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Communication and Self-Organization in Complex Systems: A Basic Approach

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in collaboration with:

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Schedule

1. Multi-Agent Systems
2. Model of Communicating Agents
3. Spatial Coordination of Decisions
4. Conclusions

Complex System

"By complex system, it is meant a system comprised of a (usually large) number of (usually strongly) interacting entities, processes, or agents, the understanding of which requires the development, or the use of, new scientific tools, nonlinear models, out-of equilibrium descriptions and computer simulations."

Journal "Advances in Complex Systems"

Multi-Agent Systems (MAS)

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agent:

➤ subunit with “intermediate” complexity

⇒ may represent local processes, individuals, species, agglomerates, components, ...

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multi-agent system:

➤ *large number* / *different types* of agents

➤ interactions between agents:

- on *different spatial and temporal scales*
- local / direct interaction
- global / indirect interactions (coupling via resources)

- "bottom-up approach": no universal equations
  $\Rightarrow$ self-organization, *emergence* of system properties
- external influences (boundary conditions, in/outflux)
- coevolution, circular causality

Complex Agent

Complex Agent

- autonomous; knowledge based / behavior based rules
- performs complex actions: BDI, rational choices, ...
- specialization, learning, genetic evolution, ...

1. Problem: information flow

“rational agent” (economics):

- ➤ complete knowledge of all possible actions and their outcomes (or known probability distribution over outcomes)
- ➤ common knowledge assumtion

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2. Problem: combinatoric explosion of the state space

- 1000 Agents with 10 rules $\Rightarrow 10^{13}$ possibilities
- *Solution:*
  restrict interactions $\Rightarrow$ control of information flow
  personally addressed interaction instead of "broadcasting"
- *freedom:* define rules *and* interactions $\Rightarrow$ *pitfall*

Minimalistic Agent

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- possible simplest set of rules $\Rightarrow$ “sufficient” complexity (depends on the system considered)

- *functional information:* simple *algorithm*, which is steadily repeated
- *structural information:* external information (*data*) received by the agent

Minimalistic Agent

- possible simplest set of rules ⇒ “sufficient” complexity (depends on the system considered)

- *functional information:* simple *algorithm*, which is steadily repeated
- *structural information:* external information (*data*) received by the agent
- *pragmatic information:* ⇒ effective information
  - emerges from the processing of the data by the algorithm
  - specific for each agent ⇒ enables actions, decisions

Model of Communicating Agents

- community of N agents, spatially distributed
- agent i:
  - (continuous) position: $\boldsymbol{r}_i$ (2 dim)
  - (discrete) “opinion”: θ_i (internal degree of freedom)

Model of Communicating Agents

- community of N agents, spatially distributed
- agent i:
  - (continuous) position: $\boldsymbol{r}_i$ (2 dim)
  - (discrete) "opinion": θ_i (internal degree of freedom)
- *example*: recycling campaign:
  "take part" (θ_i=+1) $\Longleftrightarrow$ "drop out" (θ_i=-1)
- two (opposite) opinions $\Rightarrow$ *binary choice problem*

Decisions

“classical” economic approach: utility function

- agent i tries to maximize her private utility
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- "common knowledge assumption"
- *problems:* equilibrium ??? communication ???

Our Approach:

- decisions depend on information:
  incomplete, spatially distributed (*non-uniform*)
- influences of random events, delays, ...

Our Approach:

- decisions depend on information:
  incomplete, spatially distributed (*non-uniform*)
- influences of random events, delays, ...
- assumption: agent i more likely does what others do
- problem of communication, neighbourhood
  mean-field approach: neglects local effects (non-uniformity)
  nearest-neighbour interactions: neglects non-local effects

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 *spatial* distances between agents
- permanent *local* individual contribution: s_i
- information generated has a certain life time, $1/k_\theta$
- information can spread throughout the system, D_θ
- different information $\Rightarrow$ different s_i, k_θ, D_θ

Communication field reflects:

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

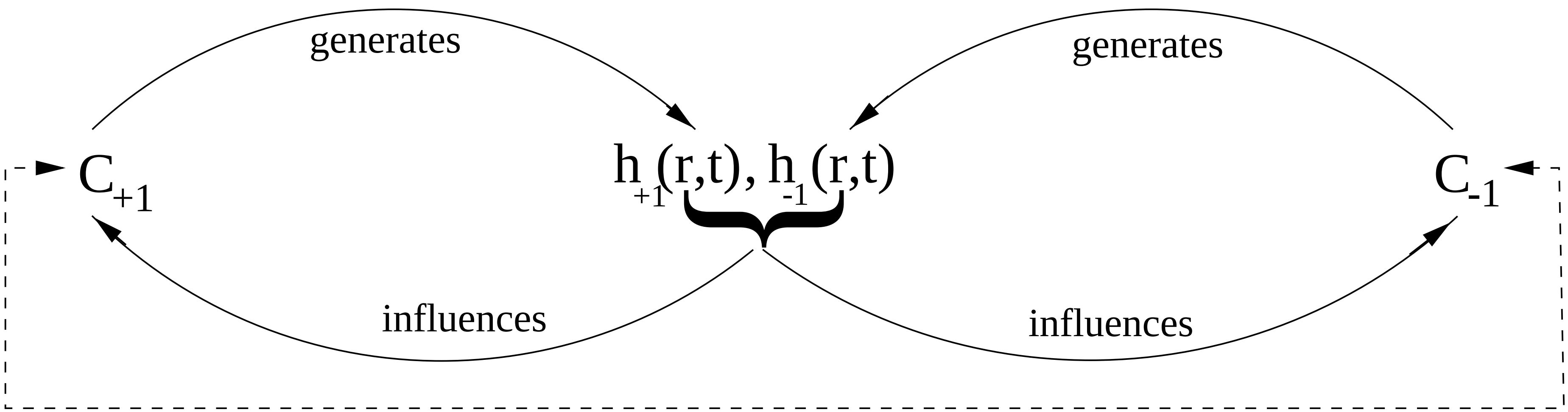
Decision of Agent i:

- binary choice: to change or to keep "opinion" θ_i
- depends on information about decisions of other agents

$$w(\theta_i'|\theta_i) = \eta \, \exp\left\{ -\frac{h_\theta(\boldsymbol{r}_i,t) - h_{\theta'}(\boldsymbol{r}_i,t)}{T} \right\}$$

- η: defines time scale
- T: "social temperature"
  measures *randomness* of social interaction
  $T \to 0$: deterministic behavior
- probabilistic approach: master equation for
  $P(\underline{\theta}, \underline{r}, t) = P(\theta_1, \boldsymbol{r}_1, ..., \theta_N, \boldsymbol{r}_N, t)$

non-linear feedback:



Mean-Field Approach

- fast information exchange $\Rightarrow$ no spatial inhomogeneities
- mean communication field: ($s_i \longrightarrow s_\theta$)

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

- subpopulations:

$$\bar{n}_\theta(t) = \frac{N_\theta}{A} \; ; \quad x_\theta(t) = \frac{N_\theta(t)}{N}$$

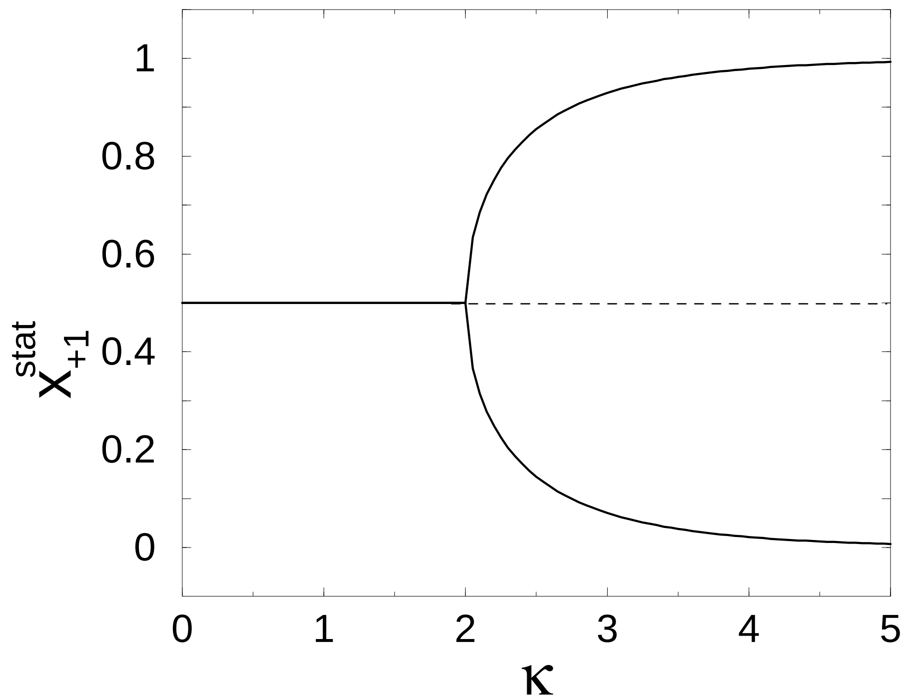
- stationary states: $\dot{x}_\theta = 0$, $\dot{h}_\theta = 0$

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

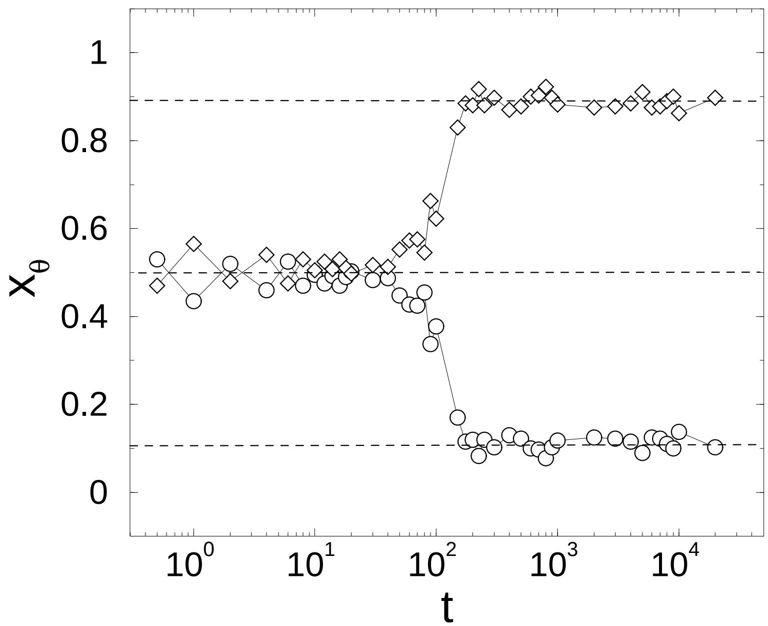
Bifurcation diagram:

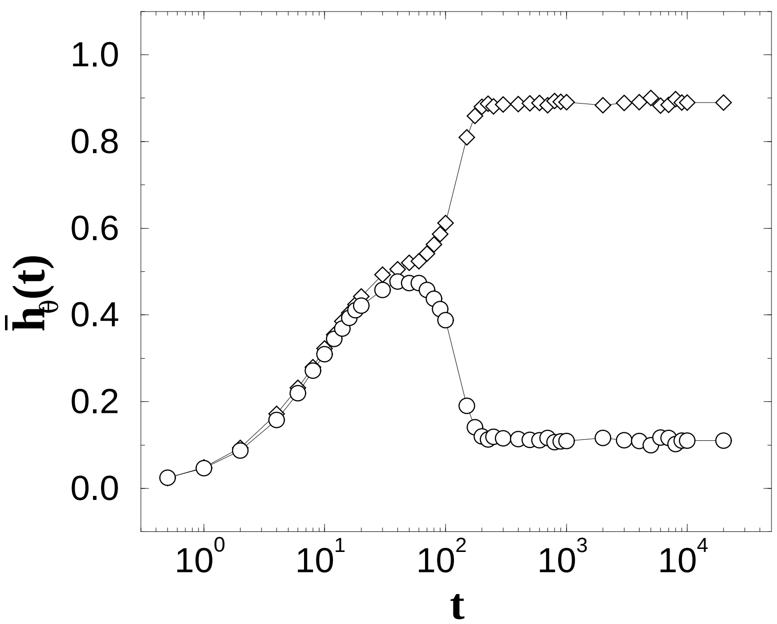


$$\kappa = \frac{2s\,N}{A\,k\,T} = 2 \Rightarrow \text{critical population size: } N^c = \frac{k\,A\,T}{s}$$

Emergence of minority and majority

Results of Computer Simulations





Computer simulation of the relative subpopulation sizes x_{+1} ($\circ$) and x_{-1} ($\Diamond$) vs. time t for a community of $N = 400$ agents. Initially, each agent has been randomly assigned opinion $+1$ or -1.

Parameters: $A = 400$, $s = 0.1$, $k = 0.1$, $T = 0.75$, i.e. $\kappa = 2.66$.

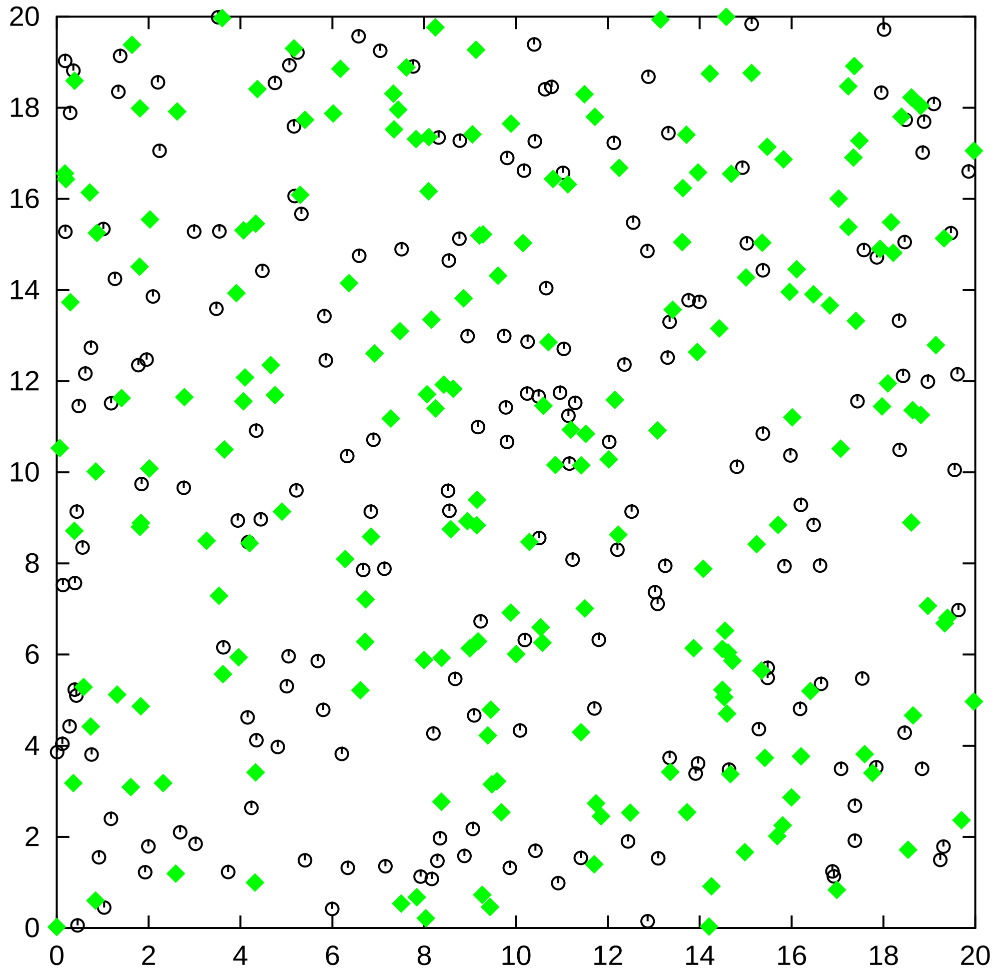
The dashed lines indicate the equilibrium distribution ($x_\theta = 0.5$) and the minority and majority sizes ($x_\theta = \{0.115; 0.885\}$).

Spatial Coordination of Decisions

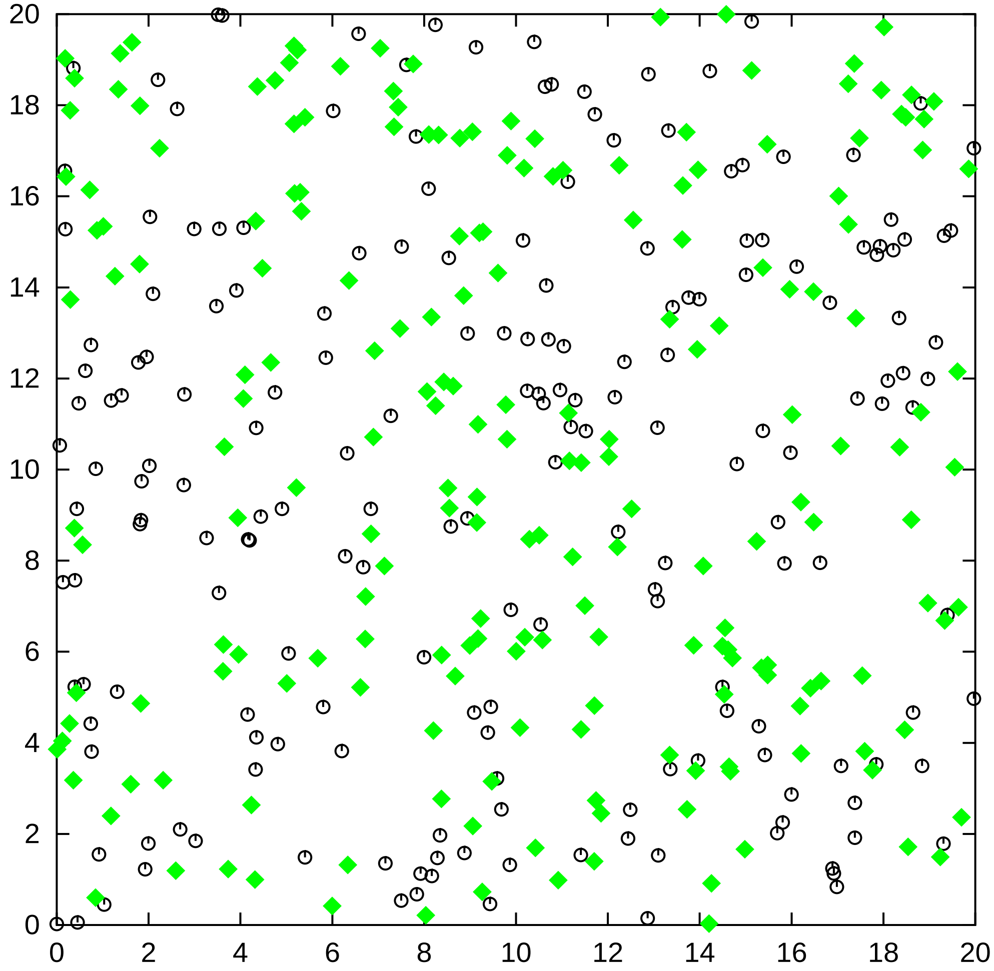
1. Case:

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

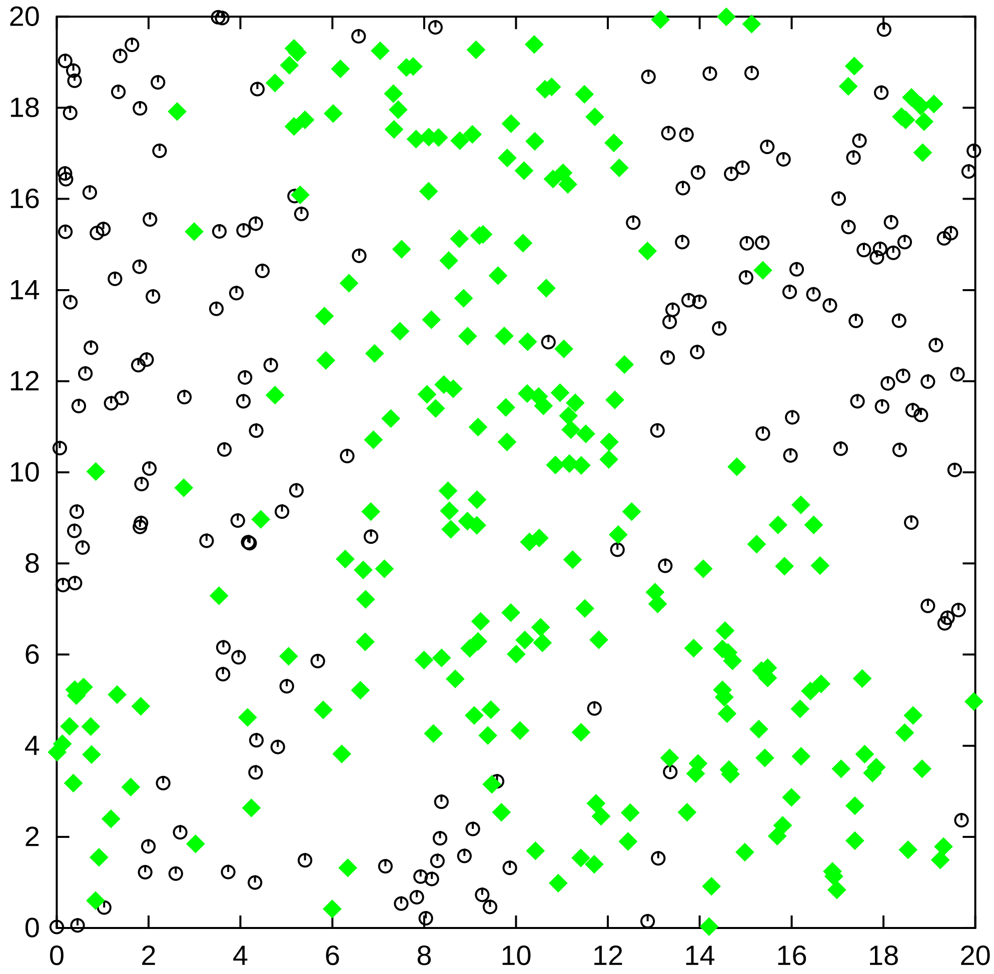
$\Rightarrow$ *Snapshots of Computer Simulations*



$t = 10^0$



$$t = 10^1$$



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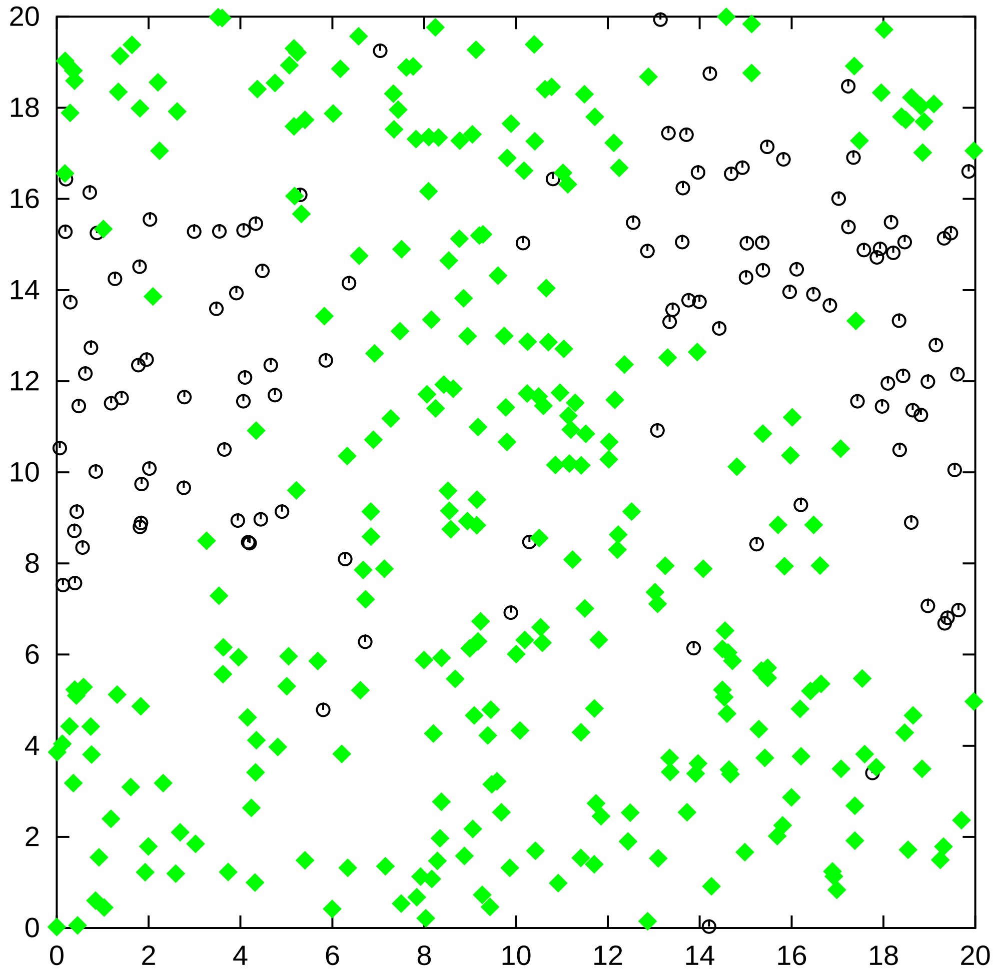
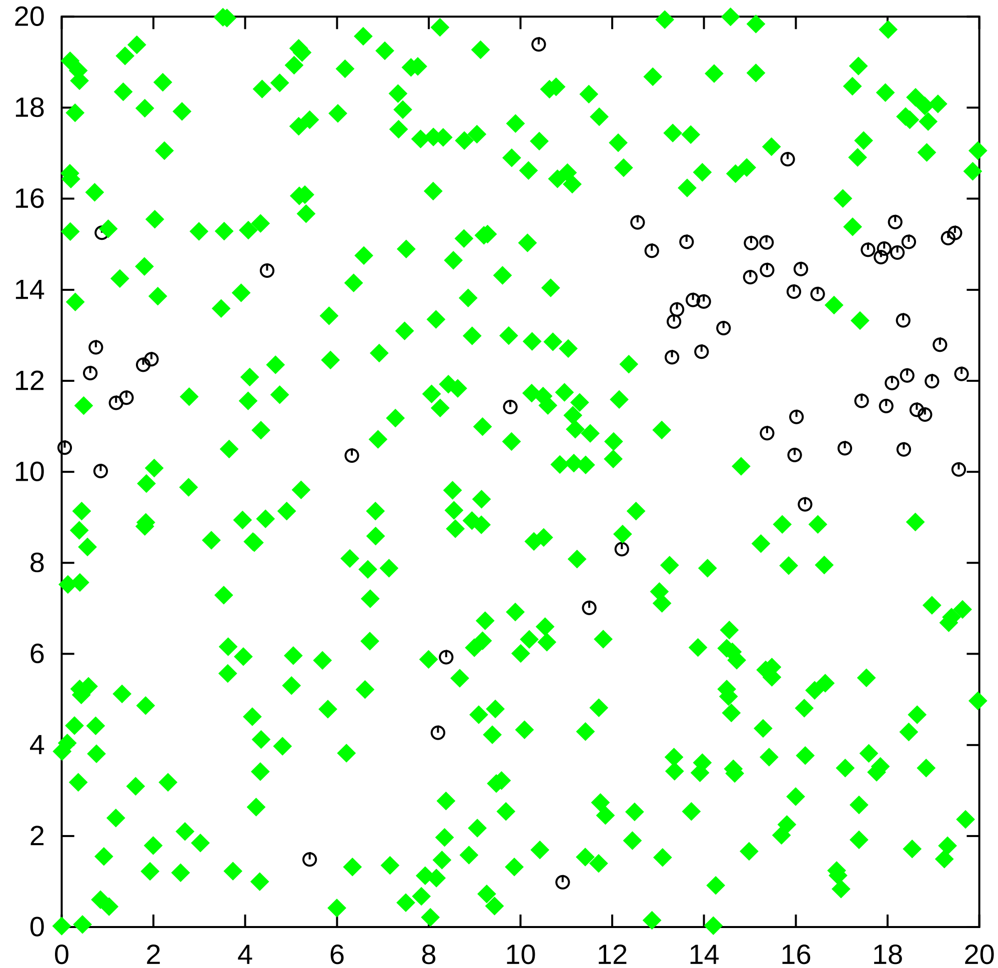
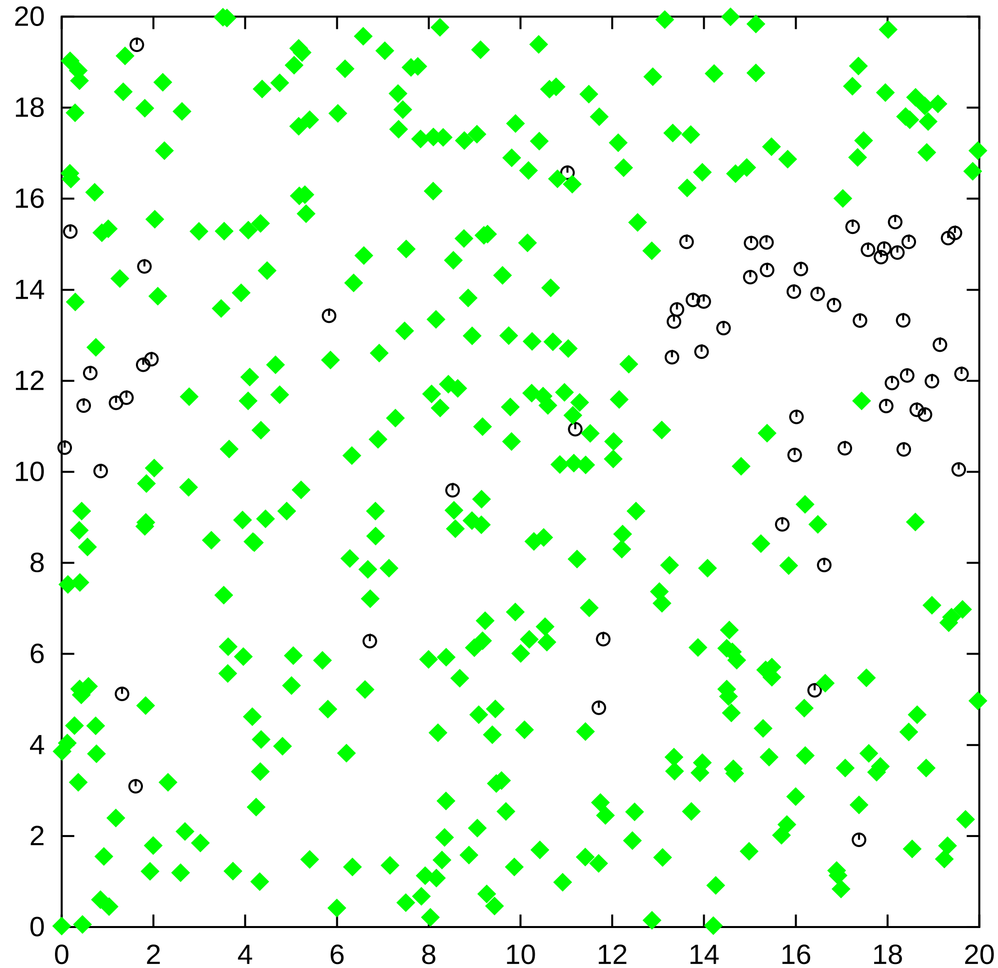


