Alfred Gierer

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Socioeconomic Inequalities: Effects of Self-Enhancement, Depletion and Redistribution

Sozioökonomische Ungleichheiten: Einfluß von Selbstverstärkung, Verknappung und Umverteilung

Alfred Gierer, Tübingen

Introduction

Understanding and planning for economic development requires consideration not only of indicators which are integrated over a society, such as gross national product, but also of the degree of socioeconomic inequalities. In particular, the aim of social well-being for all implies placing emphasis on the least privileged part of society. The income of the poorest section may itself serve as an indicator for the quality of economic strategies. Optimizing this parameter is the basis of a theory of justice developed by Rawls (1971) (assuming that this criterion would be subject to consensus in an idealized initial state of perfect equality). Irrespective of details of such concepts any reasonable and socially acceptable economic strategy is determined by its effect on the degree of inequalities in addition to the effect on overall growth, though the latter aspect has received much more attention in economic theories than the former.

Socioeconomic inequalities are to be considered at two levels, between individuals of a given society, and between regions or nations. Inequalities between individuals within a society may result from variations of income with age, social background, education, intelligence, wealth, efficiency of labour organization and other features. However, the attempt to explain the extent of inequalities by additive effects of such causes have not led to fully satisfactory results and one may doubt whether in principle the degree of inequalities and the factors affecting distribution can be directly correlated at all (for review, see Atkinson, 1975). This doubt is inherent in Pareto's attempt to specify a general mathematical power relation for income distribution independent of the detailed structures of a society, and, more recently, in the labour queue theory of Thurow and Lucas (1972) which states that jobs are distributed in accordance with individual differences in education and with other factors, but that the extent of income differences is not explicable by the extent of these individual differences. For example, different societies with different disparities in education may nevertheless show a similar income distribution. Inequalities seem to result, to a considerable extent, from the systems features of interaction between individuals or subgroups of a society.

Inequalities between nations are partially explicable by intrinsic properties such as differences in natural resources, educational standards and cultural traditions, but again these intrinsic properties are hardly sufficient to explain existing disparities in economic development. This, rather, is strongly influenced by interactions within the international economic system as a whole.

In agreement with such notions the degree of economic inequalities is treated, in this paper, as a structural feature which is autonomously generated and thus related to general rules for interaction within the system, as are many other structural features of physical as well as social systems (e.g. Hayek, 1973). Emphasis is placed upon the dynamics of self-generation and self-stabilization of inequalities, which are determined by self-enhancement, depletion and redistribution effects.

One can envisage the generation of striking economic inequalities if there is some self-enhancing feature returning more advantages to already privileged subgroups; if the generation of these advantages draws upon resources common to other subgroups, advantages are mainly reinforced and disadvantages redistributed. On the other hand, if advantages are redistributed sufficiently, if depletion of resources is largely restricted to the subgroups acquiring advantages, or if the self-enhancing features are weak or absent, a more equitable distribution of advantages would result. Self-enhancing advantages may be represented by capital or some system parameter subsuming several features, such as wealth, education, etc.; and depletion may be due to a limitation of resources (such as raw materials, energy, manpower); a system parameter may account for a combined effect.

The generation of non-uniform distributions in space resulting from short-range self-enhancing and wide-range inhibitory or depletion effects is the basis of a recent theory we have developed for biological pattern formation (Gierer and Meinhardt, 1972, 1974; for a non-formal general introduction see Gierer, 1974). The approach itself is rather general and not restricted to biology; the mathematical considerations underlying the theory can be adapted and applied to socioeconomic inequalities as well.

Biological patterns resulting from autocatalysis (self-enhancement) in conjunction with inhibition or depletion

While many mechanisms contribute to the production of spatial order in the course of development of an organism from the fertilized egg cell, the generation of strikingly unequal substructures within initially near-uniform cells or tissues is of particular importance. Such pattern formation is characterized by impressive self-regulatory properties: Patterns may regulate in proportion to total size of the pattern-forming region; in some cases, two halves of an early embryo can form two complete organisms. Secondary centers of embryonic organization can be induced by certain stimuli, but there are also inhibitory effects permitting a secondary center to arise only at some distance from a primary one. These and other aspects of biological pattern regulation may be explained by a physical theory of morphogenesis. There is empirical evidence that visible patterns are preceded and directed by morphogenetic fields which affect the differentiation and form of cells, thus giving rise to structure and form of organisms and organs. Although the chemical basis of morphogenetic fields is not yet known, they are probably concentration patterns of morphogenetic substances.

