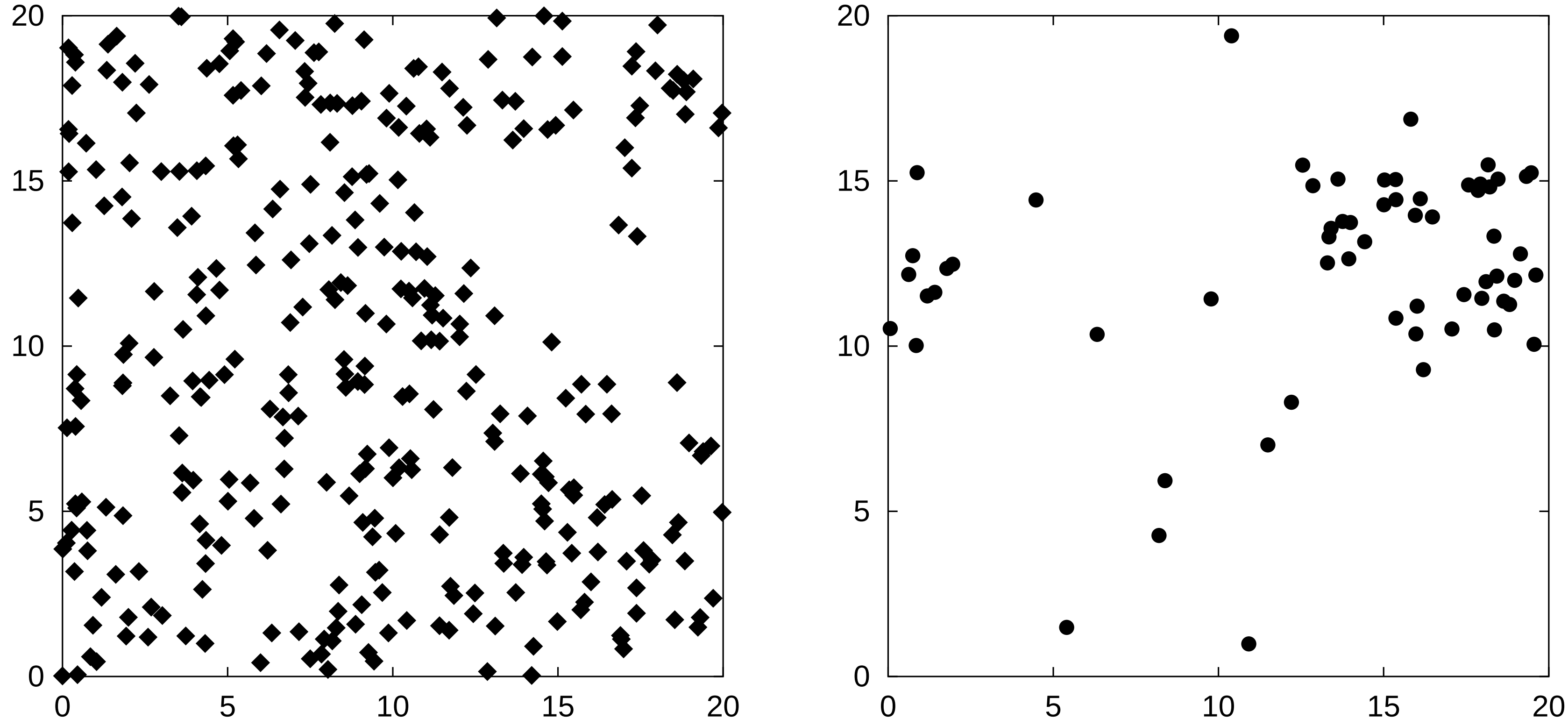
$$s_{+1} = s_{-1} \equiv s,\, k_{+1} = k_{-1} \equiv k,\, D_{+1} = D_{-1} \equiv D$$