$t = 10^3$



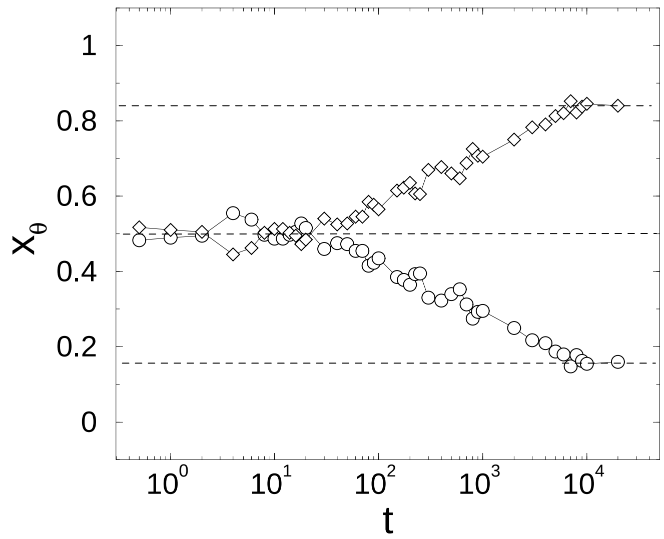
$t = 10^4$



$$t = 2 \cdot 10^4$$

Results:

1. emergence of minority and majority

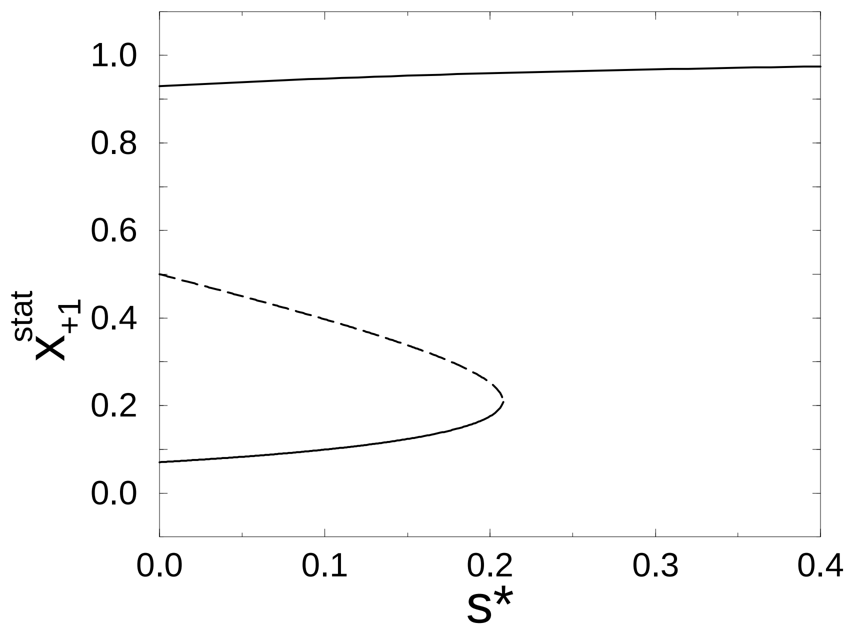


2. *spatial* coordination of decisions:
   $\Rightarrow$ concentration of agents with the same opinion
3. random events decide about minority/majority status
   of e.g. $\theta = +1$

How to break the symmetry?

1. Influence of external support

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



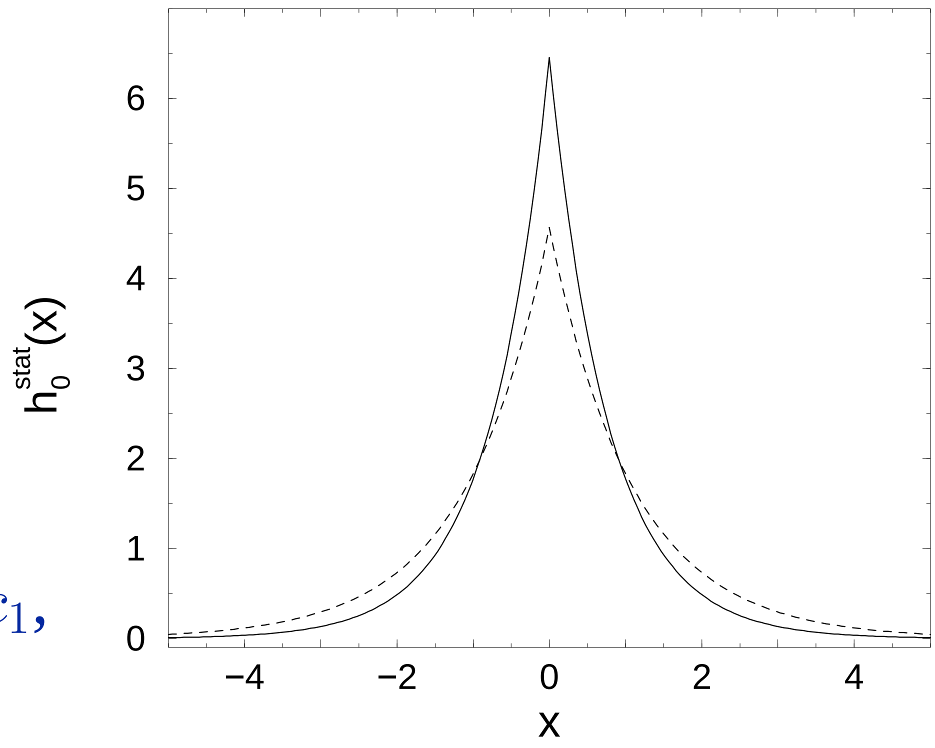
result:

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

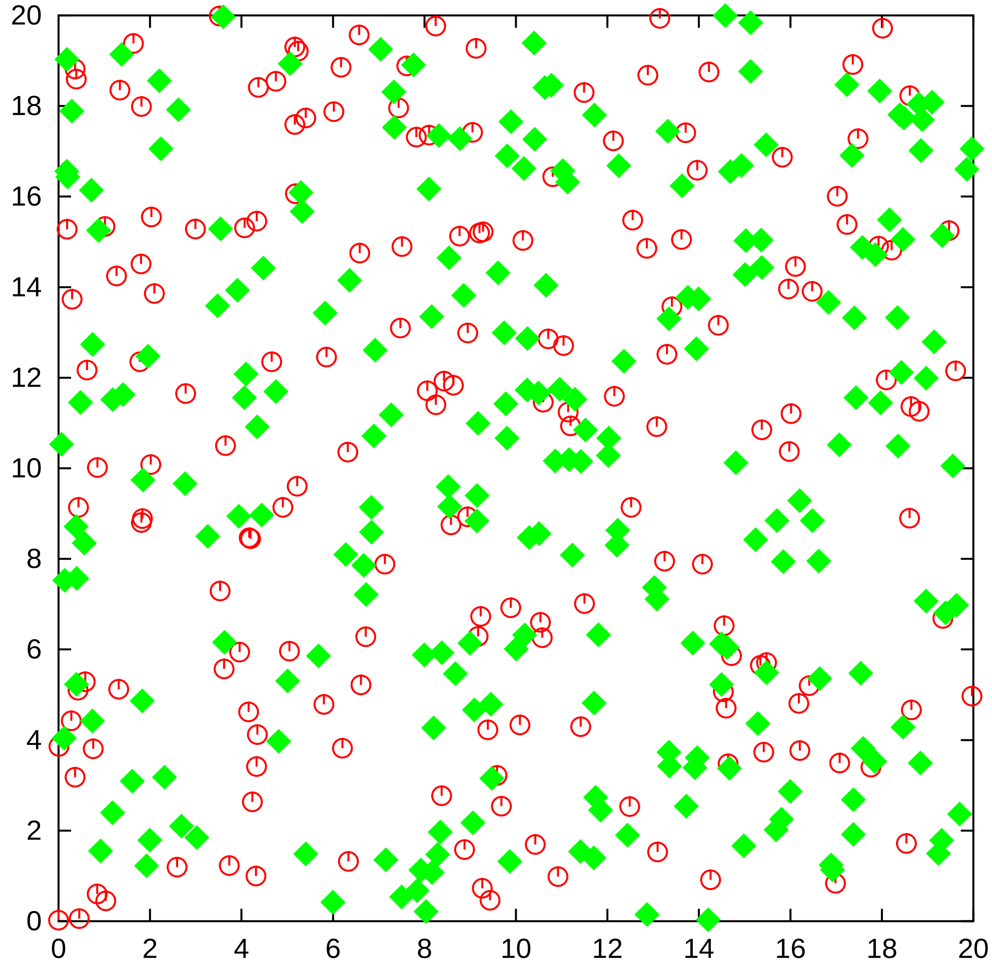
How to break the symmetry?

