Self-Organization and Collective Decision Making in Animal and Human Societies

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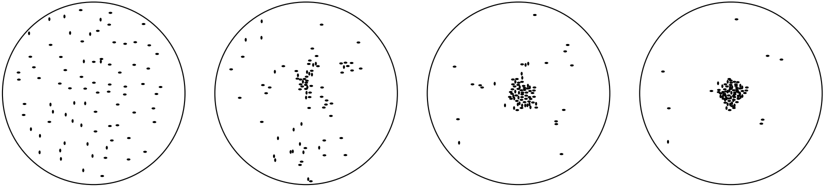
Example: Biological Aggregation

- cells, slime mold amoebae, myxobacteria generate a *chemical field* to communicate ⇒ *chemotaxis*



- Deneubourg, J. L.; Gregoire, J. C.; Le Fort, E. (1990): Kinetics of Larval Gregarious Behavior in the Bark Beetle Dendroctonus micans (Coleoptera: Scolytiadae), J. Insect Behavior 3/2, 169-182 (1990)

Modeling approach: Brownian Agents†

- variable: position r_i, dynamics: generalized Langevin equation

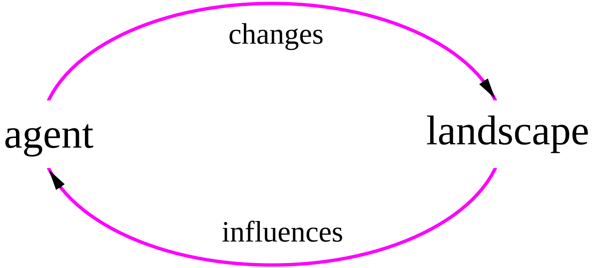
$$\frac{d\mathbf{r}_i}{dt} = \alpha_i \left.\frac{\partial h_0(\mathbf{r},t)}{\partial \mathbf{r}}\right|_{\mathbf{r}_i} + \sqrt{2\,D_n}\,\xi_i(t)$$

- adaptive landscape: *chemical field* $h_0(\mathbf{r}, t)$

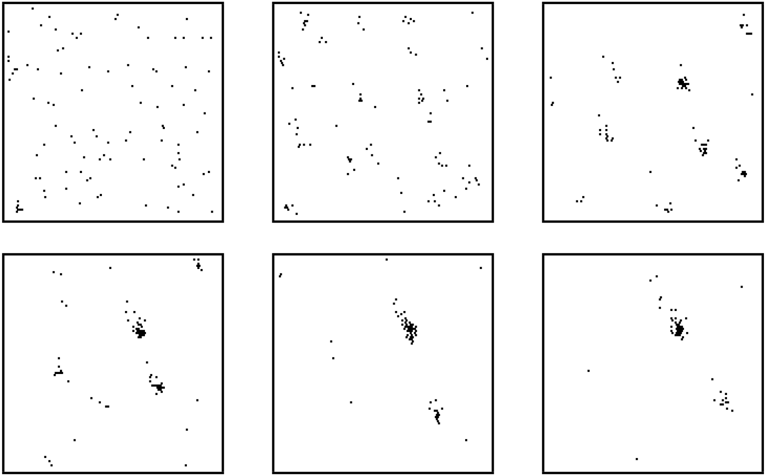
$$\frac{\partial}{\partial t} h_0(\mathbf{r},t) = \sum_{i=1}^{N} s_i\,\delta(\mathbf{r}-\mathbf{r}_i) - k_0 h_0(\mathbf{r},t) + D_0 \Delta h_0(\mathbf{r},t)$$

† F.S., *Brownian Agents and Active Particles. Collective Dynamics in the Natural and Social Sciences*, Springer, 2003 (420 pp., 192 illus.)