$$t = 10^0$$



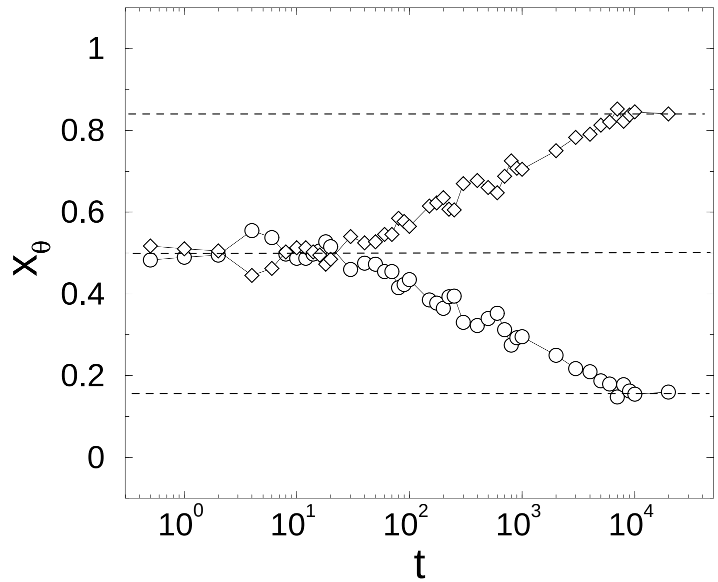
$$t = 10^2$$

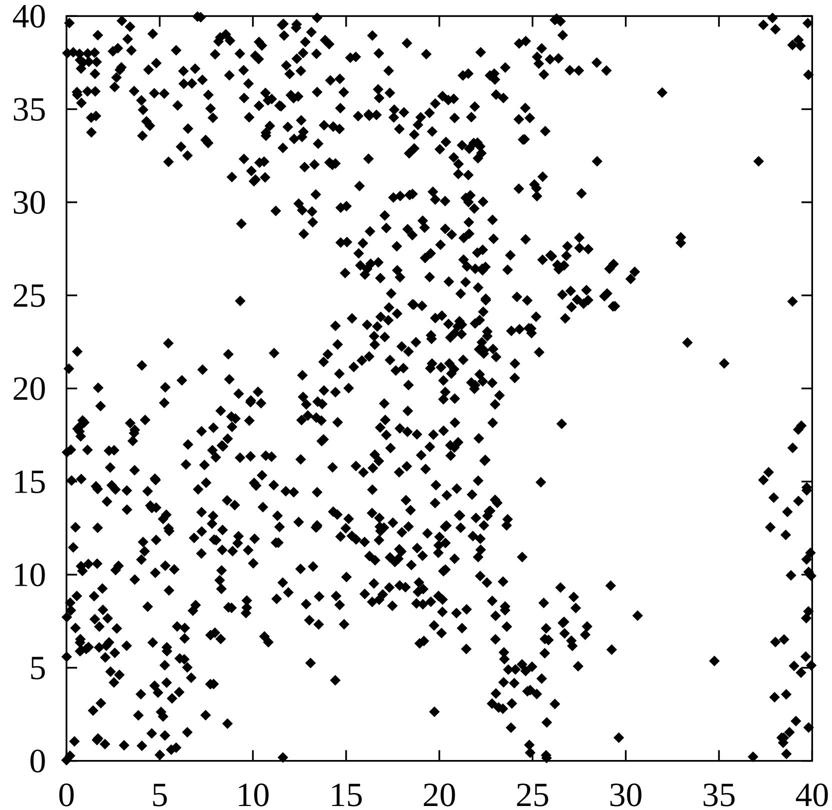


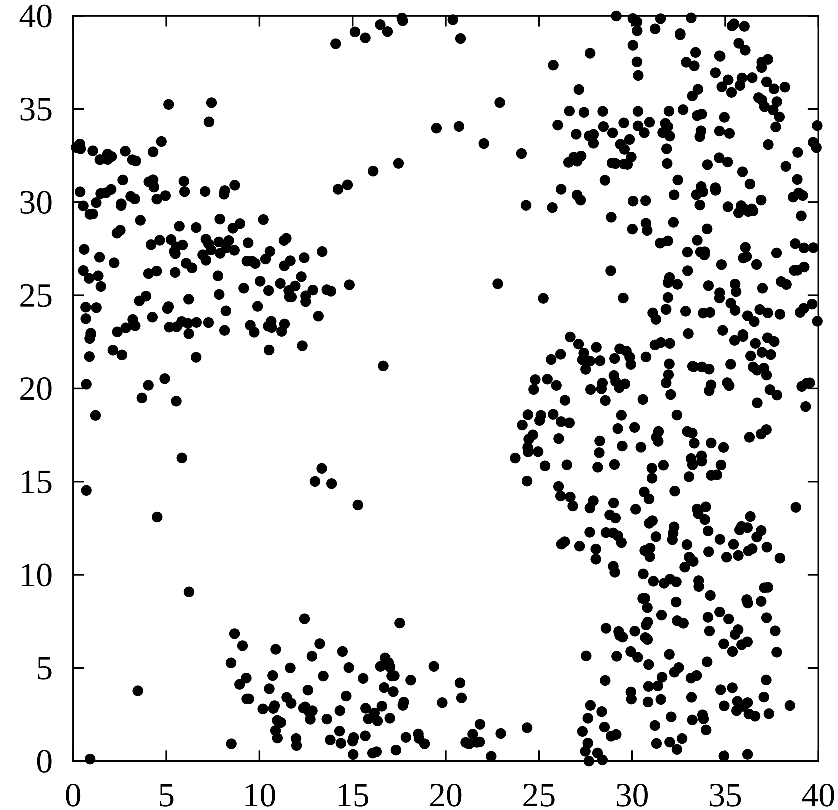
$$t = 10^4$$

Results: (first glimpse)

1. *spatial* coordination of decisions: concentration of agents with the same opinion in different spatial domains
2. emergence of minority and majority
3. random events decide about minority/majority status



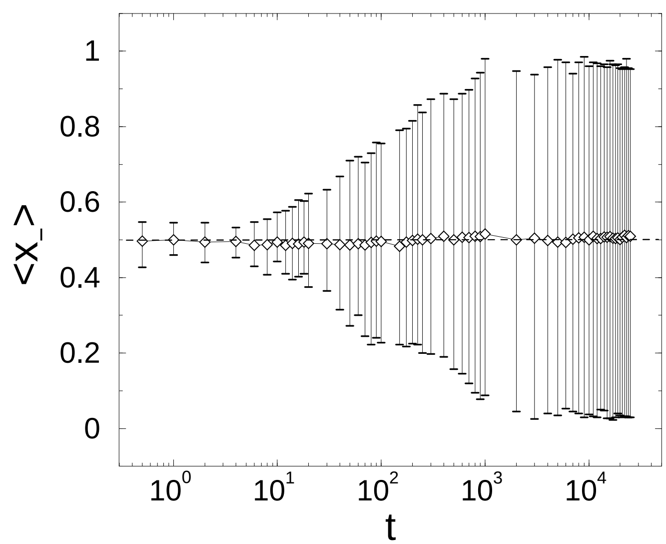