2. Influence of information exchange

- speed up information exchange $\Rightarrow D_{+1} > D_{-1}$
- problem: adjustment of parameters



- **2. Case:**
  $D_{+1}/s_{+1} = D_{-1}/s_{-1} \equiv c_1,$
  $k_{+1}/s_{+1} = k_{-1}/s_{-1} \equiv c_2$



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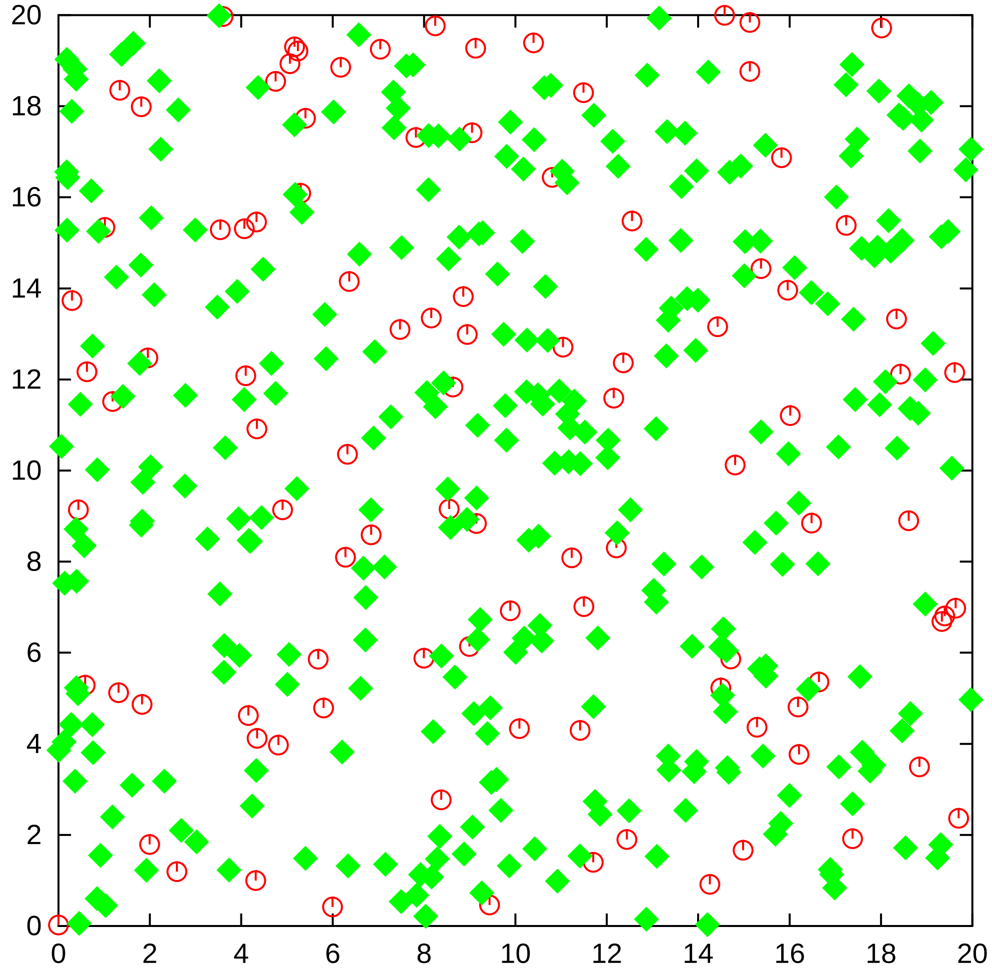

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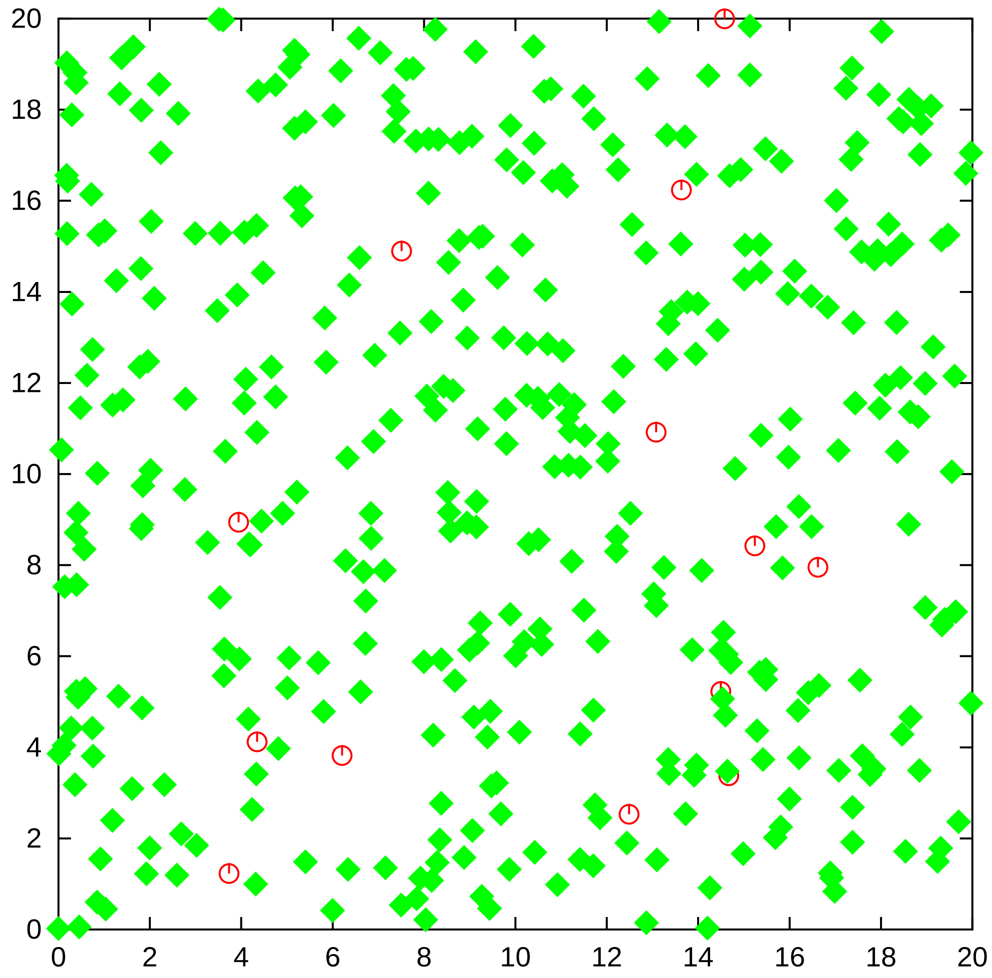

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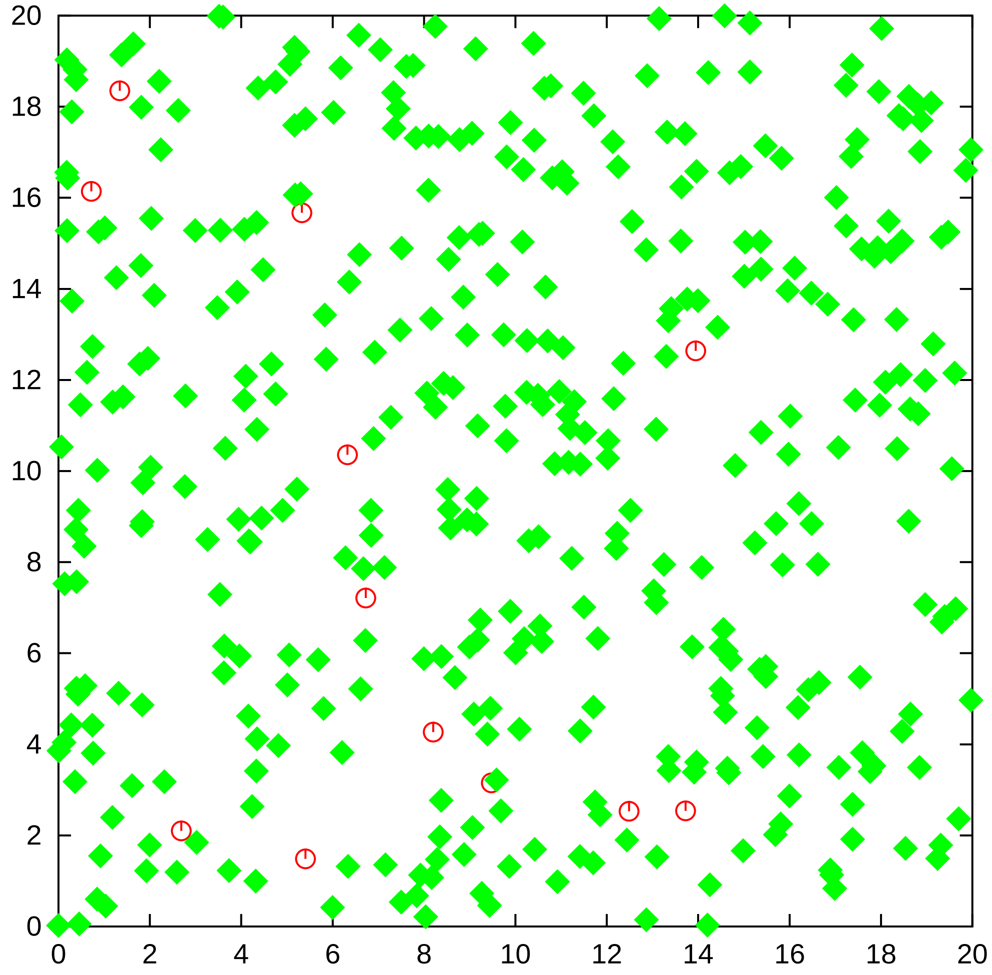