- indirect communication via adaptive landscape

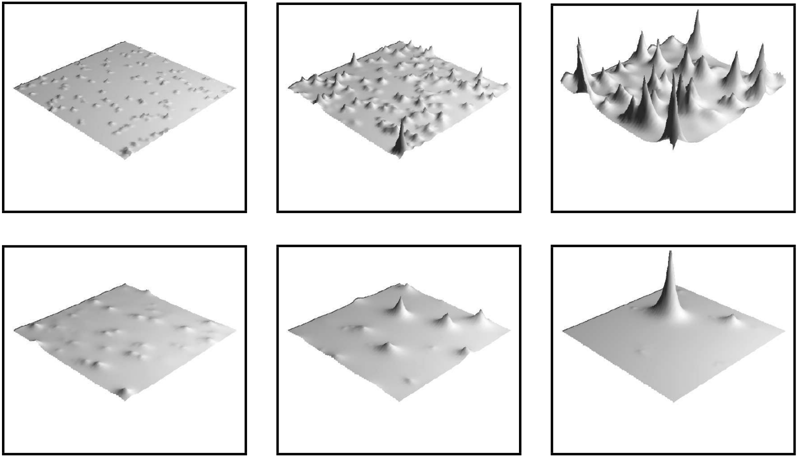


Computer Simulations



- time: (top) 10^2, 10^3, 5×10^3, (bottom) 10^4, 2.5×10^4, 5×10^4

Evolution of the adaptive landscape



- time: (top) 10^2, 10^3, 5×10^3, (bottom) 10^3, 5×10^3, 5×10^4. Note that the vertical scale in the top row is 10 times the scale of the bottom row

Summary:

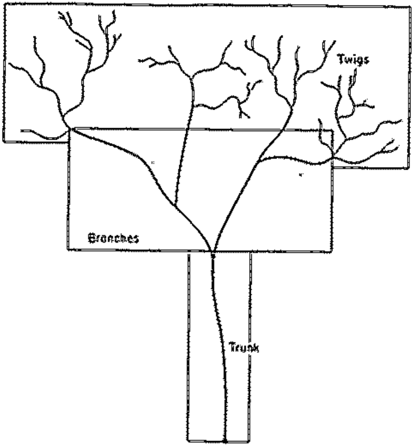
- agents follow *local rules*, create *global* structures
  - reason: nonlinear feedback between individual actions
  - agents drive system into nonequilibrium: s_0
- two characteristic time scales for field dynamics:
  - early: independent growth of “spikes” (many small clusters)
  - late: competition of “spikes” for agents
- theoretical investigations (F.S., L. Schimansky-Geier, *Physica A* **206** (1994) 359–379)
  - derivation of a selection equation: *survival of the fittest*

$$\frac{dx_i}{dt} = x_i \left[E_i - \langle E_i \rangle \right] \quad ; \quad \langle E_i \rangle = \frac{\sum_i E_i\, x_i}{\sum_i x_i}$$

- derivation of an effective diffusion equation

$$\frac{\partial n(\mathbf{r},t)}{\partial t} = \frac{\partial}{\partial \mathbf{r}} \left\{ D_{\mathrm{eff}} \frac{\partial n(\mathbf{r},t)}{\partial \mathbf{r}} \right\} ; \quad D_{\mathrm{eff}} = \frac{1}{\gamma_0} \left[k_B T - \alpha\, h_0(\mathbf{r},t) \right]$$

Example: Foraging Route of Ants

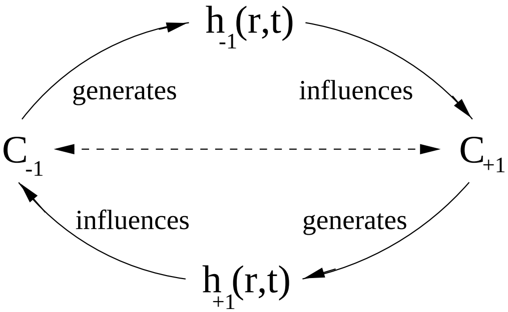


Schematic representation of the complete foraging route of *Pheidole milicida*, a harvesting ant of the southwestern U.S. deserts. Each day tens of thousands of workers move out to the dendritic trail system, disperse singly, and forage for food.

