Modeling Complex Systems:
On the Uses and Disadvantages of Selforganization

Frank Schweitzer

fschweitzer@ethz.ch

Alternative Approaches to Design

Top–Down

hierachical planning

centralized control

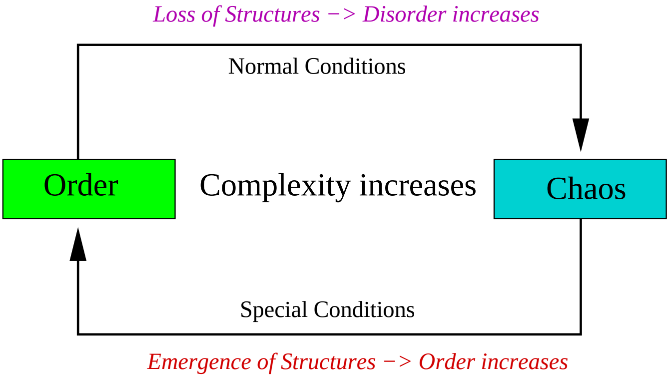
selforganization

decentralized
problem solving

Bottom–Up

Selforganization

- emergence of "order out of chaos"



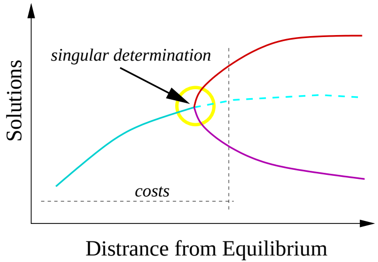
- preconditions
  - nonequilibrium, instability, feedback processes, interaction

Example: Chladni Figures

- pattern is designed/controled by
  - input of energy
  - boundary conditions

Precondition 1: Invest!

- *Lesson 1:* SO is not: order from nothing, it costs!
  - influx of free energy, material or information drives the system out of equilibrium
- *Lesson 2:* Little investments ⇒ no success!
  - new solutions emerge beyond a critical distance
- *Lesson 3:* Accept risks in the outcome!
  - critical stage at the bifurcation point ⇒ path dependence

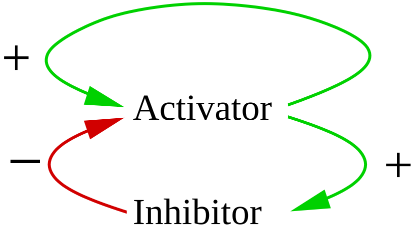


Example: Runge Pictures

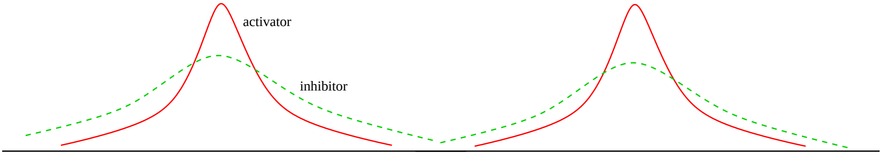
- input of ressources
- feedback processes (chemical reactions), spatial interaction (diffusion)
- result: aethetic pictures ⇒ “design” of artefacts

Precondition2: $\pm$ feedbacks

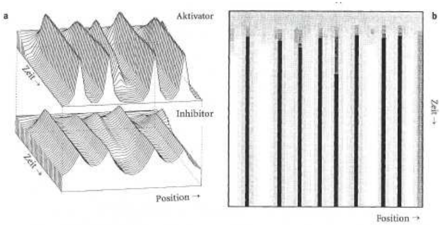
- structure formation in reaction-diffusion systems (RDS): diffusion *instabilities:* $D_1 \neq D_2$
- two species act as opponents
  - activator: local self-reinforcement $\rightarrow$ small deviations are amplified (growth)
  - inhibitor: long-range limitation of growth (antagonist)



Example: Pattern formation in sea shells

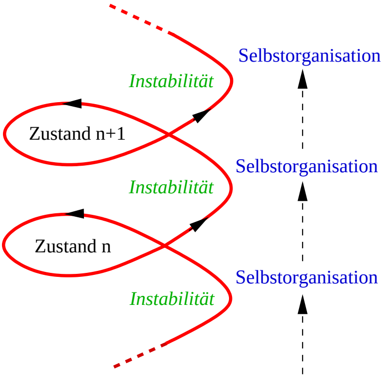


- activator maxima in periodic distance, surrounded by a inhibition cloud ⇒ no shift occurs



Precondition 3: Instability

- fluctuations/random events: test stability of the system
  - stable system: nothing happens, **instability** drives the evolution

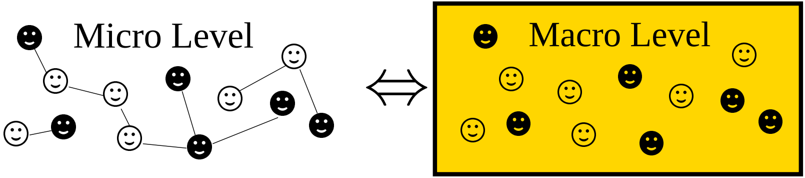


- *Lesson 4:* Selforganization needs **both**: positive **and** negative feedbacks!
  - Positive feedbacks: drive system into instability
  - negative feedbacks: allow for stabilization
- *Lesson 5:* Both feedback types act on *different* spatial and temporal scales!
  - time lags, delays in response give structures a chance to emerge
- *Lesson 6:* instability drives the evolution
  - instability from external disturbances
  - instability from internal interaction

    $\Rightarrow$ the system drives itself into instability

Precondition 4: Interaction

Shift of Perspective:



- 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)?

