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Collective Decisions in Multi-Agent Systems

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Overview

1. Collective decisions
   - Decision making
   - Consensus versus coexistence
2. Voter models
   - Linear and non-linear VM
   - Simulations of VM
   - VM with memory effects
3. Propagation of opinions
   - Spearding of minority opinions
   - Decisions in hierarchical organizations
   - Local versus global trends
4. Decisions with continuous alternatives
5. Conclusion

Decision Making

- decision making: selection among alternatives
  - *basic* process in social and economic systems
- individual perspective of social actor ("*agent*"):
  - decision outcome ⇒ increase private utility
- classical approach: *rational agent*
  - calculation of utility function
  - common knowledge assumption
  - dissemination of information: fast, loss-free, error-free
- problems
  - incomplete (limited) information ⇒ *bounded rationality*
  - how to quantify private utility in social systems? (public votes)
  - ambigious solutions, conflicts ("frustrated system")

Social elements ...
... reduce the risk of making wrong decisions

- *imitation strategies*
  - biology, cultural evolution: adapt to the community
  - economy: copy successful strategies
- "information contagion", herding behavior
  - agents more likely do what others do
  - examples: financial markets, mass panics, fashion, ...

Collective Decisions

- aggregated outcome of many individual decisions
  - most individual implications are averaged out
  - interaction among agents play crucial role
  - system utility (social welfare) $\neq \sum_i U_i^{\mathrm{indep}}$
- *our focus:*
  - prediction of global/system quantities, not of individual decisions
  - role of local/neighborhood effects in collective decisions
  - influence of social elements (herding behavior)

Consensus versus Coexistence

Public polls ⇒ collective decision processes

- examples from Europe (2005):
  - May 29: French vote for/against Europ. constitution (45/55)
  - June 5: Swiss vote for/against Schengen (54.6/45.4)
- characteristic features
  - two alternatives: YES/NO (binary decision)
  - no simple utility maximization
  - hard to predict ($\sim$ 50/50)
- find minimalistic agent models to explain generic dynamics

Voter Models

- simple model of opinion formation with consensus
- population of agents: $i = 1, ..., N$
- each agent i: spatial position i, "opinion" $\theta_i(t) \Rightarrow \{0, 1\}$
- "decision": to keep or change opinion $\theta_i(t)$

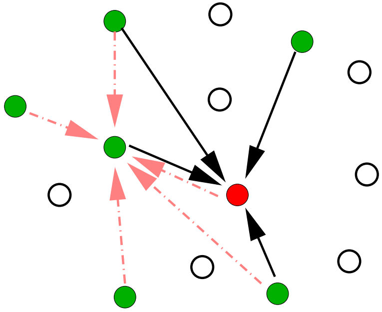
$$\theta_i(t+1) = \begin{cases} \theta_i(t) & \text{keep} \\ 1 - \theta_i(t) & \text{change} \end{cases}$$

- rate to change opinion depends on other agents

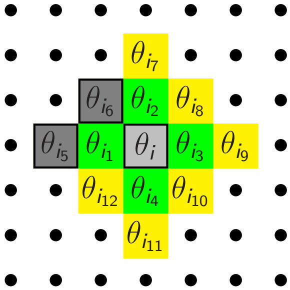
$$w(1-\theta_i|\theta_i) = \kappa(f)\; f_i^{1-\theta_i}$$

  - $0 \leq f_i^{1-\theta_i} \leq 1$: frequency of agents with *opposite* opinions in "neighborhood" of agent i
  - $\kappa(f)$: nonlinear response to frequency of other opinions

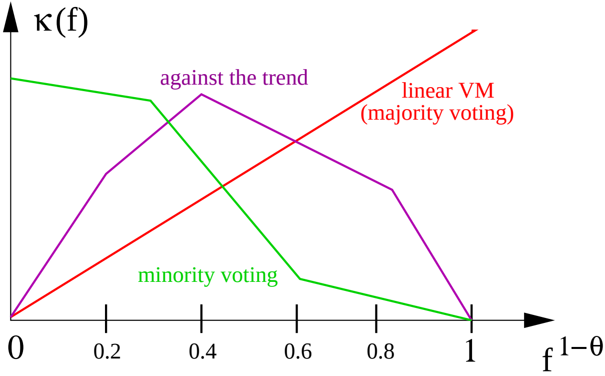
- neighborhoods are defined by an adjacency matrix $\mathcal{C}_{ij}$
  $\Rightarrow$ network structure



