SELFORGANIZATION MODELS FOR FIELD MOBILITY OF PHYSICISTS

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Field mobility as an important indicator for the development of scientific disciplines is represented in a mathematical approach using methods from the theory of selforganization, especially the Fisher-Eigen-Schuster equation of the theory of molecular evolution.

1. INTRODUCTION

In scientometrics the phenomenon of mobility of scientists is of great interest (there are changes in occupation, research area, between basic and applied research, etc. cf., bibliografies [1]) also in connection with the evolution of science. In this paper we consider only the mobility with respect to research areas (particularly to subfields of physics), the so-called field mobility, as indicator of the evolution of scientific disciplines (reviewed in [2]). We assume, that this development can be described as an evolutionary process and can be investigated using the methods of the theory of selforganization, particularly applying ideas from the theory of molecular evolution [3, 4].

We consider a linear model, its nonlinear generalization and a stochastic model (cf. [5] in this issue). The data base for some demonstrations is given by migration studies concerning physicists [6]. Describing the intellectual movements of scientists between subfields with methods of the theory of molecular evolution [7], we expect to contribute to a fruitful application of these methods to evolutionary problems in science. We have not gone very far into the scientometrical interpretation of our model because the processes in science are more complicated than the processes at the molecular level. This paper intends to be a guide-line rather than a fully developed approach.

2. A MODEL FOR FIELD MOBILITY

Let us consider a system of N subfields i, which form a scientific discipline like physics. We denote the number of scientists working in the subfield i at the time t by the continuously varying function $X_i(t)$. Such a picture is applicable for the case of a sufficiently great number of individuals in each field. At first we make the following ansatz:

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = \dot{X}_i = F_i = W_i X_i\,, \quad i = 1, \ldots, N\,. \tag{1}$$

Here the growth of a subfield is considered as an autocatalytic process with the rate W_i. The cases $W_i > 0$, $W_i < 0$ correspond to growth and decrease, respectively. In table 1 these rates for chosen subfields in physics, based on published data, are counted. In general we can assume four mechanisms which create the change of the variable X_i: creation, destruction, arrival and exit. The mobility is coupled with the both last processes and we can define:

a) mobility from subfield j to i

$$A_{ij} = \frac{\text{number of scientists which go from } j \text{ to } i}{\text{number of scientists working in } j}\,,$$

b) mobility away from field i (total exit)

$$A'_j = A_{ij} = \frac{\text{all exits to other subfiels}}{\text{number of scientists working in } j} .$$

Table 1

Growth of subfields in physics per annum (data from [6])

Table 2

Mobility matrix per annum $A = (A_{ij})$

subfield i	no. of scientists working in i at $t_1 = 1968$	$t_2 = 1970$	total growth rate W_i	subf.	1	2	3	4	5
1 earth, planet. phys.	486	581	0·097	1	—	0·003	0·010	0·007	0·012
2 condensed matter	3759	3248	−0·068	2	0·017	—	0·058	0·026	0·010
3 atom., mol., el. phys.	925	783	−0·076	3	0·009	0·018	—	0·011	0·006
4 nucl. phys.	1674	1390	−0·085	4	0·002	0·006	0·009	—	0·027
5 elem. part. phys.	1210	1064	−0·060	5	0·015	0·004	0·005	0·016	—

The coefficient corresponding to a) is given in table 2. The other both processes are represented by selfreproduction and decay. The process of "selfreproduction" is interpreted here as the process of winning "new scientists", who have never worked before in science in any subfield, by education of students, with the rate A_i. "Decay" means the process that physicists may cease to work in physics at all (becoming pensioners etc.), with the rate D_i. So we obtain the following linear equation for X_i:

$$\text{(2)} \qquad \dot{X}_i = (A_i - D_i)\, X_i + \sum_j A_{ij} X_j - \sum_j A_{ji} X_i = W_i X_i\,, \quad i, j = 1, \ldots, N\,.$$

As a further generalization we assume that we have additional couplings between subfields by nonlinear interactions, such as imitation and processes like sponsoring or suppressing. Further the growth itself may be nonlinear due to cooperative processes (hyperbolic growth) [8].

