Generation of Pragmatic Information and Self-Organization of Minimalistic Agents

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Schedule of this talk:

1. Different Aspects of Information
2. Complex vs. Minimalistic Agents
3. Example: Biological Aggregation
4. Example: Biological Trail Formation
5. Conclusions

Aspects of Information

- *physics:* structural aspects

⇒ information entropy: $H = -\sum_{i=1}^{s} p_i \ln p_i$
relation to statistical entropy: $S = k_B H$

- *informatics:* algorithms

⇒ information distribution, formal relations

- *biology:* information processing

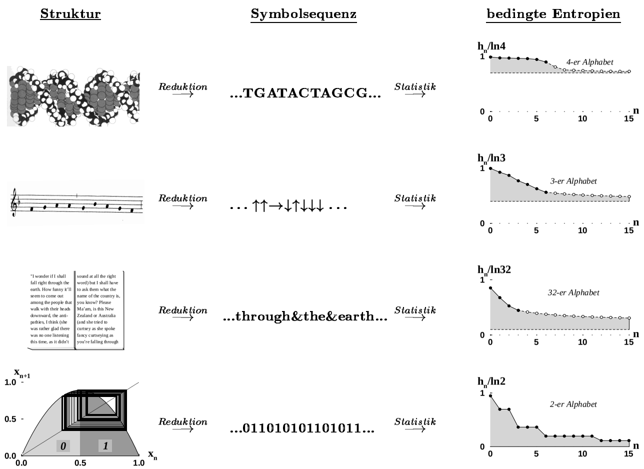
⇒ free information ⇔ bound information
ritualization, creation of codes

- *communication:* meaning

⇒ semantics, semiotics, pragmatics

Structural Information

- represents the *structural determination* of a system state
- measures the content of information, as given by the material structure
- structural information transformed into *symbolic sequences*
- analysed by means of different measures (e.g. conditional or dynamic entropies, transinformation etc.)



W. Ebeling, J. Freund, F. Schweitzer: *Komplexe Strukturen: Entropie und Information*, Stuttgart/Leipzig: Teubner, 1998, S. 107

Functional Information

- activates and interprets the existing structural information (e.g. algorithm)
- is related to *semantic aspects*
- contextual relations ⇒ information depends on the situation of the recipient
- represents the *self-referentiality* and the *operational closure* of the system

"Quantum Mechanics of Information Theory":

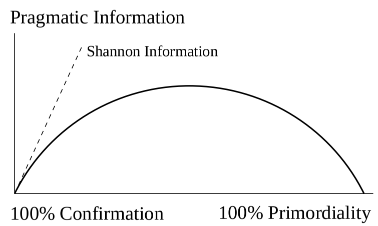
- state of a micro-object is constituted by the process of measuring

⇒ the recipient creates information during the process of reception

Purpose of functional information:
to transfer structural into pragmatic information.

Pragmatic Information

- measures the effect of information for the recipient
- "classical" view: ranges between primordiality and confirmation
- problems: initial information?, static state space?



evolutionary point of view:

Pragmatic information is generated by an *interplay of structural and functional information.*

⇒ new insight into the concept of pragmatic information:

pragmatic information is not an invariant of evolution, but must be steadily re-generated (otherwise, it disappears ...)

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
- *2. Problem:* combinatoric explosion of the state space:
  1000 Agents with 10 rules ⇒ 10^{13} possibilities
- *Solution:*
  restrict interactions ⇒ control of information flow
  personally addressed interaction instead of "broadcasting"
- *freedom:* define rules *and* interactions ⇒ *pitfall*

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

characteristics:

- mobility (active walker, active Brownian particle)
- action: agent *generates* **local** structural information
- *internal degrees of freedom:*
  → choice between different algorithms
  → sensitivity to particular structural information
  → generation of different kind of information
- no deliberative actions, no specialization, no internal memory
- cooperative interaction instead of autonomous action

Example: Biological Aggregation

- widely spread phenomenon: cells, larvae, bacteria, ...
- based on chemical communication (*chemotaxis*)
- each "agent": transmits signals, receives signals
  ⇒ guides its movement accordingly

structural information:

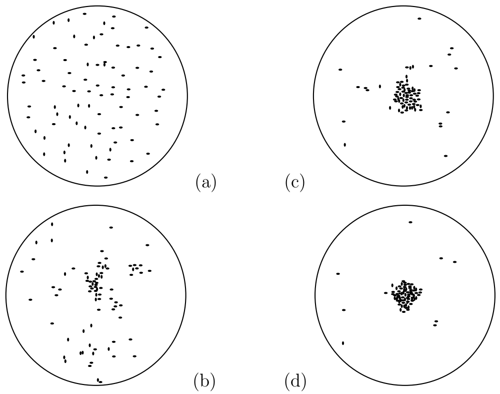
- chemical markings on the surface
- (one-component) chemical field $h_0(\boldsymbol{r}, t)$
- production, diffusion, decay

functional information: set of rules

(1) *local* check for gradients in the field
(2) *local* decision for the next step
(3) *local* production of markings
(4) movement to the new site ⇒ repeat (1)

- determine what **pragmatic** information the agent gets out of the existing structural information
  ⇒ decision for the next step

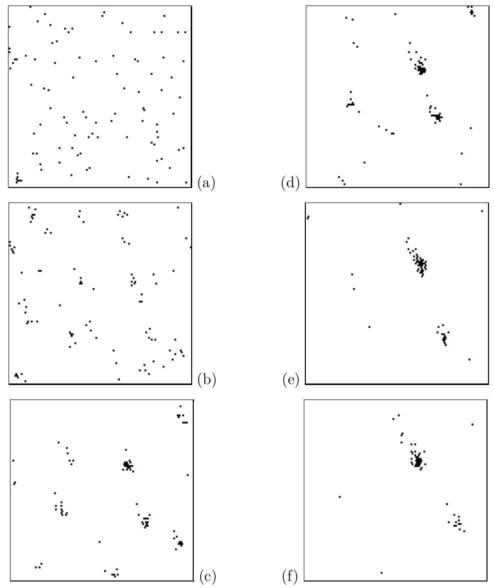
Aggregation of Larvae



Aggregation of larvae of the bark beetle *Dendroctonus micans*.
Total population 80 larvae, density 0.166 larvae/cm^2.
Time in minutes: (a) $t = 0$, (b) $t = 5$, (c) $t = 10$, (d) $t = 20$.

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

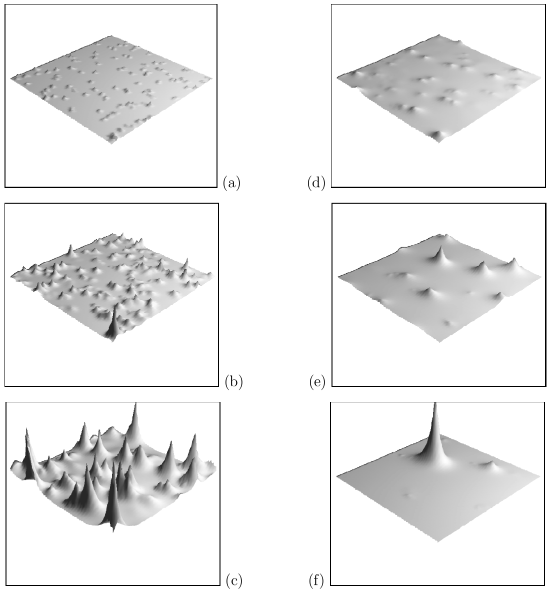
Aggregation of Active Brownian Particles



Position of 100 active Brownian particles moving on a triangular lattice (size: $A = 100 \times 100$).
Time in simulation steps: (a) $t = 100$, (b) $t = 1.000$, (c) $t = 5.000$, (d) $t = 10.000$, (e) $t = 25.000$, (f) $t = 50.000$.

Schweitzer, F.; Schimansky-Geier, L.: Clustering of Active Walkers in a Two-Component System, *Physica A* **206**, (1994) 359-379

Evolution of the Self-Consistent Field



Time in simulation steps. (left side) Growth regime: (a) $t = 10$, (b) $t = 100$, (c) $t = 1.000$, (right side) Competition regime: (d) $t = 1.000$, (e) $t = 5.000$, (f) $t = 50.000$. The scale of the right side is 10 times the scale of the left side. Hence, Fig. (d) is the same as Fig. (c).

