Coordination of Decisions in a Spatial Agent Model

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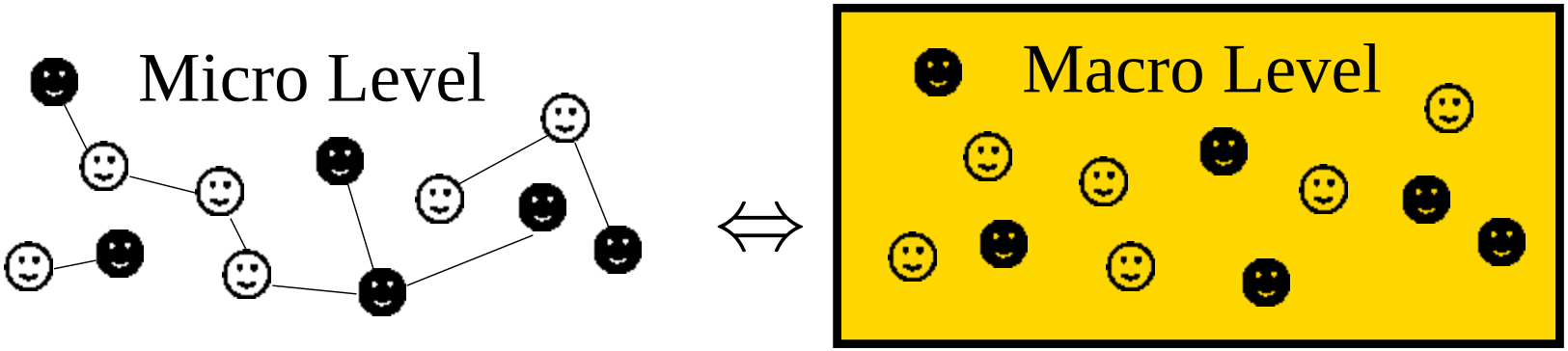
What is Physics?

Physics is ... *what physicists do* ... ?

- *(hypo-)thesis:*
  - physics as a way of thinking (*methodology*)
  - basically not restricted to phenomena of the unanimated world (... *physis* ...)
- aim: transfer of methods and tools:
  many-particle physics, non-linear dynamics, ...
- different fields of applications:
  biology, social science, ...

The micro-macro link



- How are the properties of the elements and their interactions (“microscopic” level) related to the dynamics and the properties of the whole system (“macroscopic” level)?

Lessons from Physics ?

- statistical theory of *many-particle systems*
  - microscopic properties: velocity, short-range interactions
  - macroscopic properties: conductivity, hardness ...
- *Synergetics*
  - subsystems commonly generate *order parameters*
    $\Rightarrow$ “enslaving principle” (circular causality)
  - collective effects, emergence of new qualities

Questions:

- Can we transfer methods/tools of statistical physics to *non-physical many-particle* systems?
- Can we derive a statistical theory of *multi-agent* systems?

Answer: YES ... but at what price?

Reasonable Reductions?

- 1^{st} (rigorous) solution:
  - reduce "humans" to "atoms": identical, "rational", ...
  - reduce complexity of interactions: time independent, identical, symmetrical, ...
  - successful examples in game theory, neoclassical economy, ...
- 2^{nd} (weaker) solution:
  - compromise between "realistic" and "solvable"
    $\Rightarrow$ focus on particular features, purposeful neglection
  - explore: how far can we get with "minimalistic" models?

The "Art" of Reduction

- lessons from history of art: focus on the "essentials"
- Goethe: "Wissenschaft als Kunst"

From Particles to Agents*

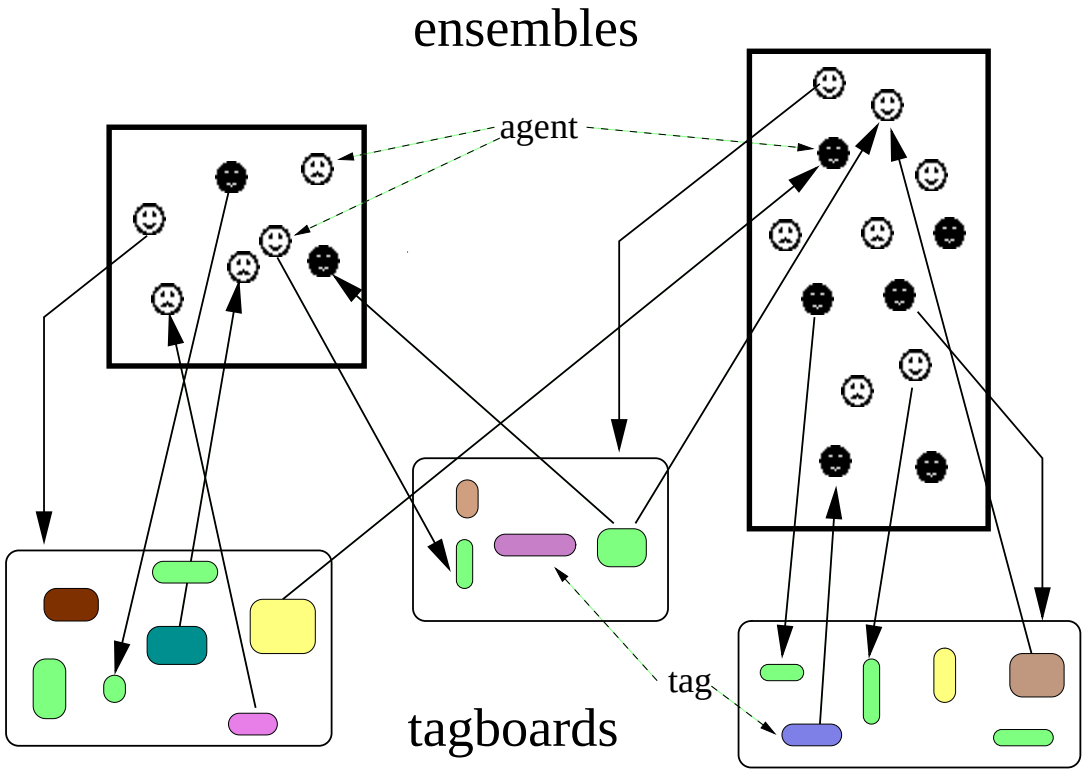
- **agent:** "particle" with "intermediate" complexity
  - *internal degrees* of freedom $\Rightarrow$ allow to act differently
  - "spatial" mobility
  - *reactivity:* perceive the environment, respond to it
  - *proactivity:* "take the initiative" environmental changes, create/disseminate information, ...
- **multi-agent system:** (MAS)
  cooperative interaction instead of autonomous action
  - economics, social science, population biology, ...