How are unequal distributions of molecules in space reproducibly formed, starting from near-uniform conditions? If patterns result from molecular interactions and movements, laws governing pattern formation should be of the type:

$$\partial c_i/\partial t = f_i(c_1 \ldots c_N) + \mathcal{D}_i(c_i), \quad i = 1 \ldots N \tag{1}$$

with functions f_i of concentrations $c_i(x, t)$ of various compounds accounting for interaction, whereas $\mathcal{D}_i$ are redistribution operators accounting for diffusion, convection and other effects of movement. Turing, the same mathematician who has pioneered mathematical decision theory discovered 1952 that spatial concentration patterns can be formed on this basis. Several groups have since then elucidated the mathematics of such pattern-forming systems (Gmitro and Scriven, 1966; Prigogine and Nicolis, 1971).

Some years ago, we studied whether simple conditions could be found for the generation and stabilization of spatial inequalities on the basis of Eq. (1) leading to patterns with the self-regulatory features empirically observed in biological systems. The following solution emerged from these studies (Gierer and Meinhardt, 1972, 1974): In the simplest case, where two factors are required, one of these factors must be activating (in the sense of self-enhancement) to generate a structure from near-uniform initial conditions, while the other must be cross-inhibiting to prevent an overall autocatalytic explosion. Inhibition can be substituted by depletion of a substrate required for and consumed by activation. The inhibitory effect must be redistributed fast and widely (due to diffusion or other mechanisms), whereas redistribution of activator has to be constrained. Local deviations from near-uniform distributions are then self-enhancing, but the inhibitory effect due to its wide redistribution causes activation somewhere to proceed only at the expense of deactivation elsewhere until a stable pattern is formed. For wide ranges of parameters, such pattern formation is self-regulating, the form of the pattern being mainly a systems feature of the interacting system and near-independent of details of initial conditions.

The conditions for pattern formation can be given a mathematical form which allows models to be assessed for their ability (or inability) to give rise to patterns. For two components $a(x, t)$ (activator) and $b(x, t)$ (inhibitor or depleted substrate) equations read:

$$\frac{\partial a}{\partial t} = f(a, b) + \mathcal{D}_a(a) \tag{2a}$$

$$\frac{\partial b}{\partial t} = g(a, b) + \mathfrak{D}_b(b) \tag{2b}$$

with f and g accounting for interaction, and operators $\mathfrak{D}_a$, $\mathfrak{D}_b$ for redistribution. Stability of the uniform solution $f = 0$, $g = 0$ can be assessed by conventional methods and is met in a straightforward manner by all models discussed in this paper. The same is true for sufficiently high rates of the inhibitory reaction. The crucial conditions are then that there is autocatalytic activation, that is

$$\left(\frac{\partial f}{\partial a}\right)_{a_0,\, b_0} > 0 \tag{3}$$

near the uniform solution $a = a_0$, $b = b_0$ for $f = 0$, $g = 0$; and that redistribution of b is wide, whereas redistribution of a is restricted.

Many different models can be generated on this basis. Which of them is correct could be decided only by biochemical studies, but the kinetics can be relatively simple, and no features unusual or unknown in molecular biology are required. Gradients, symmetric and periodic distributions in one or several dimensions, can be produced in this way.