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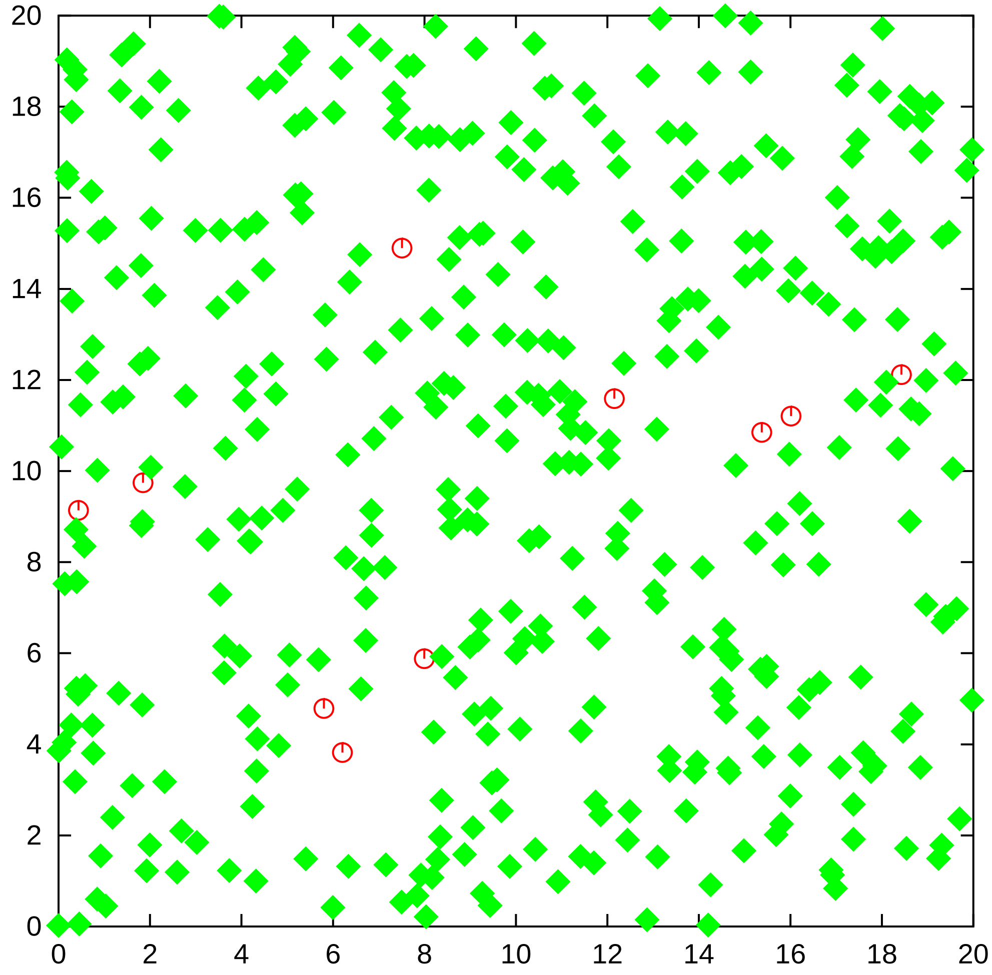

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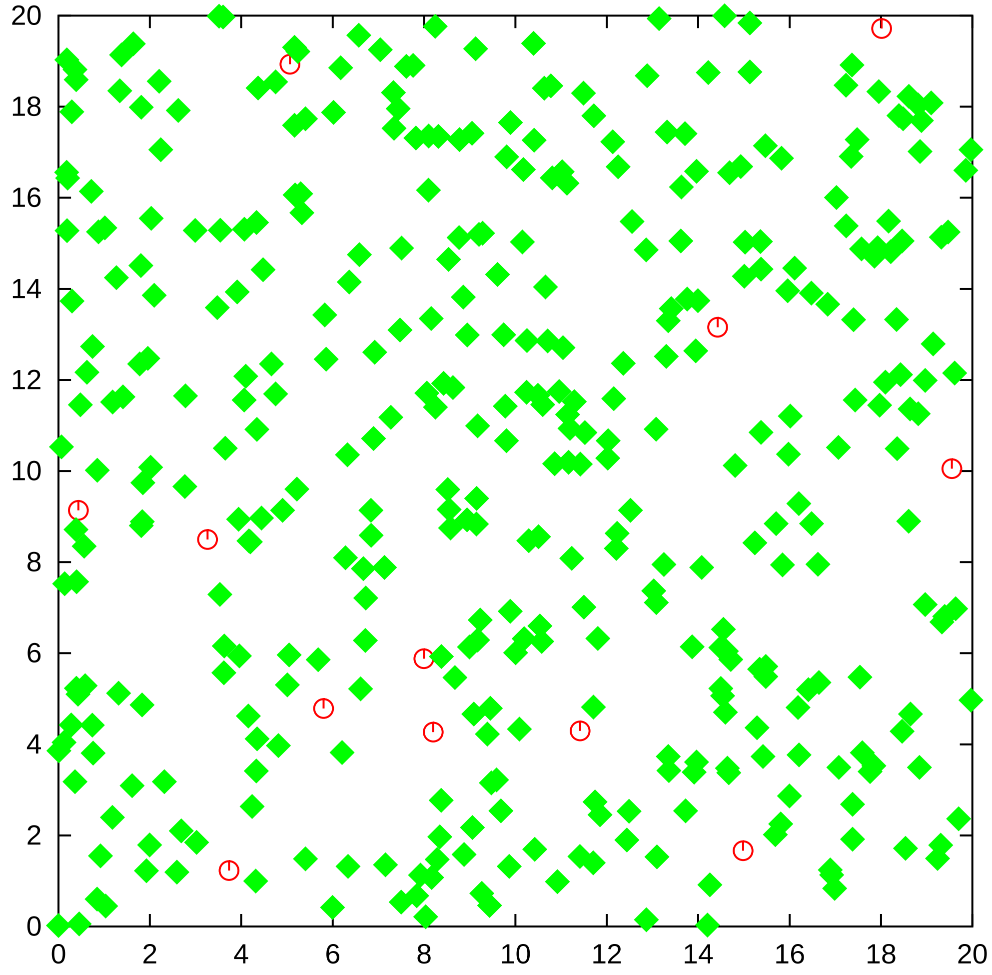

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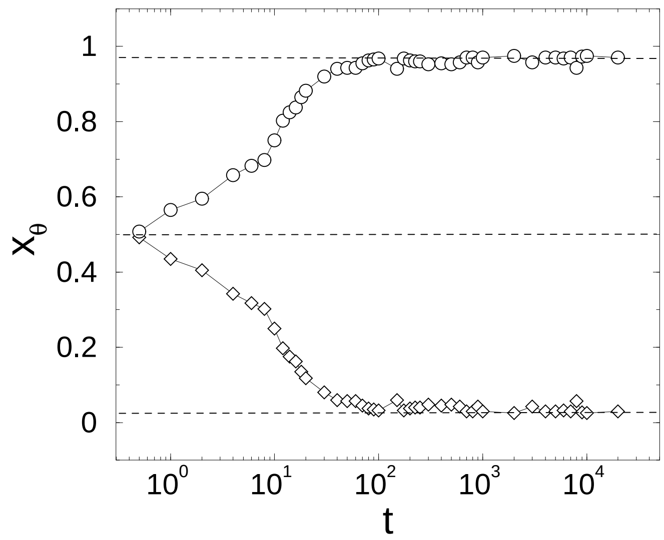

2. *no* spatial coordination of the minority
3. subpopulation with the more efficient communication becomes “always” the majority

Migration

- additional possibility to act
- movement depends on:
  ⇒ erratic circumstances
  ⇒ influence of information from supporters and opponents

Migration

- additional possibility to act
- movement depends on:
  $\Rightarrow$ erratic circumstances
  $\Rightarrow$ influence of information from supporters and opponents
- stochastic approach:

$$\frac{d\boldsymbol{r}_i}{dt} = \alpha_i \left. \frac{\partial h^e(\boldsymbol{r},t)}{\partial \boldsymbol{r}} \right|_{\boldsymbol{r}_i} + \sqrt{2\,D_n}\,\xi_i(t)$$

- $h^e(\boldsymbol{r},t)$: *effective* communication field $\Longleftrightarrow h_\theta(\boldsymbol{r},t)$

  α_i: individual response parameter

  D_n: spatial diffusion coefficient of the agents

Different Possibilities:

- migration towards supportive locations:

$$\nabla_i h^e(r,t) \rightarrow \nabla_i h_\theta(r,t)\,,\;\; \alpha_i > 0$$

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- migration depenent on dominance:

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- migration only above a certain threshold h_0:

$$\alpha_i = \Theta[h^e(r,t) - h_0]\,,\;\; \Theta[y] = 1 \text{ only if } y > 0$$

Migration *and* Opinion Change:

- response to information of like-minded

$$\nabla_i h^e(r,t) \to \nabla_i h_\theta(r,t)\,,\ \alpha_i > 0$$

- $D_\theta = 0$: information exchange due to migrating agents
- variable of interest: *social temperature* T

$$T_1^c = \frac{s\,\bar{n}}{k}\,; \quad T_2^c = \frac{\alpha}{2\mu}\,\frac{s\,\bar{n}}{k} = \frac{\alpha}{2\mu}\,T_1^c$$