* From Many-Particle Physics to Multi-Agent Systems, EXYSTENCE Thematic Institute, Max-Planck Institute for Physics of Complex Systems Dresden, 11 July - 18 September 2004

Lessons from Informatics/AI: Distributed Systems

- comprised of a large number of interacting subsystems
- "elements", "units", ... $\Rightarrow$ *agents*:
  - different types, heterogenity
  - internal complexity, autonomy, ...
- *interactions*:
  - on different temporal and spatial scales (local, global)
  - direct, indirect, hierarchical, ...
  - generalized form of "communication":
    every system change caused by agents which can be observed by other agents

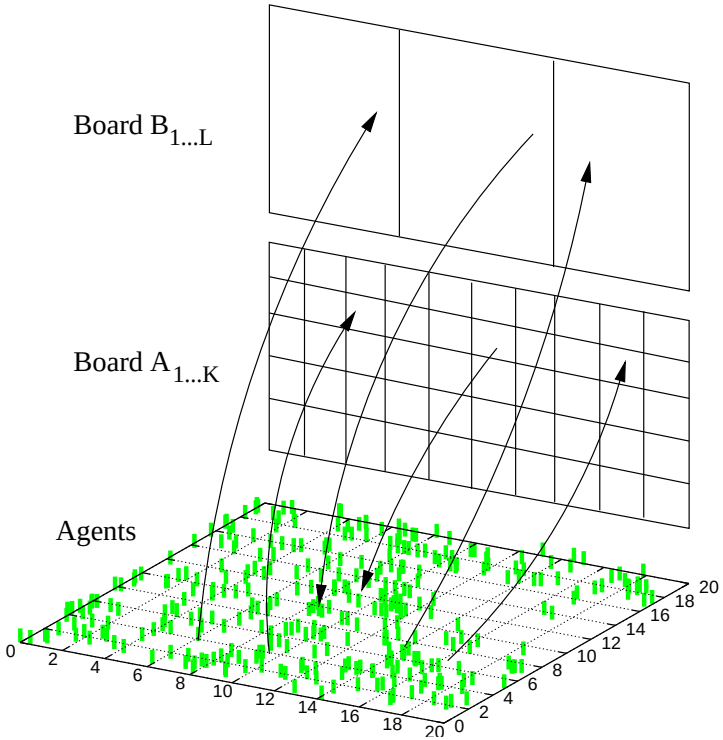
Simulation of distributed systems: Flip-Tick Architecture (FTA)



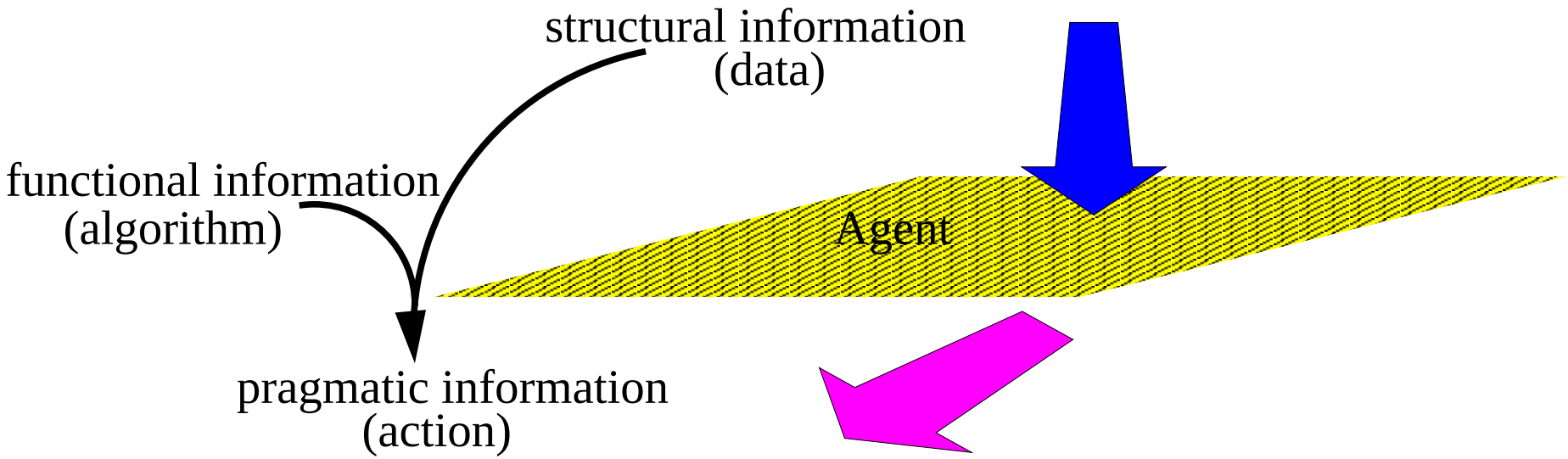
- "real-world" application: *City-Traffic* (ARTec/Fraunhofer)