A simple example for a pattern-forming system consisting of an activator $a(x, t)$ and an inhibitor $h(x, t)$ is given by

$$\frac{\partial a}{\partial t} = \mu\left(\frac{a^2}{h} - a\right) + D_a \frac{\partial^2 a}{\partial x^2} \tag{4a}$$

$$\frac{\partial h}{\partial t} = \nu(a^2 - h) + D_h \frac{\partial^2 h}{\partial x^2}\,. \tag{4b}$$

An example for a depletion model, with depleted substrate $s(x, t)$ is

$$\frac{\partial a}{\partial t} = \mu(a^2 s - a) + D_a \frac{\partial^2 a}{\partial x^2} \tag{5a}$$

$$\frac{\partial s}{\partial t} = \nu(1 - a^2 s) + D_s \frac{\partial^2 s}{\partial x^2}\,. \tag{5b}$$

Patterns are formed on the basis of Eqs. (4, 5), if

$$\nu > \mu; \quad D_h \gg D_a \text{ or } D_s \gg D_a\,.$$

Fig. 1 a shows an example for the generation of a graded distribution starting from uniform conditions, except for a slight local deviation, modelling for the generation of a polar pattern (such as the generation of a head of a polyp at one margin of a section cut from the animal). Fig. 1 b gives an example of a multiple-peak pattern initiated by random fluctuations. In this case, peaks are distributed

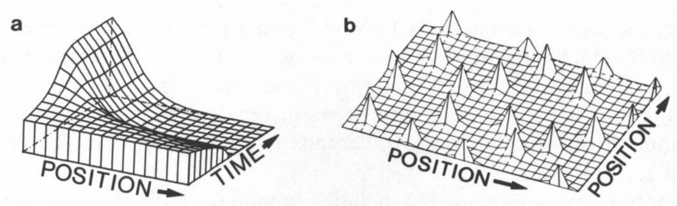

Fig. 1: Pattern formation by autocatalysis and lateral inhibition a) Starting from a near-uniform distribution, with only a very small unspecific advantage (left), a stable gradient is produced in the course of time (front to rear), providing a one-to-one correlation between position and level of activation. The gradient can thus specify an asymmetric biological structure. b) Pattern developed in a two-dimensional field initiated by random fluctuations. Range of inhibition is small compared to the total field size. Many peaks have developed in a non-regular fashion, but the pattern shows a defined texture: Due to the graded inhibitory fields around each peak small distances between peaks are avoided. Such spacing is characteristic, for instance, for stomata of plant leaves (Computer simulations are based on Eq. (4)).

irregularly, but small distances are systematically avoided due to the production of inhibitor extending into the immediate neighbourhood of a peak of activation. The distribution of stomata in plant leaves is a biological example for this type of patterns. There is a hidden order in such seemingly irregular patterns in that the proportion of the total field that is activated as well as the distance distribution between peaks are quantitatively determined and regulated.

Many other types of patterns in one or several dimensions can be modelled for on the same general kinetic basis. Patterns show the empirical self-regulation features of developing systems and quantitative aspects of specific systems (such as regenerating hydra) have been modelled.

The conditions of short-range autocatalysis in conjunction with widely redistributed inhibitory effects can be shown to be mathematically required for pattern formation in the simplest two-factor case. They can be generalized to multicomponent systems as long as a distinction between subsets of components with small and large redistribution is possible. In this case, patterns can be formed if activation is a systems property of the first, and cross-inhibition of the second subset (Gierer, 1981).

Adaptation to socioeconomic problems[1])

To model for socioeconomic inequalities, we introduce a system parameter for advantage a which subsumes self-enhancing (activating) factors such as

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[1] Preliminary accounts of this adaptation have been given in publications of two symposia, one on "Pattern formation of dynamic systems" (see *Gierer*, 1979, r.c.) and the other (held by the American Association for the Advancement of Science) on "Autopoiesis, dissipative structures and spontaneous social orders" (*M. Zeleny*, editor), AAAS Selected Symposium 55, Published by Westview Press for AAAS, 1980, p. 133–149.

wealth, education, and social background, and a parameter s (inversely related to scarcity) which subsumes factors such as the availability of energy, water, land, raw materials, qualified manpower and other resources, and in general represents the (limited) availability of resources depleted as a consequence of activation. In the simplest case, advantage is wealth, which is self-enhancing when in form of capital.

This notion can be extended to include "human capital", taken as an index of the economic effects of education, for example. More generally, a is a system parameter encompassing all effects contributing to self-enhancing advantages including psychological components such as – for example – self-confidence. Since depletion of s corresponds to increasing the scarcity of resources required to generate advantages, s might be inversely related to the price levels of limiting resources.