Hölldobler, B. and Möglich, M.: The foraging system of *Pheidole militicida (Hymenoptera: Formicidae)*, *Insectes Sociaux* **27/3** (1980) 237-264

Brownian Agents

- position r_i, $\theta_i \in \{-1, +1\}$ (found food or not)
- $\omega_i \in \{0; 1\}$ (scouts, recruits), sensitivity η_i



Simulation

F.S., K. Lao, F. Family, *BioSystems* **41** (1997) 153–166

Collective Decisions of Social Agents

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

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

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

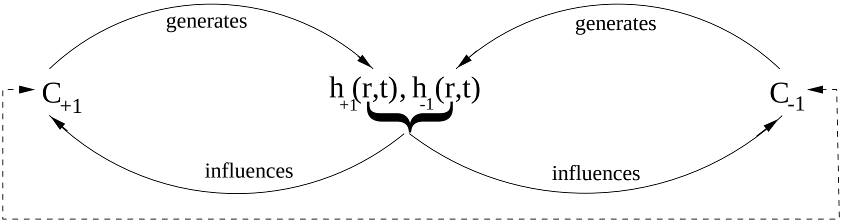
Spatio-temporal communication field

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

- multi-component scalar field reflects:
  - existence of *memory* (past experience)
  - *exchange of information* with *finite* velocity
  - influence of *spatial distances* between agents

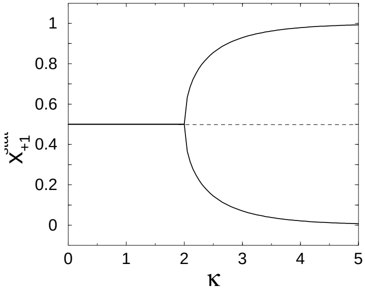
  $\Rightarrow$ *weighted* influence (space, time)

non-linear feedback:



Fast Information Exchange

- no spatial heterogeneity ⇒ mean-field approach

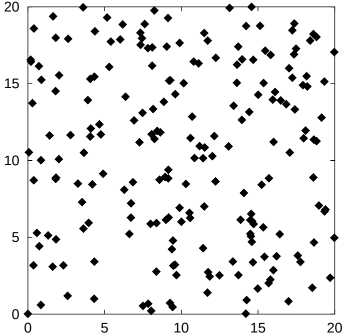


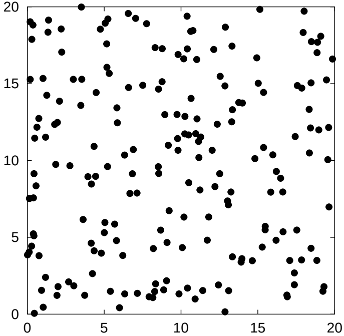
$$\kappa = \frac{2s\,N}{A\,k\,T} = 2 \Rightarrow \text{critical population size: } N^c = \frac{k\,A\,T}{s}$$

Emergence of minority and majority

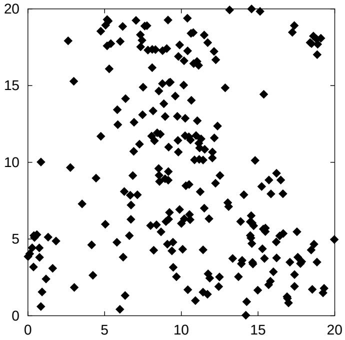
Spatial Influences on Decisions

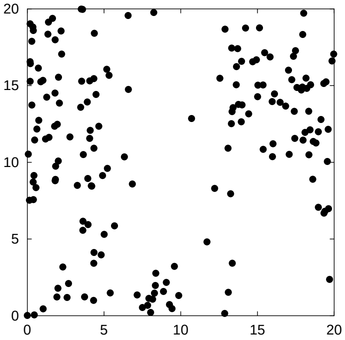
$s_{+1} = s_{-1} \equiv s,\ k_{+1} = k_{-1} \equiv k,\ D_{+1} = D_{-1} \equiv D$