Spatial Communication via Tagboards

- arrays of “blackboards” with restricted access
  agents post/retrieve *locally* different information (tags)
- limited *lifetime* and *dissemination* of information



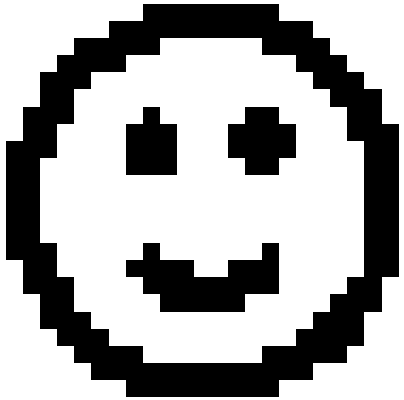
From Data to Action:



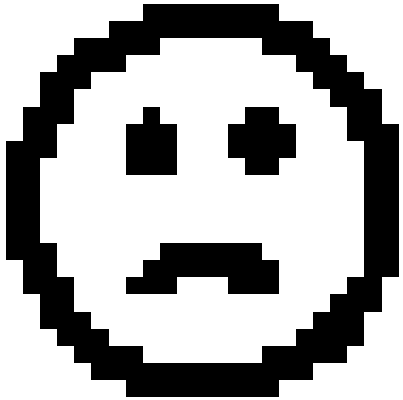
"Social" Agents: Cooperators and Egoists

➤ *microscopic description:* agent i (position: $\boldsymbol{r}_i$)

- internal degree of freedom $\theta_i \Rightarrow$ "behavior"
  $\mathcal{C}$: to cooperate $\Rightarrow \theta_i = +1$
  $\mathcal{D}$: "to defect" $\Rightarrow \theta_i = -1$



defector



cooperator

Coordination of Decisions

- decisions: *basic* process (micro-economics, social system)
- based on *information*:
  economy: prices, quality, ...
  social system: harms and benefits, ...
  decision of other agents, ...
- classical approach: *rational agent*
  calculation of utility function
  common knowledge assumption
  dissemination of information: fast, loss-free, error-free
- *bounded rationality:*
  decisions based on incomplete (limited) information

How to reduce the risk?

- *imitation strategies*
  biology, cultural evolution: adapt to the community
  economy: copy successful strategies
- *information contagion*: agents can observe payoffs
  transmission of two information: decision, payoff
  social percolation: hits and flops
- *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

Spatial Model of Communicating Agents

- N agents: position $\boldsymbol{r}_i \in \mathbb{R}^2$, "opinion" $\theta_i \in \{-1, +1\}$
- *binary choice*: to change or to keep "opinion" θ_i

$$w(-\theta_i|\theta_i) = \eta \, \exp\left\{ -\frac{h_\theta(\boldsymbol{r}_i, t) - h_{-\theta}(\boldsymbol{r}_i, t)}{T} \right\}$$

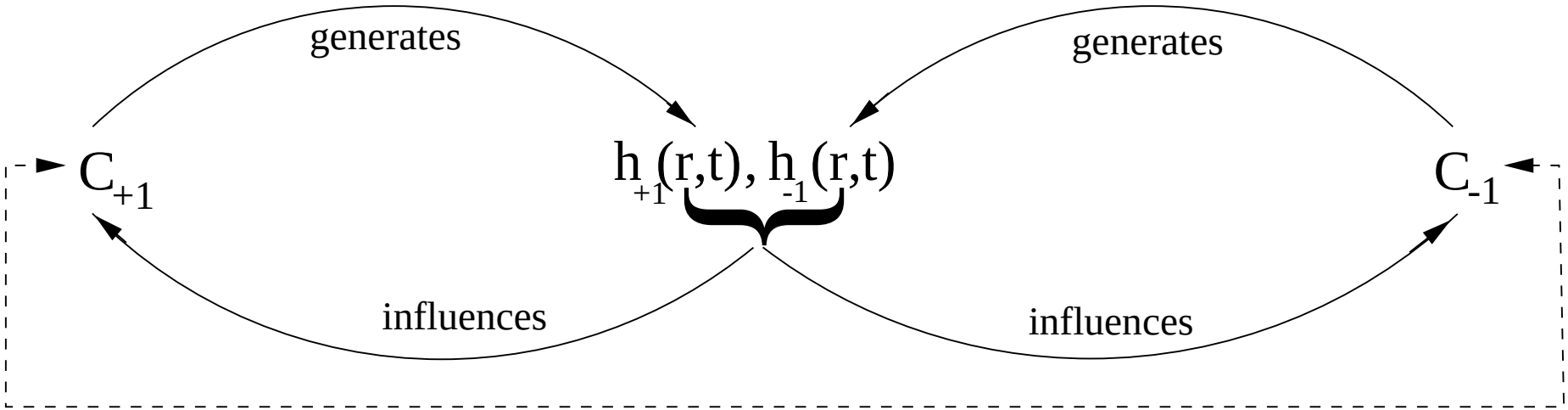
  - depends on information about decisions of other agents
    $\Rightarrow h_\theta(\boldsymbol{r}_i, t)$
  - η: defines time scale
  - T: "social temperature"
    measures *randomness* of social interaction
    $T \to 0$: deterministic behavior

Spatio-temporal communication field

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

- multi-component scalar field reflects:
  - existence of *memory* (past experience)
  - *exchange of information* with *finite* velocity
  - influence of *spatial distances* between agents
    $\Rightarrow$ *weighted* influence (space, time)

non-linear feedback:



Fast Information Exchange

- no spatial heterogeneity $\Rightarrow$ mean-field approach
- mean communication field: ($s_i \to s_\theta$)

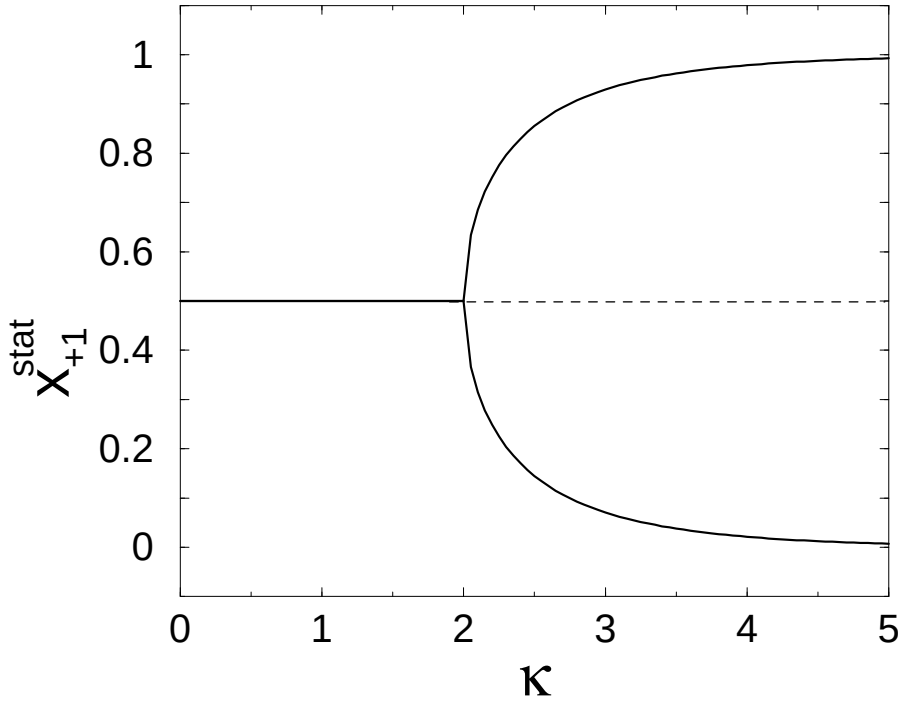
$$\frac{\partial \bar{h}_\theta(t)}{\partial t} = -k_\theta \bar{h}_\theta(t) + s_\theta \bar{n}_\theta$$

- 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:



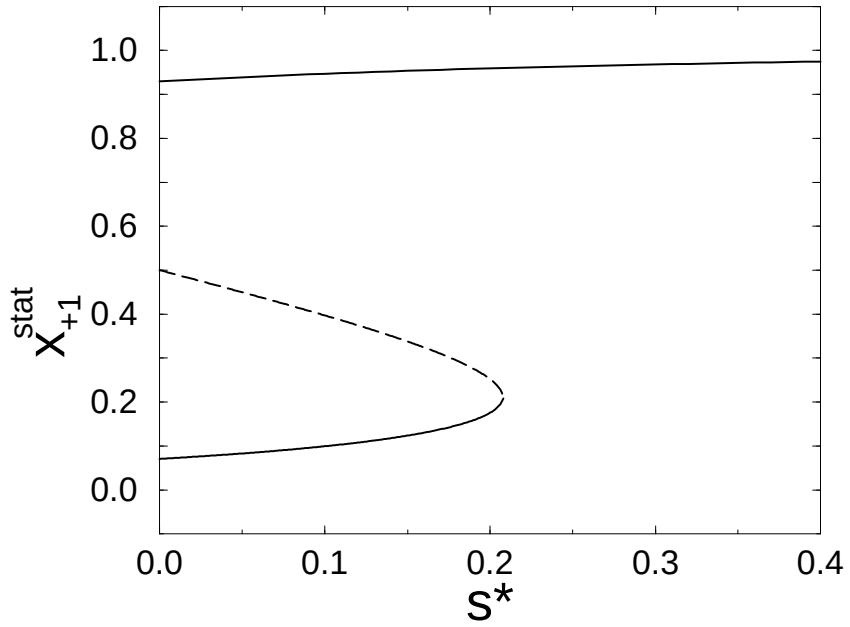
$$\kappa = \frac{2s\,N}{A\,k\,T} = 2 \Rightarrow \text{critical population size: } N^c = \frac{k\,A\,T}{s}$$

Emergence of minority and majority

How to break the symmetry?

1. Influence of external support

- examples: strong leader, influence of government policy, mass media, ...
  $\Rightarrow$ additional contribution: $s^\star$