System size: $A = 1600$, total number of agents: $N = 1600$, time: $t = 5 \cdot 10^4$, frequency: $x_+ = 0.543$

Results: (closer inspection)

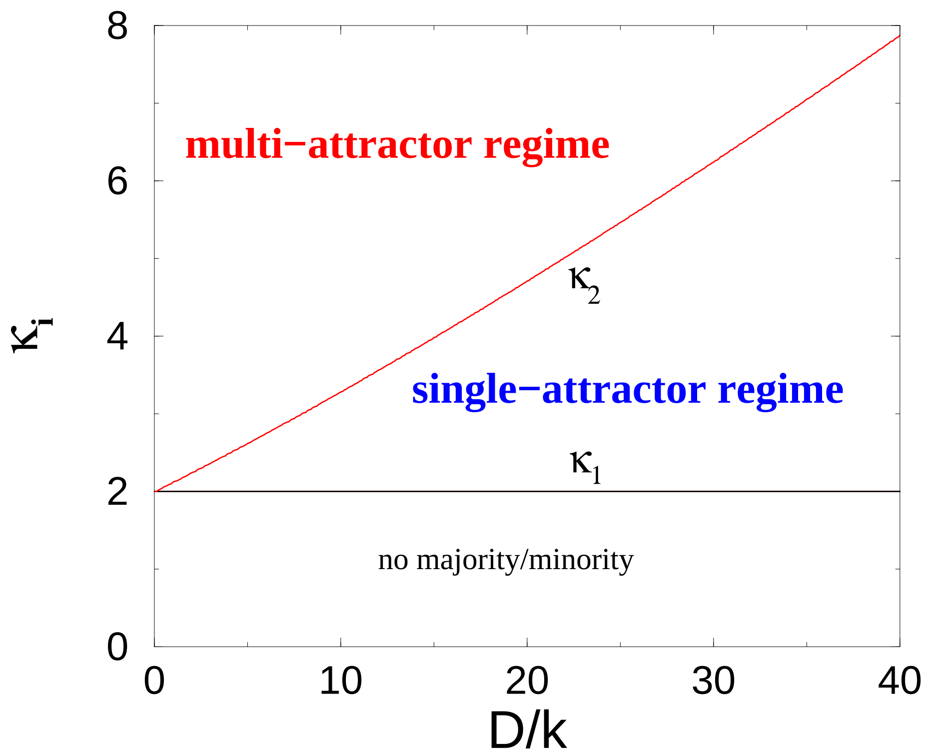
- *single-attractor regime:* fixed minority/majority relation
- *multi-attractor regime:* variety of spatial patterns
almost every minority/majority relation may be established



- dependence on information dissemination (D), memory (k), agent density (N/A) ??