The main adaptations of the biological theory to be applicable to economic problems are concerned with the choice of parameter space and the mode of redistribution. Biological patterns are formed within physical space. Coherent patterns in real space arise because redistribution, for instance by diffusion, occurs predominantly between neighbours in space. Although some socioeconomic processes are related to order in real geographic space (such as urbanization and the generation of polycentric structures), most economic problems concern distributions in an artificial parameter space, such as the distribution of income and wealth as function of income and wealth, respectively. We must, therefore, describe the distribution of advantages in a space chosen to lead to an intelligible coherent pattern, given the initial conditions as well as rules for preferential redistribution among neighbours in this parameter space. For complex problems there is no guarantee that a suitable parameter space can always be chosen. Often an adequate choice is the array of subgroups arranged in order of initial advantages, leading to a monotonically decreasing distribution. In this representation, the development of subgroups in the course of time and the correlated development of inequalities can be analysed on the basis of models including some simple types of redistribution (e.g. taxation), overall growth, and the coupling or uncoupling between various sections of the society, or between nations or regions.

However, some types of redistribution, particularly random fluctuations of wealth or income, cannot be adequately dealt with using this representation because the initial monotonous array would be upset in the course of time. Then, a more suitable representation is the probability distribution $w(a)$ of advantages. It will be shown later how the equations for self-enhancement can be introduced to calculate, in conjunction with depletion and redistribution, the distribution of advantages $w(a)$.

To model the development and distribution of economic advantages such as wealth (including "human capital") and income we may introduce advantage a describing generalized wealth, accumulating as a function of the difference between production p, generation of advantage per unit time, and removal r by consumption, depreciation and other effects. p is a function of a (thereby accounting for the self-enhancing effects) and of resource availability, s.

Removal by consumption and depreciation will generally be a function of p, which in turn depends on a and s, as well as of a explicitly; further, a redistribution term ($\mathfrak{D}_a$) for a is included accounting, for instance, for taxation, subvention etc. s is assumed to be produced at a limiting overall rate (q_0); its depletion is described by a function q which may depend on p, a, and/or s, and its redistribution by an operator $\mathfrak{D}_s$. Then one obtains for each of N equally sized subgroups (n = 1...N)

$$\frac{da_n}{dt} = p(a_n, s_n) - r(p(a_n, s_n), a_n) + \mathfrak{D}_a(a_1 \ldots a_N, a_n) \tag{6}$$

$$\frac{ds_n}{dt} = q_0 - q(p(a_n, s_n), a_n, s_n) + \mathfrak{D}_s(s_1 \ldots s_N, s_n)\,. \tag{7}$$

According to the notions of self-enhancement, depletion and removal, p and q increase with increasing a and s near the uniform distribution. Removal term r increases with a. Functions p, r and q must be such that the uniform solution in the absence of redistribution $f(a_0, s_0) = 0$, $g(a_0, s_0) = 0$ ($f = p - r$; $g = q_0 - q$) is stable. (This stability can be assessed by conventional methods.)

Upon strong redistribution of s described by $\mathfrak{D}_s$ and weak redistribution of a described by $\mathfrak{D}_a$ inequalities develop if small deviations of subgroups, $a_n = a_0 + \Delta a_n$, from the uniform solution $a_n = a_0$ are self-enhancing; this requires

$$\left(\frac{\partial f}{\partial a}\right)_{a_0, s_0} = \left(\frac{\partial p}{\partial a}\right)_{a_0, s_0} - \left(\frac{\partial r}{\partial a}\right)_{a_0, s_0} > 0\,. \tag{8}$$

In biochemical models of pattern formation it is reasonable to assume that the removal term r is proportional to a; condition Eq. (8) for pattern formation then requires that the production term p increases more strongly than linearly with a, as modelled by the a^2 terms in Eq. (4 a, 5 a). In economy, however, subgroups of higher income and wealth often consume a smaller proportion of their total income and wealth, freeing a larger share for investment and other activities generating further advantages. According to the kinetic conditions of Eq. (8), near-linear terms of self-enhancement are then sufficient for the generation of inequalities.