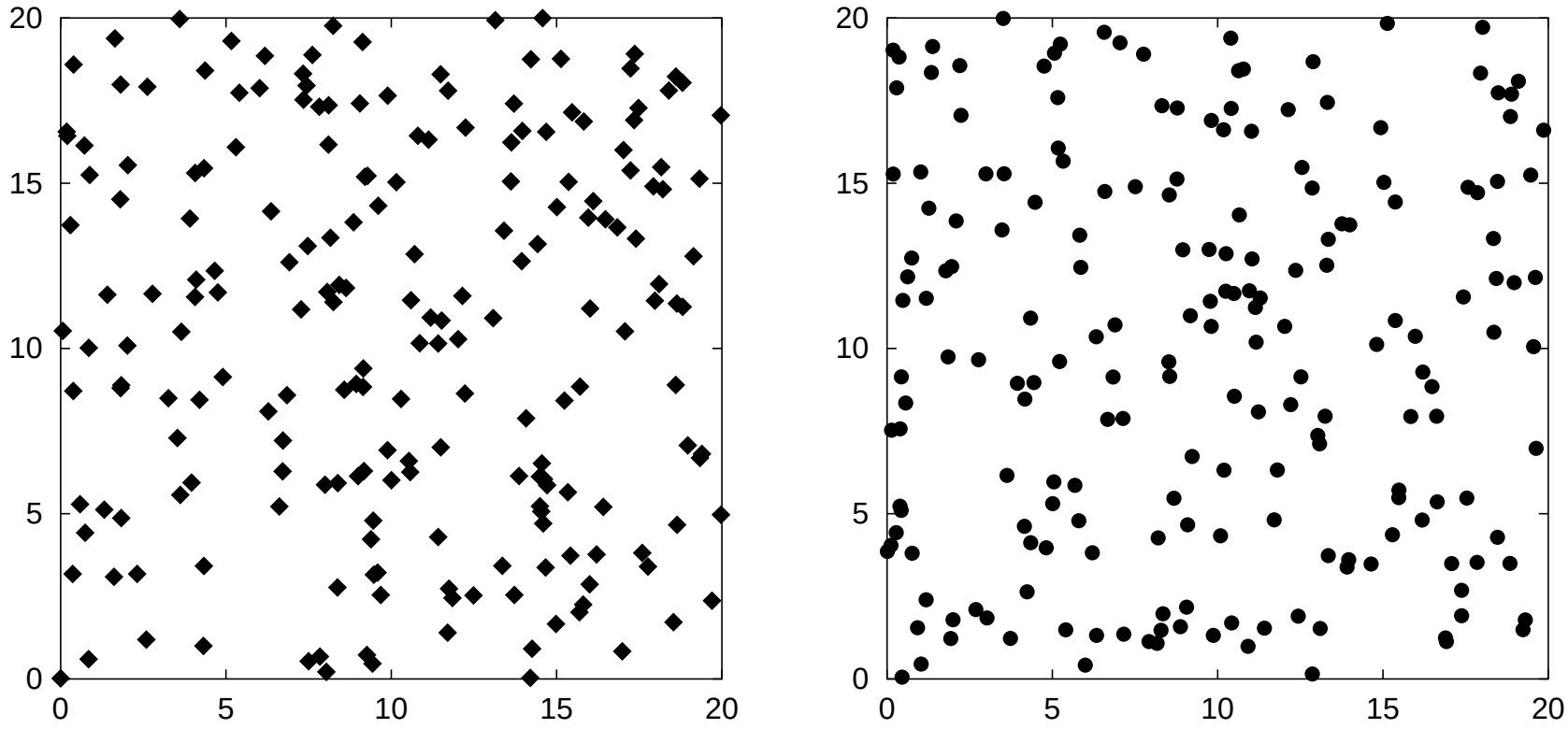


result:

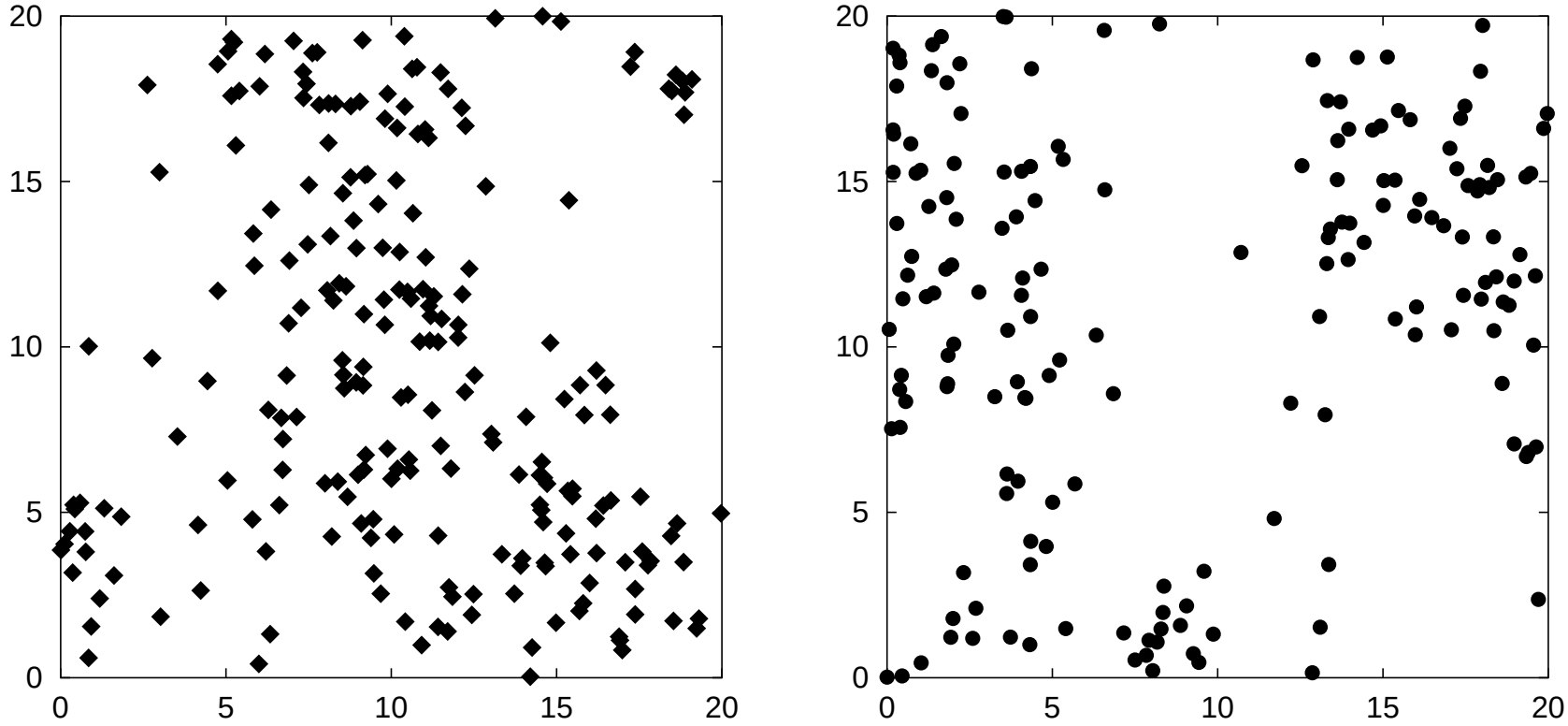
- possibility of minority status vanishes
- no chance for the opposition
- "fundamentalistic dictatorships", "banana republics"