Analytical Investigations: The 2-Box Case

- existence of new bifurcation parameters: $\kappa_1 = 2$, $\kappa_2(D/k)$
  multi-attractor regime: $\kappa > \kappa_2(D/k)$



Result:

- to avoid multiple outcome (i.e. uncertainty in decision)
  - speed up information dissemination (mass media, ...)
  - reduce memory effects (distraction, ...)
  - increase randomness in social interaction

$\Rightarrow$ system “globalized” by ruling information

Result:

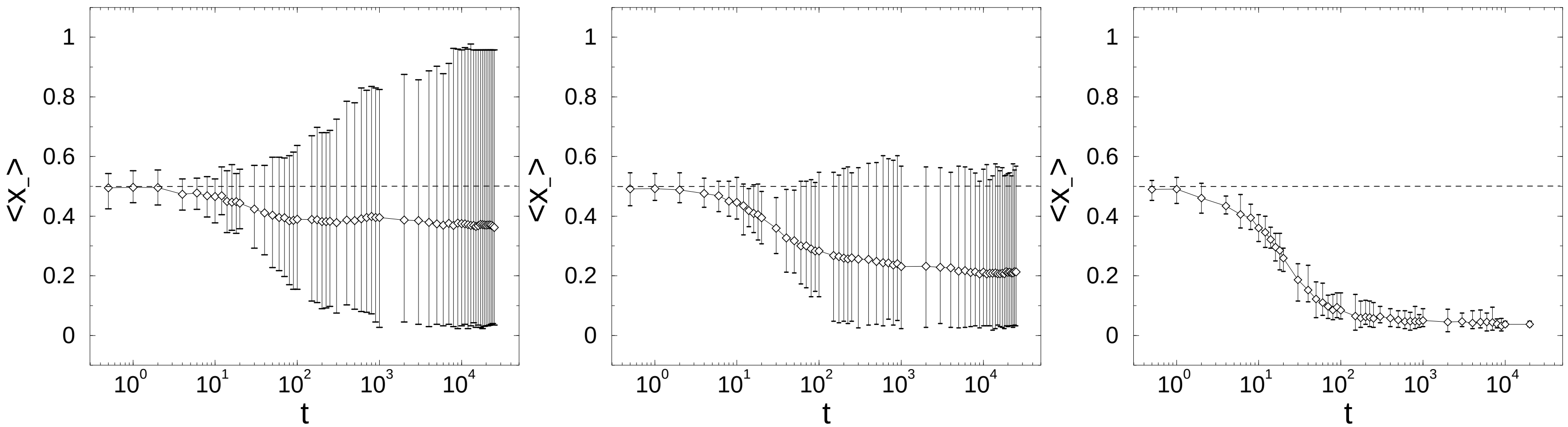
- to avoid multiple outcome (i.e. uncertainty in decision)
  - speed up information dissemination (mass media, ...)
  - reduce memory effects (distraction, ...)
  - increase randomness in social interaction

$\Rightarrow$ system “globalized” by ruling information

- to enhance multiple outcome (i.e. openess, diversity)
  - increase self-confidence, local influences
  - prevent “globalization” via mass media

Influence of information dissemination

vary: $d = D_{+1}/D_{-1}$



d=1.1 d=1.2 d=1.5

- subpopulation with the more efficient communication becomes “always” the majority

Conclusions: Coordination of decisions

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  $\Rightarrow$ non-linear voter models (CA)
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Conclusions: Coordination of decisions

- based on local NN interaction (persuasion)
  $\Rightarrow$ non-linear voter models (CA)
- based on dissemination of information
  $\Rightarrow$ spatial model of communicating (Brownian) agents (BA)
- emergence of spatial domains of likeminded agents
- emergence of majority/minority
- non-stationary coexistence or extinction (CA)
- multi-attractor regime: multiple outcome (BA)
- “efficient” communication supports majority status

- advantage:
  - link agent-based (microscopic) model to analytical (macroscopic) model
  - allows prediction of collective behavior

Frank Schweitzer: *Brownian Agents and Active Particles. Collective Dynamics in the Natural and Social Sciences*
Springer Series in Synergetics, 2003 (422 pp, 192 figs)