Models assume a relatively simple form if redistribution of s_n described by $\mathfrak{D}_s$ is sufficient to render a near-uniform value $s_n = s$ for availability of limited resources. If we introduce, in addition, the economically reasonable assumption that depletion is proportional to production

$$q = \text{const.}\ p$$

$s(t)$ is at any time an average over a function of p and is given by the solution of

$$q_0 = \text{const.} \sum_{n=1}^{N} p(a_n, s)\,. \tag{9}$$

This equation is coupled to Eq. (6) to calculate the dynamics of advantages of subgroups a_n.

It is easy to show, by conventional stability analysis, that all models of this class have a stable uniform solution $f(a_0, s_0) = 0$. The essential conditions for the generation of inequalities are than that the relation (8) holds, and that redistribution of a_n is limited.

Redistribution of a_n can be introduced by a redistribution operator $\mathfrak{D}_a$ (Eq. (6)) to account, for example for taxation. In some cases the operator may be quite simple; for instance, if redistribution is proportional to a, this leads to a term contributing to $\frac{da_n}{dt}$

$$\frac{da_n}{dt} = \ldots + d_a \cdot (\bar{a} - a_n); \; \bar{a} = \frac{1}{N} \cdot \sum_{n=1}^{N} a_n \tag{10}$$

with $\bar{a}$ being the average over a_n.

If, in equations of type (6, 7), the array of subgroups is ordered according to initial advantages, the array will remain monotonic for simple types of redistribution such as that of Eq. (10). However, many types of economic redistribution, especially those involving randomizing effects, may be more easily modelled by choosing advantage a itself as parameter space for the distribution of advantages, income or wealth. Advantage distribution $w(a)$ is closely related to the monotonic array of $a(n) = a_n$. The reverse function $n(a)$ describes approximately the number of subgroups with advantage above a, and the probability distribution of advantages $w(a)$ is thus proportional to $-\Delta n(a)/\Delta a$. Once $w(a)$ is calculated, the distribution of any monotonic function of a, such as production term $p(a)$ or removal term $r(a)$ can be derived from $w(a)$.

To calculate the advantage distribution w, the dynamics of the autocatalytic process can be introduced into the dynamics of w. The function $w(a, t)$ can be considered as the density of subgroups in a space; and the term $\partial a/\partial t$ (Eq. (6)) as velocity $v(a)$ of subgroups in a space. It follows that the density change $\partial w/\partial t$ is proportional to the difference of influx and outflux per unit width given by

$$\frac{\partial w}{\partial t} = -\frac{\partial (wv)}{\partial a} \tag{11 a}$$

v is given according to Eq. (6) by

$$v = \frac{\partial a}{\partial t} = f(a, s) + \mathfrak{D}_a(a); \; f = p - r. \tag{11 b}$$

Eq. (11 b) must be coupled to an equation describing, for any time during the development of the distribution, the value assumed by the depleted substrate $s(t)$. Again this can easily be calculated on the assumptions leading to Eq. (9) that s is distributed rapidly and uniformly, and depletion q of s is proportional to the production term p. Then, at any given time, s is the solution of

$$q_0 \sim \int w(a, t)\, p(a, s)\, da\,. \tag{12}$$

Eq. (11 a) allows the introduction of various types of redistribution in a space. Redistribution from privileged to underprivileged subgroups (e.g. by taxation) can take the form of a contribution to velocity v

$$v_t = \mathcal{D}_a(a) = \overline{\chi(a)} - \chi(a); \; \overline{\chi(a)} = \int \chi(a)\, w\, da\,.$$

In the simplest case (Eq. (10)) v_t is a linear function $d_a(\bar{a} - a)$.