Spatial Influences on Decisions

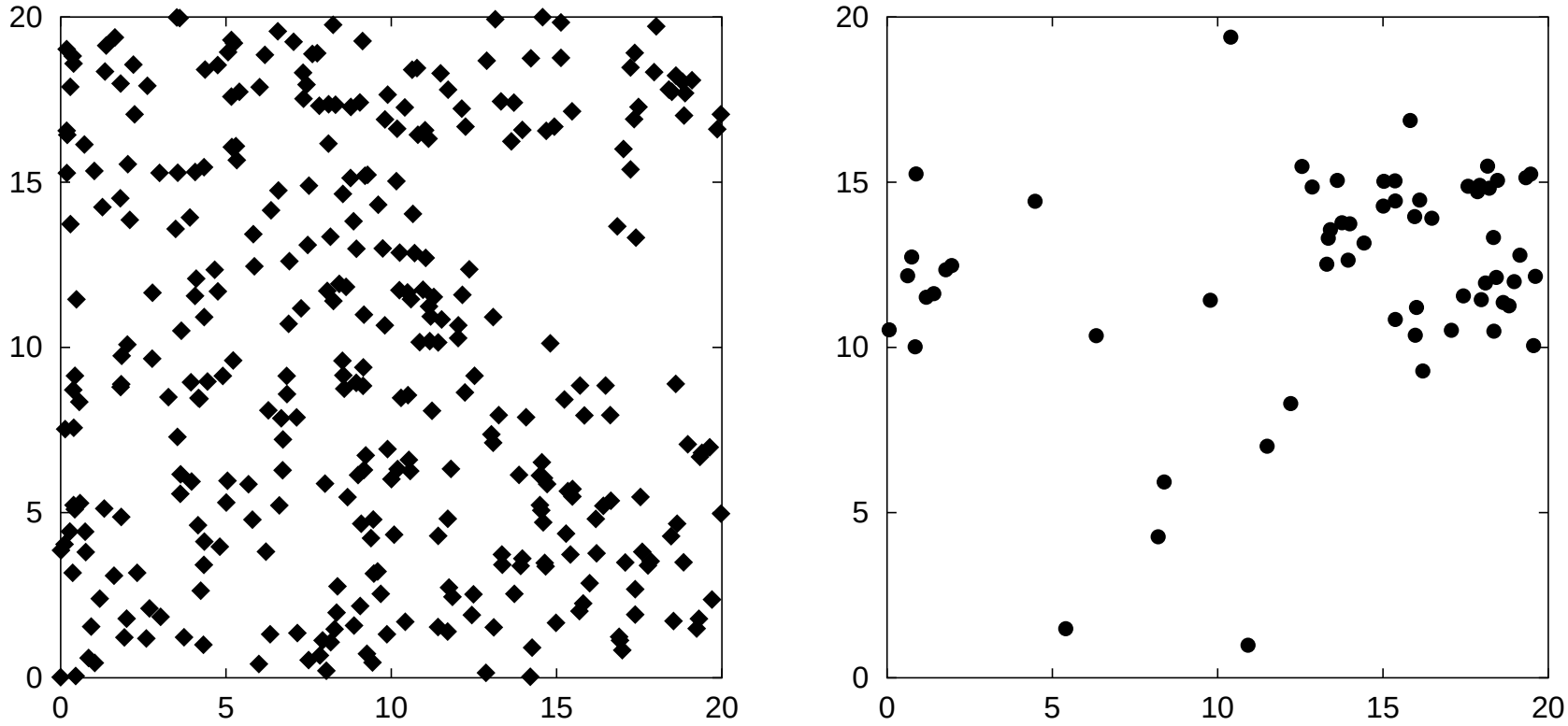
$$s_{+1} = s_{-1} \equiv s,\ k_{+1} = k_{-1} \equiv k,\ D_{+1} = D_{-1} \equiv D$$