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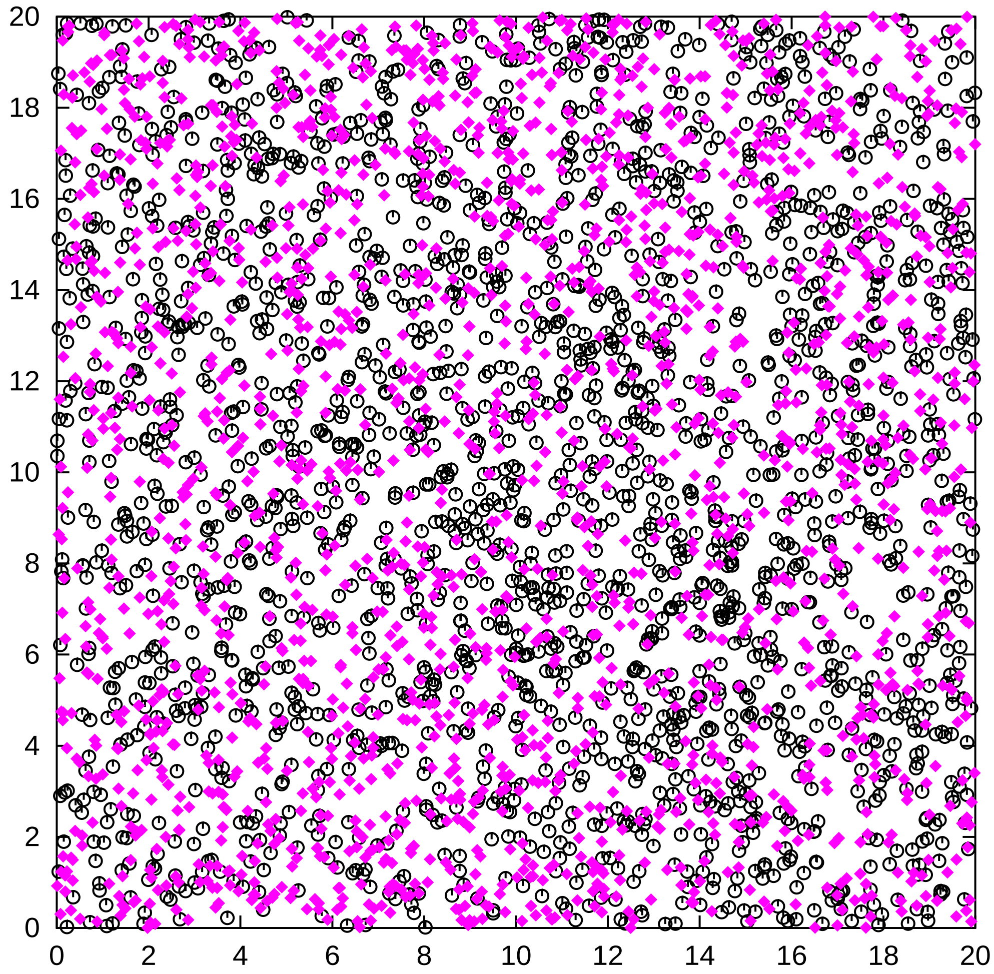
Results of Computer Simulations:

1. $T_2 < T < T_1$: "phase transition"
   $\Rightarrow$ emergence of minority and majority, spatial aggregation
2. $T < T_2$: "phase separation"
   $\Rightarrow$ segregation and spatial aggregation



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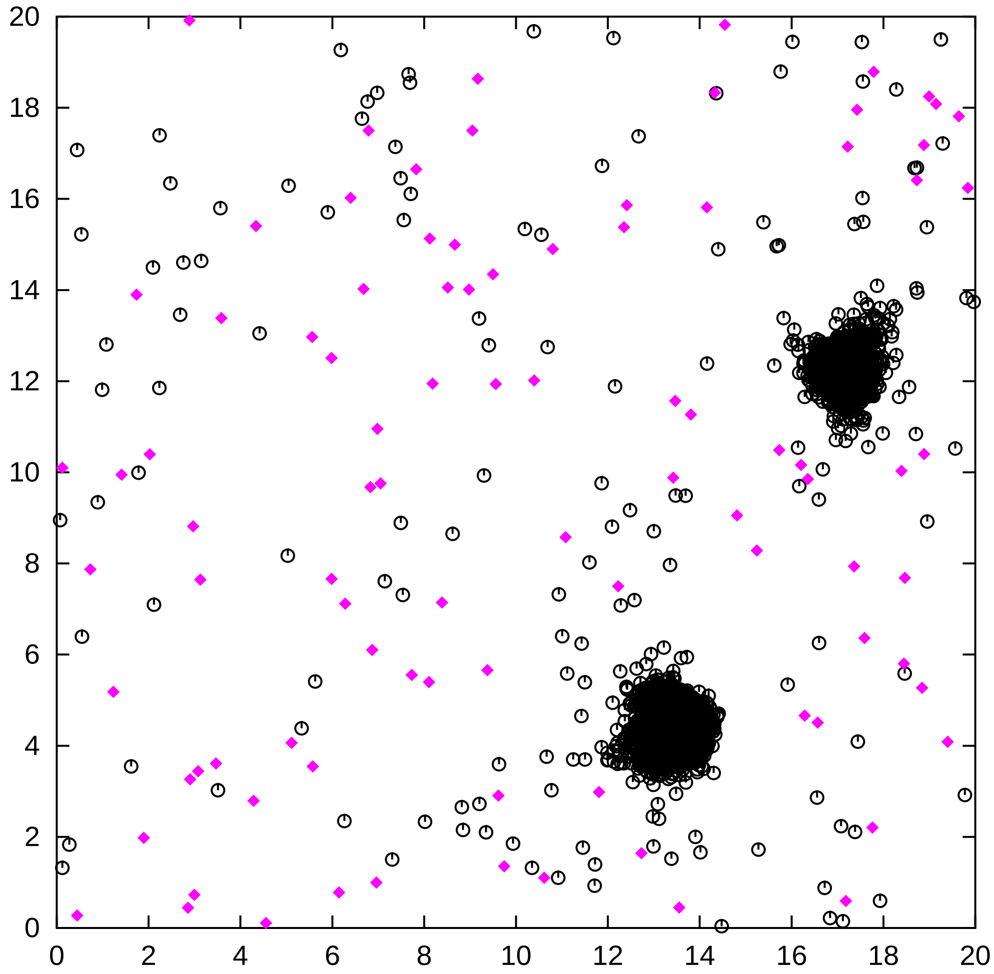

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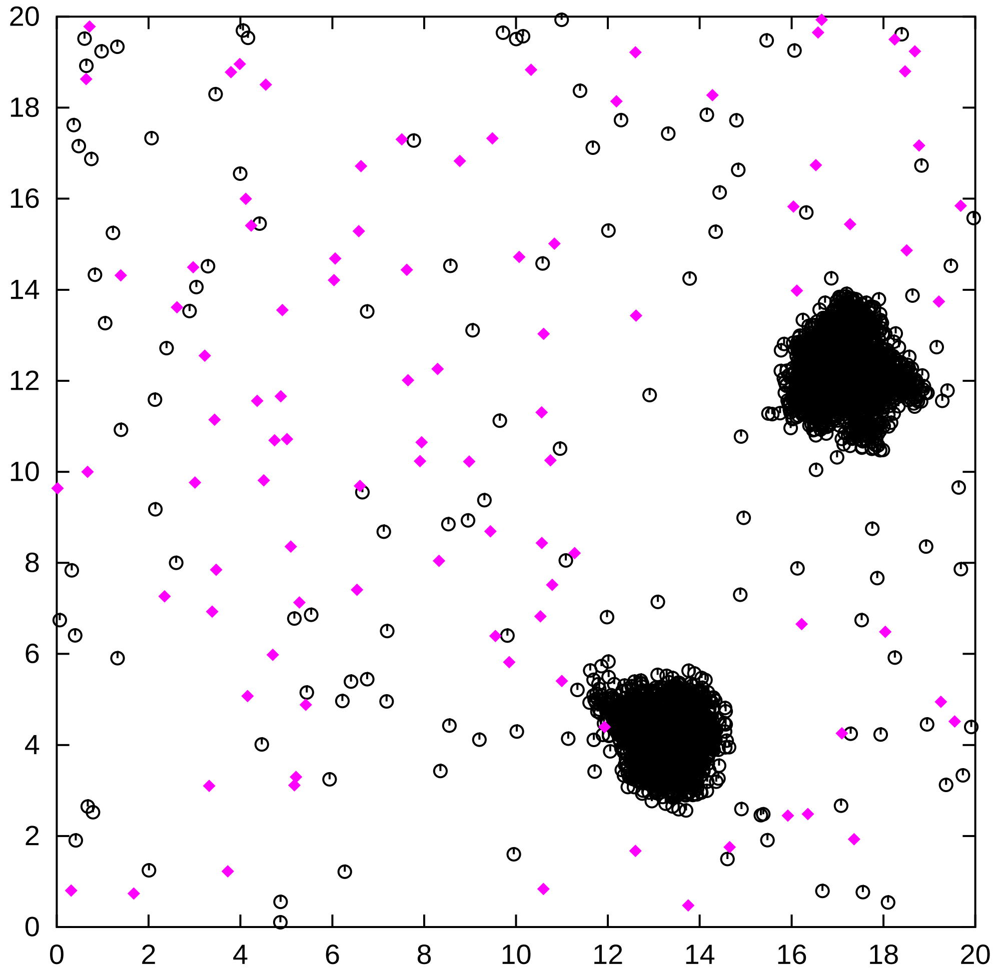