Schweitzer, F.; Schimansky-Geier, L.: Clustering of Active Walkers in a Two-Component System, *Physica A* **206**, (1994) 359-379

Communication

individual agent: acts **locally**

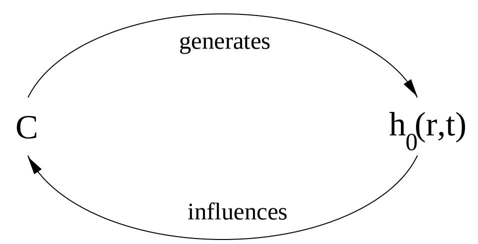
- receives structural information ("reading")
- generates structural information ("writing")
- action depending on pragmatic information

interaction between agents: indirect communication

- structural information ⇒ external "field"
  - → *stores* information generated by the agents (q)
  - → *memory effect*: information with a certain "life time" (τ)
  - → *distribution*: information diffuses (D)
    no restrictions for information flow (broadcasting)
    finite velocity of distribution
- consideration of local inhomogeneities
- different kind of information → multi-component field

⇒ **non-linear feedback between agents and information field**

Nonlinear Feedback



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Example: Biological Trail Formation

biological phenomenon: ⇒ rather *complex*

- trail systems of ants, mice, hoofed animals, ... pedestrians
- reasons: searching and homing behavior, group interaction, effort savings
- mental capacities: geocentric and ecocentric navigation, “deliberative” movement

complex problem:

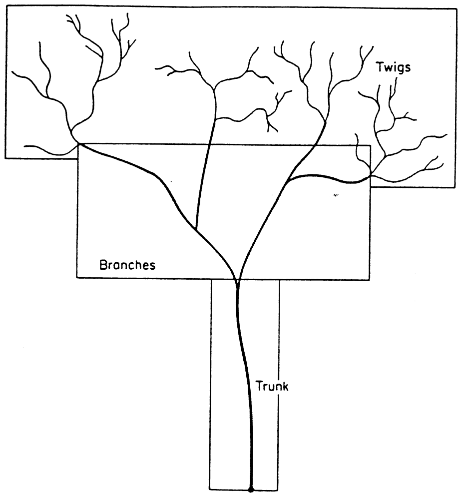
- *search* for *unknown* food sources
- *link* the sources found to the nest
- *adapt* the trail system in a changing environment
- do *not* count on external information, guidance

agent model: ⇒ rather *minimalistic*

- two kinds of structural information: $\{-1; +1\}$
- functional information (algorithm) basically the same
- internal parameter $\theta_i = \{-1, 0, +1\}$ determines:
  - which structural information is processed
    ⇒ different kind of pragmatic information
  - which structural information is generated
  - level of sensitivity
- step-by-step increase of the agent’s complexity: scouts, recruitment, death, ...

Slide 14

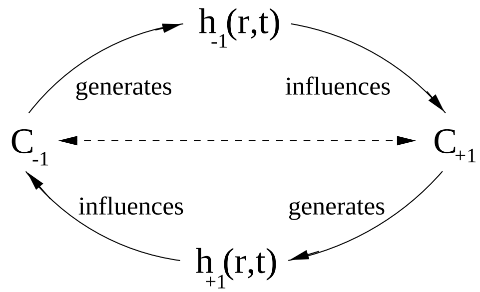
Foraging Route of Ants (*Pheidole milicida*)