$$t = 10^0$$



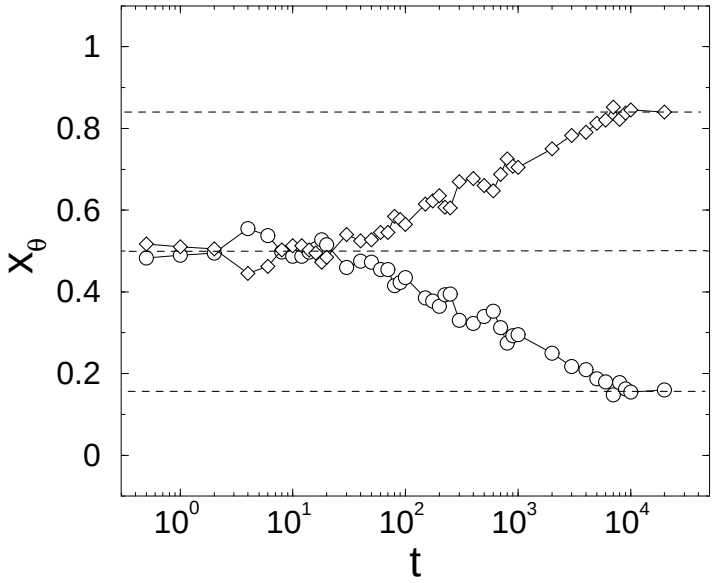
$t = 10^2$

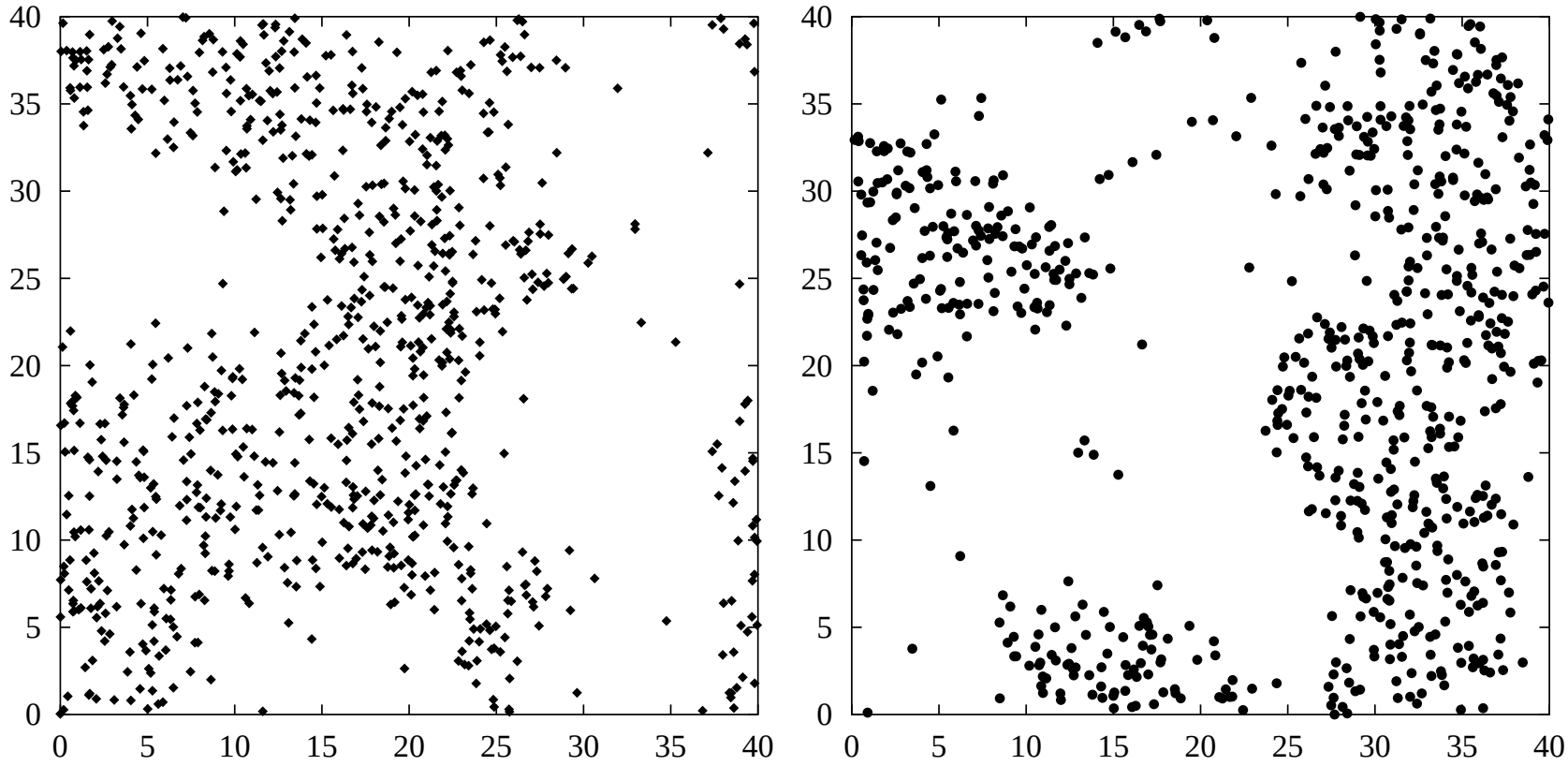


$t = 10^4$

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

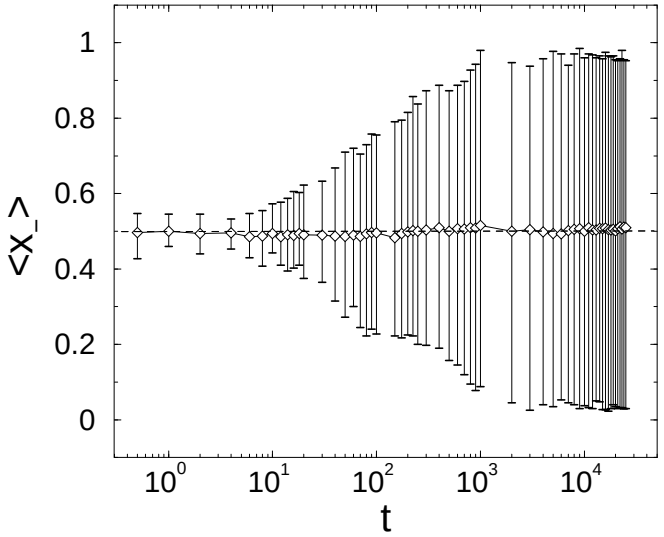




System size: $A = 1600$, total number of agents: $N = 1600$, time: $t = 5 \cdot 10^4$, frequency: $x_+ = 0.543$