Complex Systems

"Complex systems are systems with multiple interacting components whose behavior cannot be simply inferred from the behavior of the components. ..."

New England Complex Systems Institute

"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"

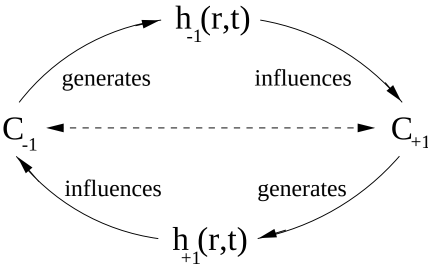
Example: Agent-Based Models

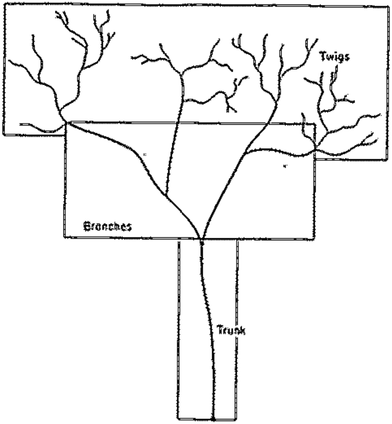
- *task:* search for new ressources, markets, ...
- problem: *NO apriori information*
  - Combine *exploration* and *exploitation*
    i.e., link “basis” with “resource”
  - other requirements: efficient (low costs), *adaptive*
- solution: *agents generate* relevant information
  - new kind of information: **success**
- result: solution is “created” (distributed problem solving)

Simulation

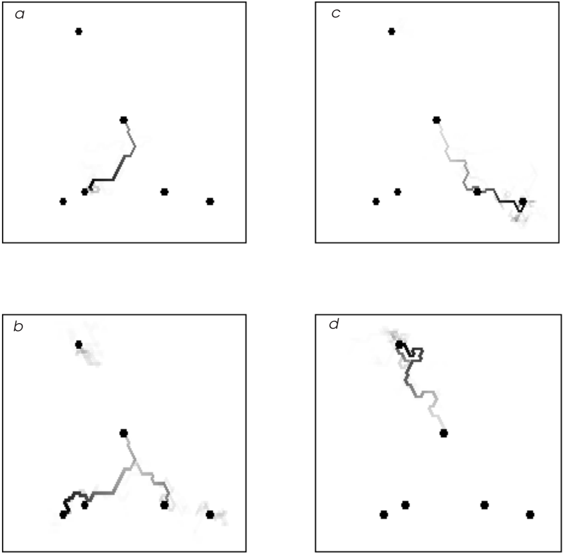
Indirect Communication

- Brownian agents “write” and “read” chemical information





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


a
b
c
d

Downside of Selforganization

- positive feedbacks ⇒ herding behavior
  - *imitation strategies*
    biology, cultural evolution: adapt to the community
    economy: copy successful strategies
  - if decisions based on incomplete (limited) information:
    How to reduce the risk? Do what your neighbors do!
- negative examples
  - crashes in stock markets
  - traffic jams
  - urban sprawl, megacities
  - mass panics ...
- solutions
  - design of boundary conditions ⇒ architecture
  - infrastructure: enforce alternatives ⇒ urban planning

Example: Human crowds

- Langevin dynamics of *Brownian agent i*

$$\frac{d\mathbf{v}_i(t)}{dt} = -\frac{1}{\tau_i}\mathbf{v}_i(t) + \mathbf{f}_i(t) + \sqrt{\frac{2\,\varepsilon_i}{\tau_i}}\,\boldsymbol{\xi}_i(t)$$

- "social force" model

$$\mathbf{f}_i(t) = \frac{1}{\tau_i}v_i^0\mathbf{e}_i - \nabla_{\mathbf{r}_i}\Big[V_B(|\mathbf{r}_i - \mathbf{r}_B^i|) + V_{\mathrm{int}}(\mathbf{r}_i, t)\Big]$$

- result: selforganized "behavior"

simulation: movement on the corridor

D. Helbing *et al.*, http://rcswww.urz.tu-dresden.de/˜helbing/

Practical applications:

- optimization of shopping centers, railway stations, airports, ...
- modelling panics (Helbing, Schreckenberg)
  $\Rightarrow$ evacuation scenarios
- simulations: Keine Panik Panik I. Farkas *et al.*, http://angel.elte.hu/panic/

Selforganisation

- spontaneous creation, development and differentiation of ordered structures
- collective phenomena, *emergence of new systems qualities*

Self-Organization is the process by which individual subunits achieve, through their cooperative interactions, states characterized by new, emergent properties transcending the properties of their constitutive parts.

Biebricher, C. K.; Nicolis, G.; Schuster, P.
Self-Organization in the Physico-Chemical and Life Sciences
EU Report 16546 (1995)

Self-organization is defined as

... spontaneous formation, evolution and differentiation of complex order structures ...

... forming in non-linear dynamic systems by way of feedback mechanisms involving the elements of the systems ...

... when these systems have passed a critical distance from the statical equilibrium as a result of the influx of unspecific energy, matter or information.

SFB 230 "Natural Constructions" (1984-1995)