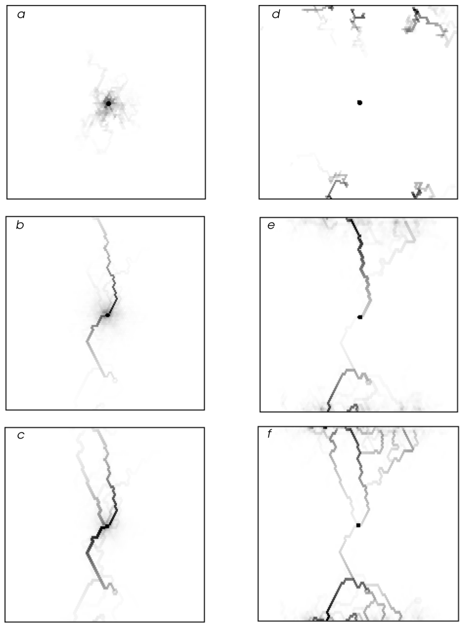
Schematic representation of the complete foraging route of *Pheidole milicida*, a harvesting ant of the southwestern U.S. deserts. Each day tens of thousands of workers move out to the dendritic trail system, disperse singly, and forage for food.

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

Nonlinear Feedback



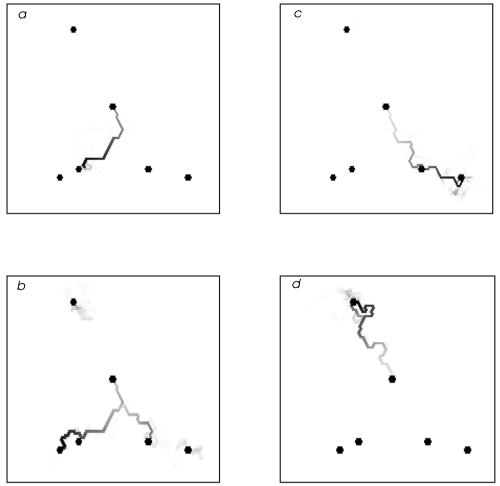
Trunk Trail Formation to Extended Forage Areas



Formation of trails from a nest (middle) to a line of food at the top and the bottom of a lattice. (a-c) show the distribution of chemical component (+1), and (d-f) show the distribution of chemical component (−1). Time in simulation steps: (a), (d) $t = 1.000$, (b), (e) $t = 5.000$, (c), (f) $t = 10.000$.

Schweitzer, F.; Lao, K.; Family, F.: Active Random Walkers Simulate Trunk Trail Formation by Ants, *BioSystems* **41** (1997) 153-166

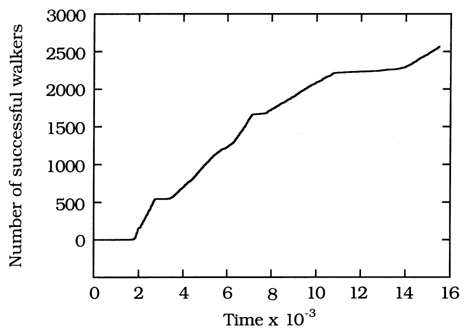
Trunk Trail Formation to Separate Food Items



Formation of trails from a nest (middle) to five randomly placed food clusters. The distribution of chemical component (−1) is shown after (a) 2000, (b) 4000, (c) 8500, and (d) 15000 simulation time steps, respectively.

Schweitzer, F.; Lao, K.; Family, F.: Active Random Walkers Simulate Trunk Trail Formation by Ants, *BioSystems* **41** (1997) 153-166

Cumulative Number of Successful Walkers



Schweitzer, F.; Lao, K.; Family, F.: Active Random Walkers Simulate Trunk Trail Formation by Ants, *BioSystems* **41** (1997) 153-166

Conclusions

Minimalistic multi-agent system: two levels of description

agent's level:

- simplex - not complex ⇒ "intermediate" complexity
- *local* response/changes of the environment
- internal degrees of freedom ⇒ variety of responses
- parallel *independent* actions *coupled* by information flow

system's level:

- emergence of complexity: autonomous "intelligent" system
- adaption to changes in the environment
- failure tolerant (single agents, external pertubations)

⇒ Reason: *Self-Organization*
solutions result from the non-linear interaction
boundary conditions (semi-structured environment)

characteristics of the approach:

- *non-deterministic*
  random events (fluctuations) play a considerable role
- *non-finalistic*
  final (global) solutions cannot be predicted from local interactions ⇒ solutions *emerge* ⇒ *path dependent*
- *bottom-up approach:* create a solution ⇒ self-organization
  top-down approach: design a solution ⇒ planning

Self-Organization

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", Stuttgart, 1984 - 1995