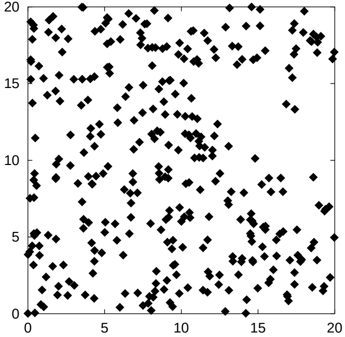


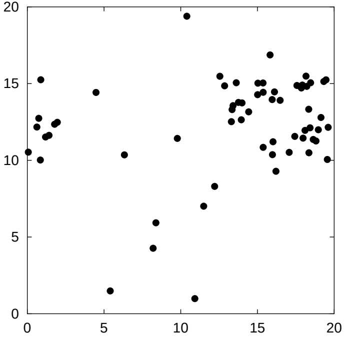
$$t = 10^0$$





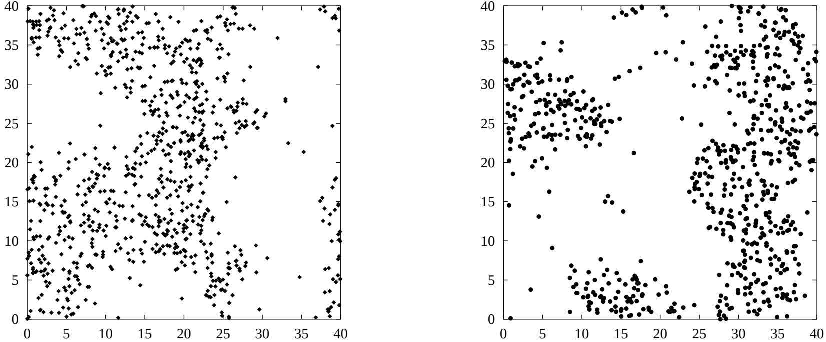
$$t = 10^2$$





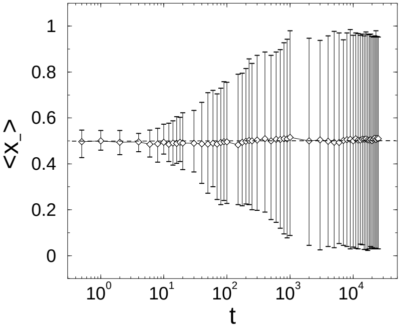
$$t = 10^4$$

Is the outcome determined?



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

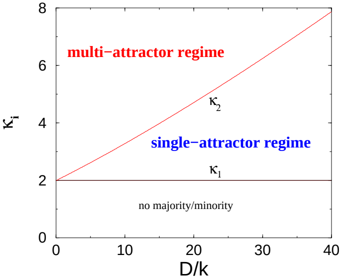
- almost every minority/majority relation may be established



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

Analytical Investigations

- impact of information $\kappa = 2\nu/T$: relation between net information density $\nu = \bar{n}\, s/k$ and efficiency $\sim 1/T$
- existence of two bifurcations:
  $\kappa > \kappa_1 = 2$: minority/majority
  $\kappa > \kappa_2(D/k)$: multi-attractor regime

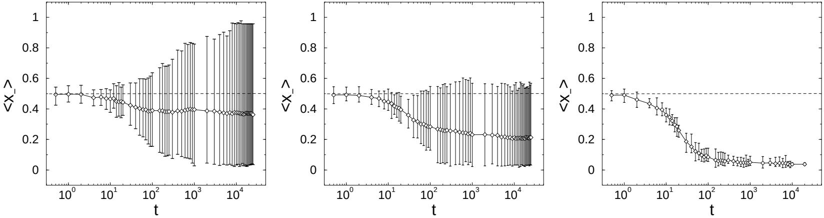


Result:

- to *avoid* multiple outcome (i.e. uncertainty in decision)
  - speed up information dissemination (mass media, ...)
  - increase randomness in social interaction (T)
    $\Rightarrow$ system "globalized" by ruling information $\Rightarrow$ becomes predictable
- to *enhance* multiple outcome (i.e. openess, diversity)
  - increase self-confidence, local influences (s)
  - prevent "globalization" via mass media (small D)
    $\Rightarrow$ locality matters $\Rightarrow$ system becomes unpredictable

Communication on different time scales

- 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

Self-organization in distributed systems:

- based on the non-linear coupling of “individual” actions
- feedback mechanism: self-consistent “field”
  indirect communication, exchange of information
- non-equilibrium system: communication is costly
  generation of information requires “energy”
- self-organization: emergence of spatial patterns

Model of Brownian Agents:†

- *stochastic* approach to structure formation in distributed systems ("micro level")
- considers internal degrees of freedom and energetic conditions of agents
- gradual transition from "physical" to "biological" and "social" phenomena by *adding complexity* to the agents
- very flexible, versatile tool for investigating complex systems

† F.S., *Brownian Agents and Active Particles. Collective Dynamics in the Natural and Social Sciences*, Springer, 2nd ed. 2004, 420 pp., 192 ill.