- simplified geometry: regular grid



Nonlinear response $\kappa(f)$



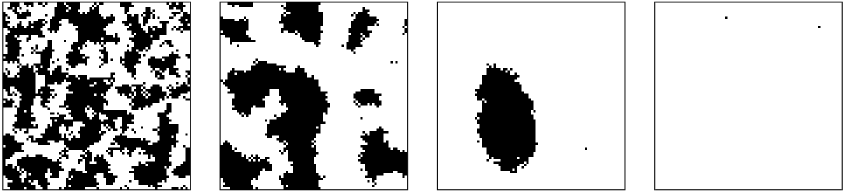
Results of computer simulations

1. Linear voter model

- stochastic simulation, $w(1-\theta|\theta) = f^{1-\theta}$
- initially $x = 0.5$, random distribution

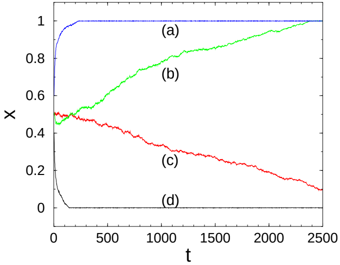
Online Simulation

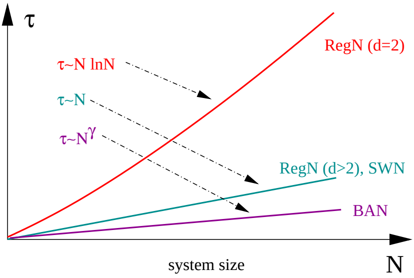
- results:
  - coordination of decisions on medium time scales
  - asymptotically: "no opposition" ($\rightarrow$ equilibrium)



$t = 10^1, 10^2, 10^3, 10^4$

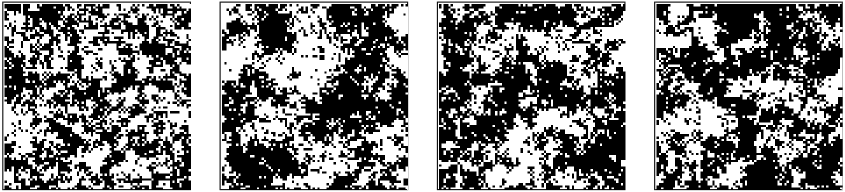
Time to reach consensus τ



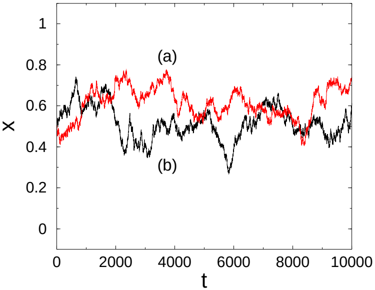


Coexistence? ⇒ 2. Non-linear voter model

- Online simulation 1:
  - coexistence, but no spatial coordination
- Online simulation 2:
  - small pertubation for $f^{1-\theta} = 1$ ($\rightarrow \varepsilon = 10^{-4}$)
  - coordination of decisions on long time scales
  - asymptotically: coexistence, but non-equilibrium

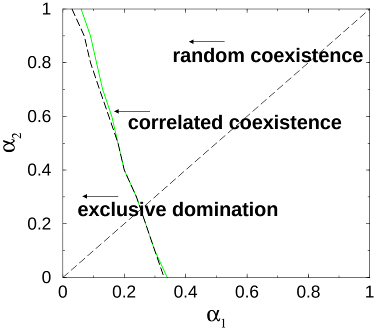


$\varepsilon = 10^{-4}$ $t = 10^1, 10^2, 10^3, 10^4$



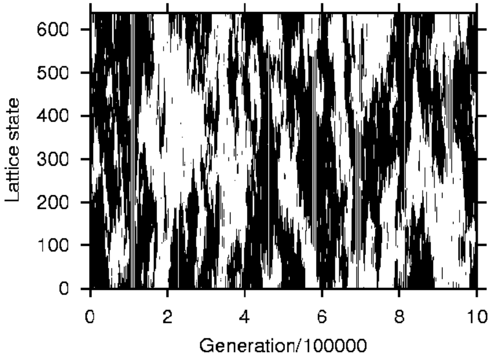
(a) $\varepsilon = 10^{-4}$, $\alpha_1 = 0.2$, $\alpha_2 = 0.4$ (linear VM)

(b) $\varepsilon = 10^{-4}$, $\alpha_1 = 0.25$, $\alpha_2 = 0.25$



Phase diagram for coexistence

1d CA:



- long-term nonstationarity
- only *temporal* domination of one opinion

Results:

- collective decisions ⇒ nonlinearity in the voter model
- consensus:
  - time scale?, symmetry of outcomes?
- coexistence:
  - non/stationarity? spatial correlations?, different attractors?[1]
- missing
  - memory effects, various opinions
  - influence of social structure, agent's utility

[1]Schweitzer, F.; Zimmermann, J.; Mühlenbein, H.: Coordination of Decisions in a Spatial Agent Model, Physica A 303/1-2 (2002) 189-216

Including memory effects

- $\nu_i(\tau_i)$: reluctance of agent i to change opinion θ_i
  - persistence time τ_i (opinion was *not* changed) $\Rightarrow$ "history"
  - reflects local experience with agents in neighborhood

$$\frac{d\nu}{d\tau} = \mu\,\nu(1-\nu) \quad \Rightarrow \quad v_i = \frac{1}{1+e^{-\mu\tau_i}}$$

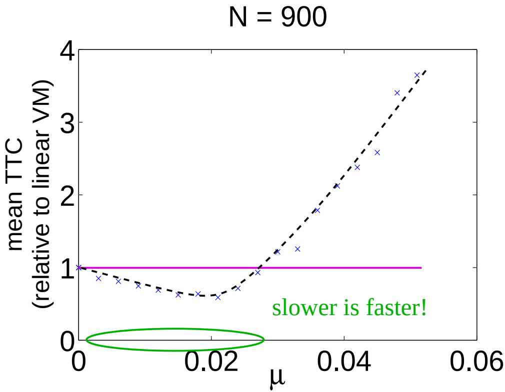
- decision dynamics:

$$w(\theta_i'|\theta_i) = [1-\nu_i(\tau_i)]\; f_i^{\theta_i'}$$

  - $\mu > 0$: slowing down of opinion dynamics
- consensus vs. coexistence of opinions ??
  - decision between 3 opinions: $\{-1, 0, +1\}$

Simulation Video

Time to reach consensus



- *heterogeneity* of agents important:
  - local groups of "confident" agents convince an indifferent neighborhood

Do not change the Status Quo

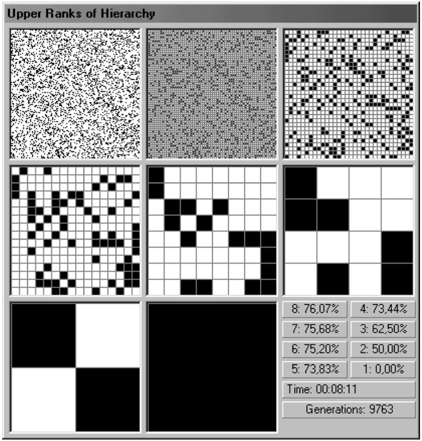
- conservative society: if you are in doubt, stay to the established opinion (Galam 2000, 2002)
- N agents with $\theta_i \in \{-1, +1\}$; ruling opinion $\theta_G = +1$
- government proposal $\Rightarrow$ N_+ supporters, N_- objectors

  ? how much support needed to accept the proposal?

  ! depends on mechanism of collective opinion formation!

example: local interaction between 4 agents

- majority rule: $\{4+, 0-\} \rightarrow 4+$, $\{3+, 1-\} \rightarrow 4+$, $\{1+, 3-\} \rightarrow 4-$, but: $\{2+, 2-\} \rightarrow 4+$
- n consecutive random interactions



initial condition: 24% supporters (black), 76% objectors
result: after 7 iterations or voting levels ⇒ 100% support
⇒ *minority wins*

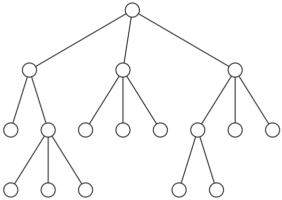
(Galam 2000, 2002)

Decisions in hierarchical organizations

Problem: propagation of new ideas through organization

- initialization on lowest level $\Leftrightarrow$ conviction at the top level??
- depends on acceptance threshold f_c and social structure
  - asymmetry of $\mathcal{C}_{ij}$
  - reporting/authority links

$$\theta_i(t+1) = \Theta\left[f_i^{(1)}(t) - f_c\right]$$



Online simulation

Local versus global trends

- agents exploit two different information
  - *local:* "do what your neighbors do"
  - *global:* "do not follow the trend"
- dynamics: N agents on a lattice, two opinions $\theta_i \in \{-1, +1\}$

$$\theta_i(t+1) = \begin{cases} +1 & \text{with } p = \dfrac{1}{1+\exp\{-2\beta h_i(t)\}} \\ -1 & \text{with } 1-p \end{cases}$$

$$h_i(t) = \sum_{j \in NN} J_{ij}\theta_j - \alpha\theta_i \left| \frac{1}{N} \sum_j \theta_j \right|$$