The representation of inequalities in terms of the distribution $w(a)$ allows, in addition, the introduction of redistribution by random gains and losses of advantages (which may themselves depend on a). These would give rise to a contribution to $\partial w/\partial t$ (Eq. (11 a)) which is of the diffusion type

$$\frac{\partial w}{\partial t} = \ldots + \frac{\partial^2 (w\psi(a))}{\partial a^2}\,. \tag{13}$$

Taken together, these effects of autocatalysis and redistribution lead to a dynamics for the distribution $w(a, t)$ of the type

$$\frac{\partial w}{\partial t} = -\frac{\partial (wf(a, s))}{\partial a} - \frac{\partial (w(\overline{\chi(a)} - \chi(a))}{\partial a} + \frac{\partial^2 (w\psi(a))}{\partial a^2} \tag{14}$$

to be coupled to Eq. (12) for $s(t)$.

For some functions of this type, special considerations are required to deal with boundary conditions for $a = 0$ and with possible singularities of solutions. In any case, however, it is easy to adapt Eq. (12, 14), for the purpose of computer calculations, to a discrete array of finite elements in a space (a_1 to a_N of equal spacing $a_k = k \cdot a_s$, and $w_k(t) = w(k \cdot a_s, t)$ with $k = 1 \ldots N$). To calculate the development of the distribution w_k by computer, at each iteration, a proportion of w_k which is proportional to the velocity v as given by Eq. (11 b) is shifted from a_k to a_{k+1} if v is positive, and from a_k to a_{k-1} (except for $k = 1$) if v is negative. Randomizing redistribution takes the form of a contribution (Eq. (13)):

$$\frac{dw_k}{dt} = \ldots + \frac{\Delta^2 (w_k \cdot \psi(a_k))}{\Delta k^2}\,. \tag{15}$$

Other types of redistribution, accounting, for instance, for the effect of inheritance patterns can also be envisaged. Any contribution of redistribution is of the general form

$$\frac{dw_i}{dt} = \ldots + \sum_{k=1}^{N} g_{ik} \cdot w_k\,.$$

Since for any distribution, $\sum \frac{dw_i}{dt} = 0$ and $\sum w_i = 1$, there is the constraint

$$\sum_{i=1}^{N} g_{ik} = 0 \qquad k = 1 \ldots N$$

Whether or not a redistribution is neutral (in other words, whether gains of advantages by some subgroups completely match losses by others) depends on the matrix g_{ik}; randomizing redistributions of the type Eq. (15) (with suitable boundary conditions to avoid flux towards negative advantages) are neutral.

Simple computer models

A relatively simple example of a function leading to inequalities due to self-enhancement and depletion is given by a system exhibiting nearly linear self-enhancement of advantages a (except for a saturation term A), a linear effect of depleted factor s upon autocatalytic production p, depletion of s in proportion to p and continuous uniform redistribution of s. Consumption and depreciation will generally be complex functions of $p(a, s)$, and of a and s directly. However, a main condition for the generation of inequalities is that removal term r is less "elastic" with respect to a than p; this will be the case if the proportions of income and wealth consumed decrease with increasing advantage. For the demonstrations of this paper this effect will be approximated by taking removal term r as nearly proportional to a_n^ν with ν considerably below 1 (say 1/2). We further assume redistribution of a by taxation to be linear according to Eq. (10), and initiation by small variations in basic production ϱ_n°, or in initial values a_n. The equations of type (6, 9) then read

$$\frac{da_n}{dt} = \varrho_n^0 + \frac{\varrho a_n s}{1 + a_n/A} - \mu a_n^\nu - d_a \cdot (a_n - \bar{a}) \tag{16a}$$

$$\bar{a} = \frac{1}{N}\sum_{1}^{N} \cdot a_n; \qquad s = \frac{Nq_0}{\sum_{1}^{N} \frac{a_n}{1 + a_n/A}}. \tag{16b}$$

Fig. 2 a shows striking inequalities generated on the basis of Eq. (16), when initiated by a small random fluctuation of ϱ_n^0 (redistribution $d_a = 0$). The final degree of inequality is nearly but not absolutely invariant with variations in the details of initial conditions. In Fig. 2 b the distribution is re-ordered according to the monotonic array of advantages a_n. Fig. 2 c demonstrates that strong redistribution of advantages described by d_a in Eq. (16 a) completely prevents the production of self-enhancing inequalities. Without a saturation term ($A \to \infty$; $p = \varrho_n^0 + \varrho a_n s$) all advantages become confined to the richest subgroup