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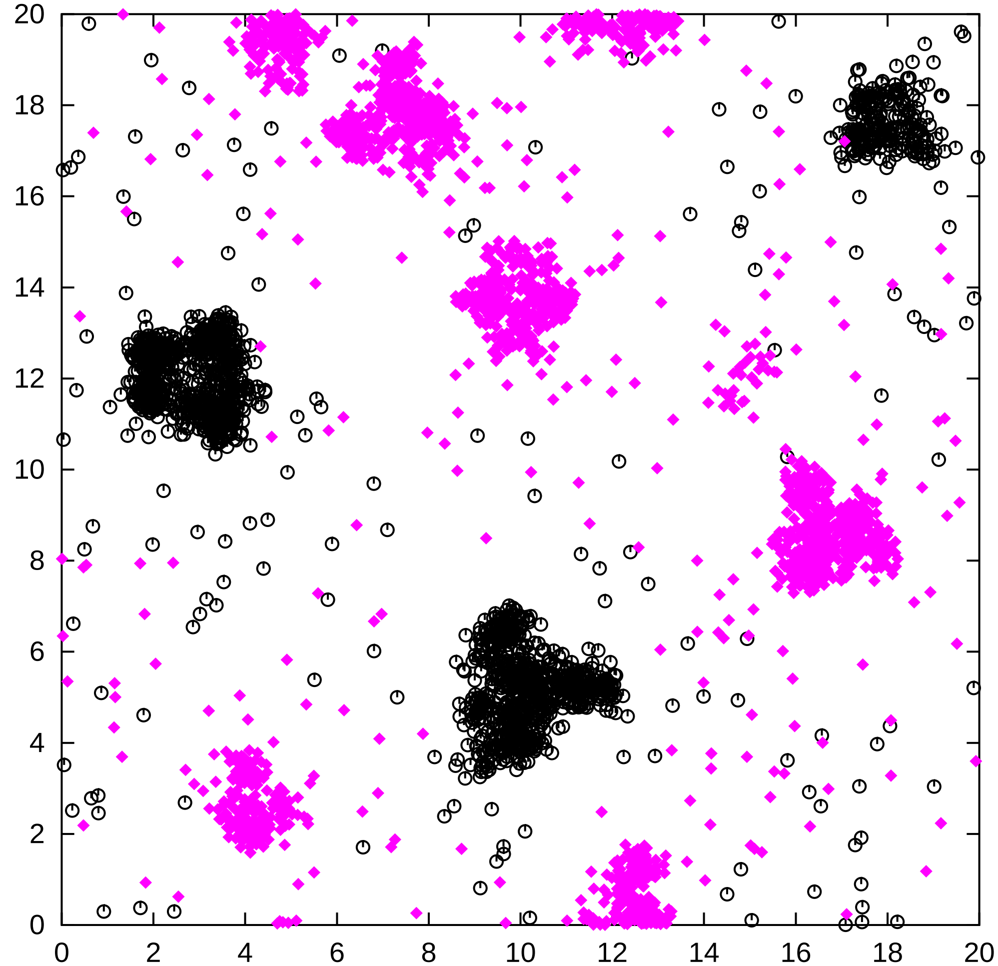

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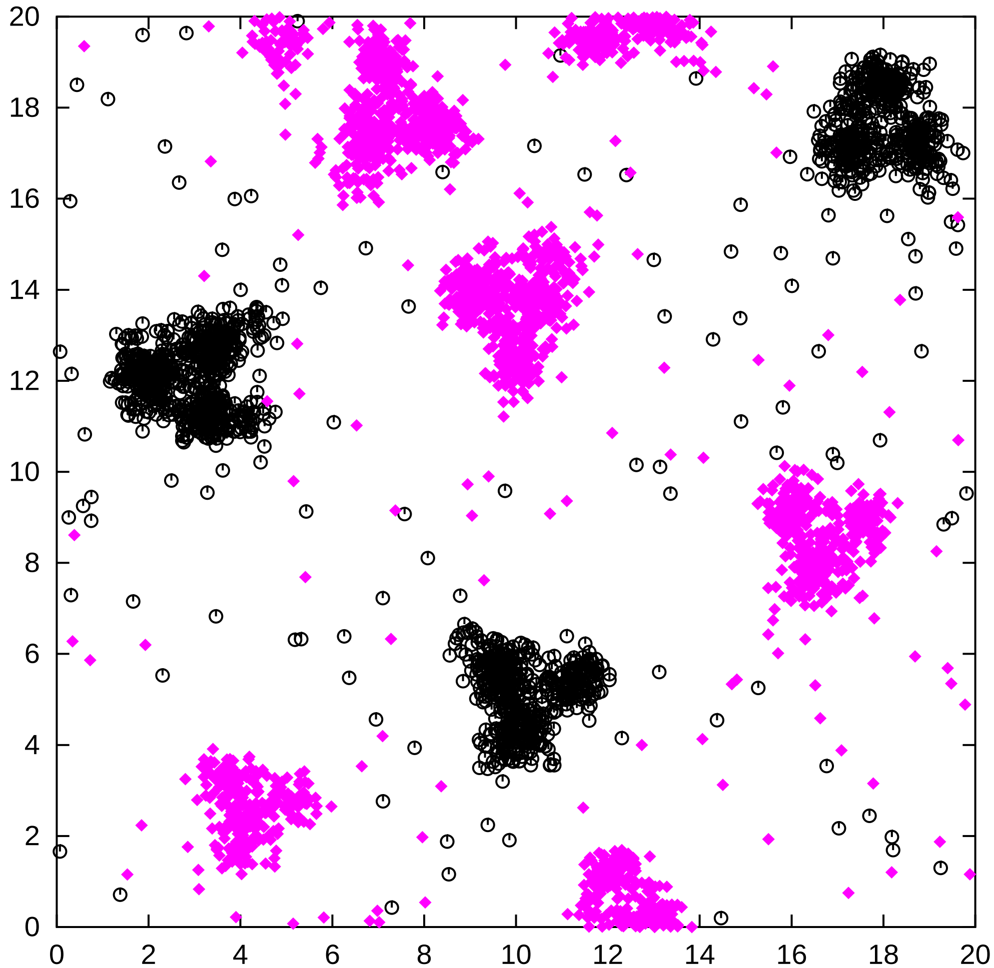

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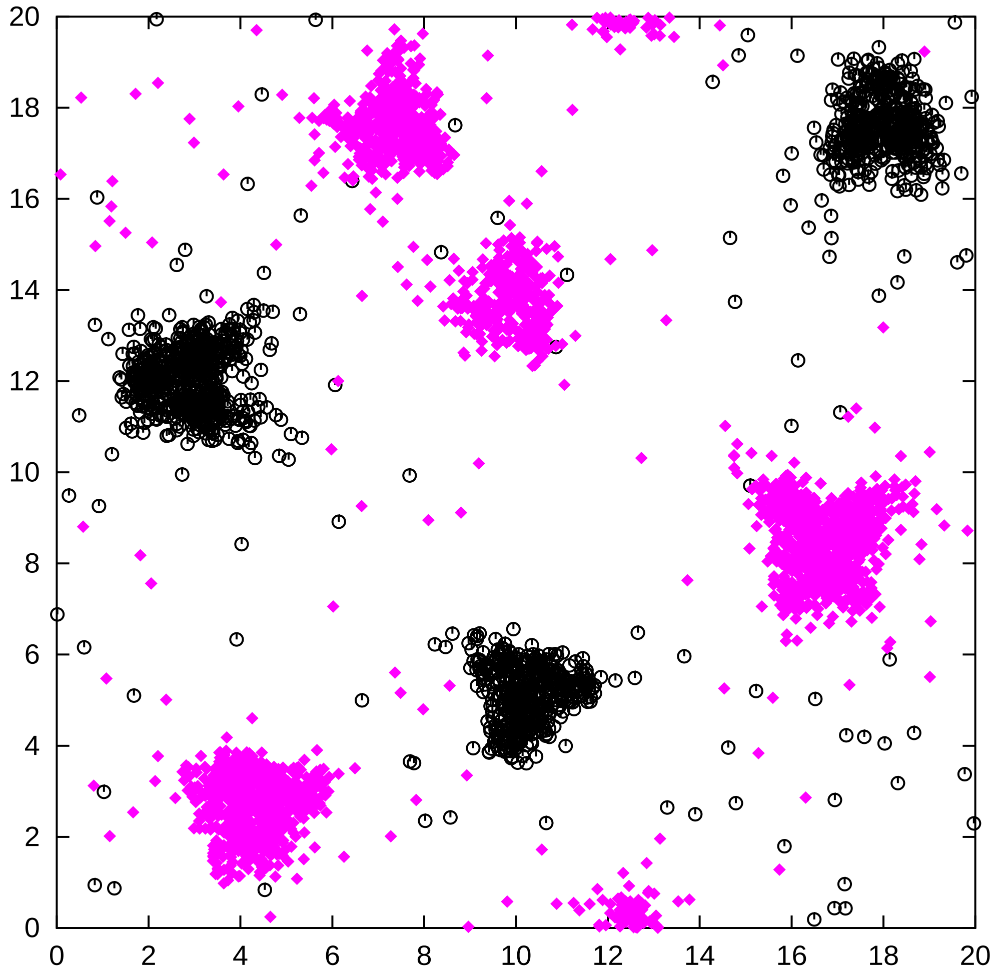

$t = 10^4$

Conclusions

- simple model of interacting agents: $\boldsymbol{r}_i$, θ_i
- communicate via multi-component communication field
  - reflects spatial distances, memory effects, information exchange with finite velocity
  - spatio-temporal inhomogeneities

Conclusions

- simple model of interacting agents: $\boldsymbol{r}_i$, θ_i
- communicate via multi-component communication field
  - reflects spatial distances, memory effects, information exchange with finite velocity
  - spatio-temporal inhomogeneities
- decisions dependent on local information: change of opinion, migration
- no "common knowledge assumption", no "utility function"

Spatial coordination of individual decisions:

- emergence of minority and majority above critical population size
- regions of coordinated decisions $\Rightarrow$ self-organization

Spatial coordination of individual decisions:

- emergence of minority and majority above critical population size
- regions of coordinated decisions $\Rightarrow$ self-organization
- more effective communication $\Rightarrow$ preference of one decision
- “tue Gutes und sprich darüber”