Results: (closer inspection)

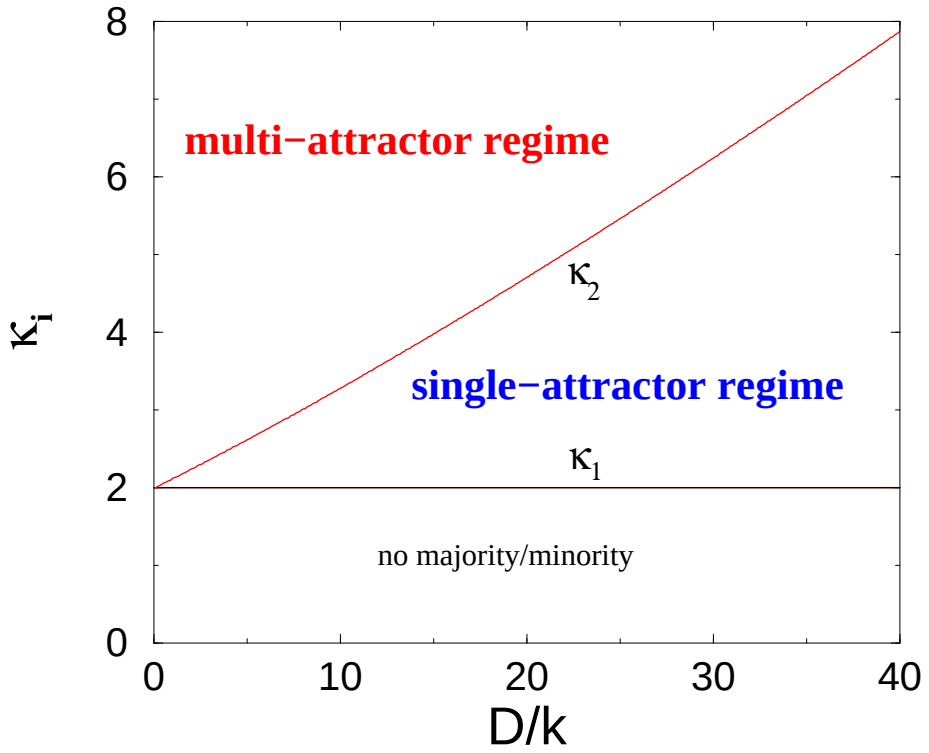
- *single-attractor regime:* fixed minority/majority relation
- *multi-attractor regime:* variety of spatial patterns
  almost every minority/majority relation may be established



- 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

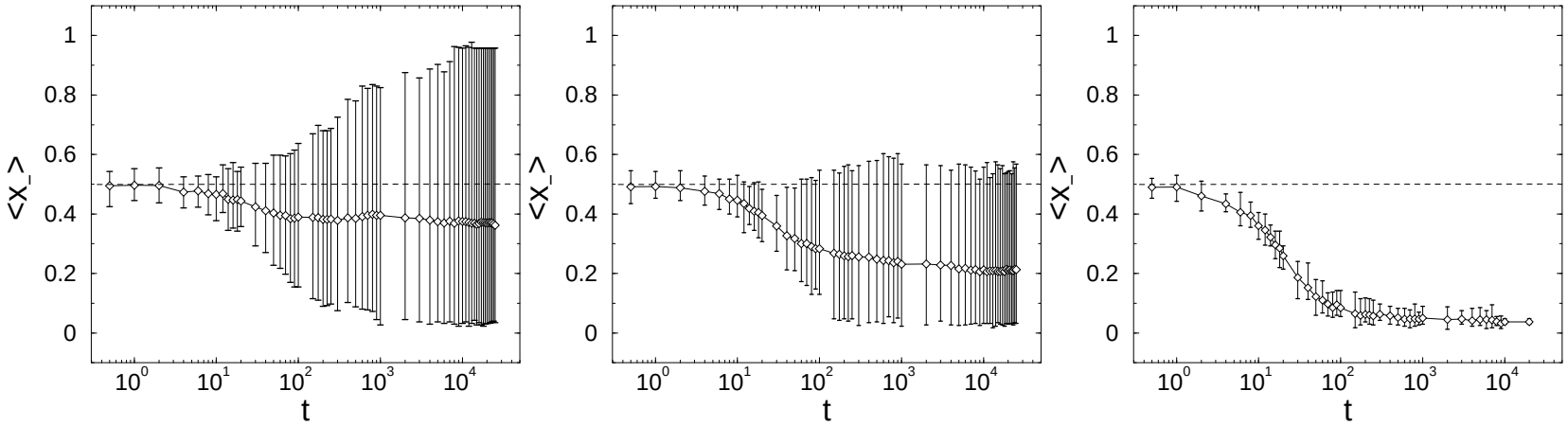
$\Rightarrow$ system "globalized" by ruling information

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

How to break the symmetry?

2. 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

- based on dissemination of information
  $\Rightarrow$ spatial model of communicating (Brownian) agents (BA)
- *emergence*: spatial domains of likeminded agents, majority/minority
- multi-attractor regime: multiple outcome
- "effi cient" 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 fi gs)

“Every theory, whether in the physical or biological or social sciences, distorts reality in that it oversimplifi es. But if it is a good theory, what is omitted is outweighted by the beam of light and understanding thrown over the diverse facts.”

PAUL A. SAMUELSON