So we introduce the following coefficients for equation (2):

$$\text{(3)} \qquad A_i = A_i^0 + A_i^1 X_i\,; \quad D_i = D_i^0 + D_i^1 X_i$$
$$A_{ij} = A_{ij}^0 + A_{ij}^1 X_i\,.$$

Equations (2) and (3) correspond to the Eigen-Schuster equation for prebiotic evolution [9].

So we can establish links between the genesis and evolution of species and of scientific subfields. Solutions of such equations are presented in the literature. The coefficients A_i^0, A_i^1, A_{ij}^0, D_i^0, D_i^1 and A_{ij}^1 reflect social forces and conditions. At least in principle all these coefficients can be determined by an analysis of careful scientometric investigations following the method demonstrated above for a special example.

A possible direction of further investigations could be the search for optimum conditions with respect to the rate coefficients.

3. A STOCHASTIC MODEL

Scientific work is always accompanied by random influences, especially important in the case of a small number of contributors to a given field. Due to the discrete nature of our elements (scientists) we consider now the development of scientific disciplines as a Markovian process [10]. The system is characterized by a set of integers (N_1, N_2, N_3, ...) at the time t, where N_i is the number of scientists working in i, and we regard the Master equation for the probability density $P(N_1, N_2, \ldots, N_i, \ldots, t)$:

$$\frac{\partial}{\partial t} P = WP . \tag{4}$$

For the transition rates W_{ij} which determine the evolution operator W we introduce now four elementary processes. In principle the interpretation of these processes is identical to the deterministic case — see also section 2 (for the mathematical technique used see e.g. [4] p. 148).

a) Selfreproduction of a given idea (field)

We assume that the transition $N_i \to N_i + 1$, (the number of scientists in i is increased by one) occurs with the probability:

$$W(N_i + 1 \mid N_i) = A_i^0 N_i + A_i^1 N_i (N_i - 1) . \tag{5}$$

b) Decay

The corresponding transition $N_i \to N_i - 1$ occurs with the probability:

$$W(N_i - 1 \mid N_i) = D_i^0 N_i + D_i^1 N_i (N_i - 1) . \tag{6}$$

c) Field Mobility and discoveries

The phenomenon of field mobility is described here as a process corresponding to the transition $N_j \to N_j - 1$ and $N_i \to N_i + 1$. So we make the following ansatz:

$$W(N_i + 1, N_j - 1 \mid N_i N_j) = A_{ij}^0 N_j . \tag{7}$$

All characteristic features of the subfield i, which can influence the transition from j to i are taken into account by the coefficients A_{ij}^0. The description of this process corresponds to the description of mutation processes in the theory of molecular evolution. The appearance of mutations (i.e. new possibilities) is a very important evolutionary condition [4] (p. 269). The special transition: $N_j \to N_j - 1$, $N_i = 0 \to N_i = 1$, when i represents a "new" subfield, corresponds in this model to a scientific discovery.

The coefficient A_{ij}^0 is then a measure for the probability that a scientist working in j creates an idea which may be itself a foundation for a new field.

d) Interaction

The consideration of interactions corresponds to a generalized model of the mobility phenomenon, including cooperative relations (i.e. more complicated processes as simple exchange) in the scientific community.

It is well known that every scientist stays in close connection with others and follows up continuously their work. So we find transitions from j to i when i is more attractive for working than j:

$$\begin{pmatrix} N_j \to N_j - 1 \\ N_i \to N_i + 1 \end{pmatrix}.$$

We express the transition probability of this process by:

$$W(N_i + 1,\ N_j - 1 \mid N_i N_j) = A^1_{ij} N_i N_j\,, \tag{8}$$

where $A_{ij}{}^1$ is an interaction matrix.

A special case is the interaction by imitation

$$A^1_{ij} = (\mathrm{IM})\, N^{-1} A_i\,. \tag{9}$$

Following the general rules for Markov processes the time behaviour of the distribution function $P(N_1, N_2, \ldots, N_i, N_i, \ldots, t)$ constructed with the given transition probabilities (see eqs. (5)—(9)), characterizes completly the state of the system. As a new element in the evolution of science in comparison with the molecular evolution we find the imitation of scientific ideas. Further, in contrast to the biological species, where the individuals die out with the species itself, in social systems the representative (i.e. in our case the scientists of a field) may survive in the scientific community by transition to another field.

We note that by averaging equation (4) with the given transition probabilities, and factorization of the mean, we obtain eq. (2) for the mean $\langle X_i \rangle$.

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