Online Simulation[2]

[2](Bornholdt 2001, cond-mat/0105224)

Summary

Baseline model:

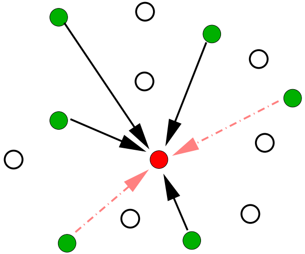
- decision between discrete alternatives: $\{0, 1\}$, $\{-1, 0, 1\}$ ...
- consideration of local neighborhood: $\mathcal{C}_{ij}$ (network, grid, ...)
- agent's utility: maximize consensus with neighborhood
  - decision: adopt opinion of local majority
- global/systems dynamics: consensus versus coexistence

Advanced model:

- consider social relations (friends/foes)
- spectrum of opinions
- more complex agent's utility

Continuous alternatives

- alternatives: $\theta_i(t) \in [0, ..., 1]$ (social behavior)
- different social relations of agent i:
  - *ingroup*: friends ⇒ try to reach *consensus* (attraction)
  - *outgroup*: foes ⇒ try to depart (repulsion)
  - neutral ⇒ no relation
  - $t = 0$: probabilities $p_{\rm in}$, $p_{\rm out}$ (decrease with distance)
    ⇒ adjacency matrix: $\mathcal{C}_{ij}$



K_i: size of ingroup
L_i: size of outgroup

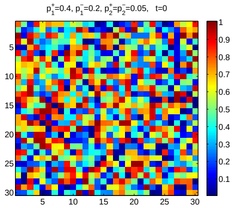
- agent's decision: adopt opinion θ_i which maximizes private utility

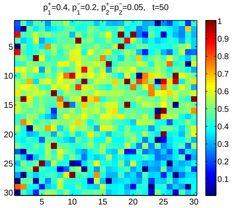
$$U(\theta_i^{t+1}) = -\alpha \times (\theta_i^{t+1} - \theta_i^t)^2 + \\ +(1-\alpha) \times \left[-\sum_{k \in I(i)} (\theta_i^{t+1} - \theta_k^t)^2 + \sum_{l \in O(i)} (\theta_i^{t+1} - \theta_l^t)^2 \right]$$

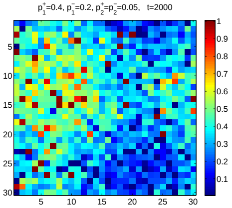
  - α: weights between importance of own opinion θ_i and opinions of "others"

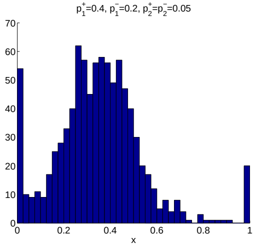
Simulation Video

Results of computer simulations with $N = 900$ agents







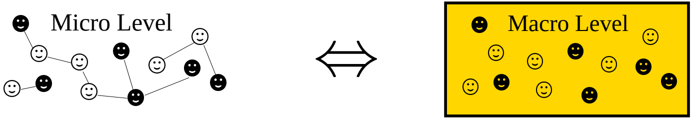


heterogeneous social behavior

- coexistence
- spatial concentration
- stationarity (slow dynamics)

Conclusions

- collective decisions ⇔ aggregated individual decisions??
- theory of complex systems:
  - *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)?*



- approach: multi-agent models
  - agent: "intermediate" internal complexity $\rightarrow \theta_i$
  - simple update dynamics: non-linear VM, utility maximization, ...
  - interaction: local neighborhood $\rightarrow \mathcal{C}_{ij}$: topology, in/outgroups

- *minimalistic agent models:*
  - cover generic features of collective decisions
    e.g. influence of hierarchies, memories, lobbies, ...
  - fitting with data within reach
  - but: will not predict your next "Volksabstimmung"
- KISS *(Keep It Simple, Stupid)* principle
  - details: not as much as possible, only as much as necessary
  - systematic understanding: role of parameters, feedbacks ...
  - abstract modeling level: elucidates dynamic key features
- Where is the "Social"??
  - N.Gilbert: *Putting the social into social simulation*
    (Wednesday, 17:15)

Thanks to:

- Laxmidhar Behera
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- Serge Galam
- Stefan Bornholdt
- ...