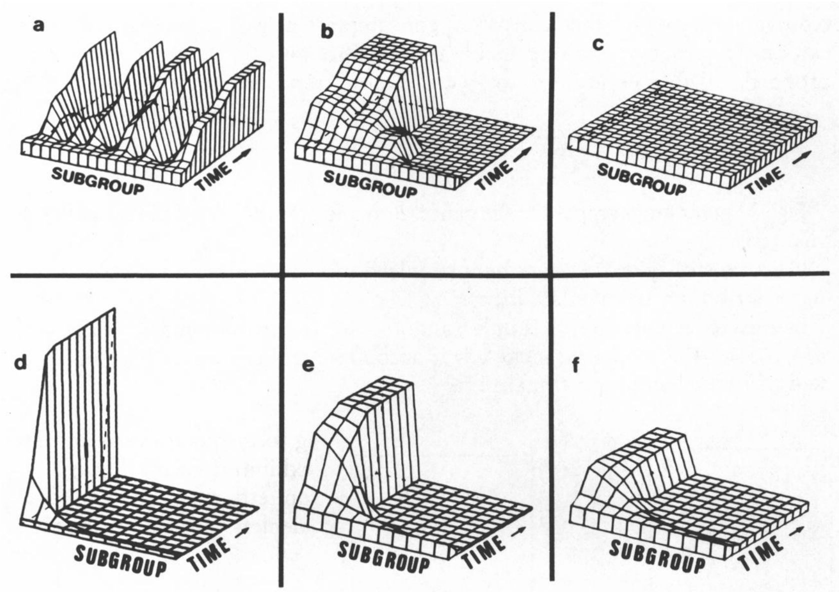

Fig. 2: Model for socioeconomic inequalities a) Stable inequalities between subgroups are formed from near-uniform initial conditions when initiated by slight random fluctuations (Eq. (16 a, b)). b) Re-ordering of Fig. a according to the monotonic array of initial advantages. c) If redistribution (term d_a in Eq. 16 a)) is sufficiently dominant, the generation of inequalities is totally prevented. d) Without a saturation term ($A \rightarrow \infty$ in Eq. (16 a)), activation becomes confined to a single subgroup with the highest initial advantage. e) Non-linear redistribution (Eq. (16 a′, b)) leads to activation of a defined part of the subgroups even in the absence of saturation ($A \rightarrow \infty$). f) Example for the generation of inequalities based on a generalization of Eq. (16 a) including an explicit depreciation term (Eq. (16 a″, b)).

(Fig. 2 d). Thus it is the saturation term A (modelling for decreasing efficiency of advantage with respect to self-enhancement) which leads to defined proportions of subgroups with high and low levels of advantages respectively, the proportion depending on the parameters of the system. The proportioning effect can also be obtained by overproportional redistribution (e.g. due to progressive taxation), as described by the following equation:

$$\frac{da_n}{dt} = \varrho_n^0 + \varrho a_n s - \mu a_n^v - d_a(a_n - \bar{a}) - d_a'(a_n^2 - \overline{a^2}) \,. \qquad (16\,a')$$

An example is shown in Fig. 2 e.

The simple Eq. (16 a) does not deal explicitly with effects such as depreciation of capital or outdating of education and training which contribute to removal of advantages. These effects may be considered as formally subsumed under the removal term r which then consists of consumption as well as generalized depreciation. However, it is also possible to introduce an explicit depreciation term proportional to a in addition to a consumption term proportional to a^ν:

$$\frac{da_n}{dt} = \varrho_n^0 + \frac{\varrho a_n s}{1 + a_n/A} - \sigma a_n - \mu a_n^\nu - d_a(a_n - \bar{a}) . \qquad (16\,a'')$$

Fig. 2 f gives an example for the generation and stabilization of inequalities on this basis.

Equations of type (16) may be introduced into the equation (14) for advantage distribution to calculate $w_n = w(a_n)$.

In this representation, a simple randomizing redistribution term (15) with ψ = const. $(1 + a)$ can be included. It accounts for fluctuations both independent of as well as proportional to a.

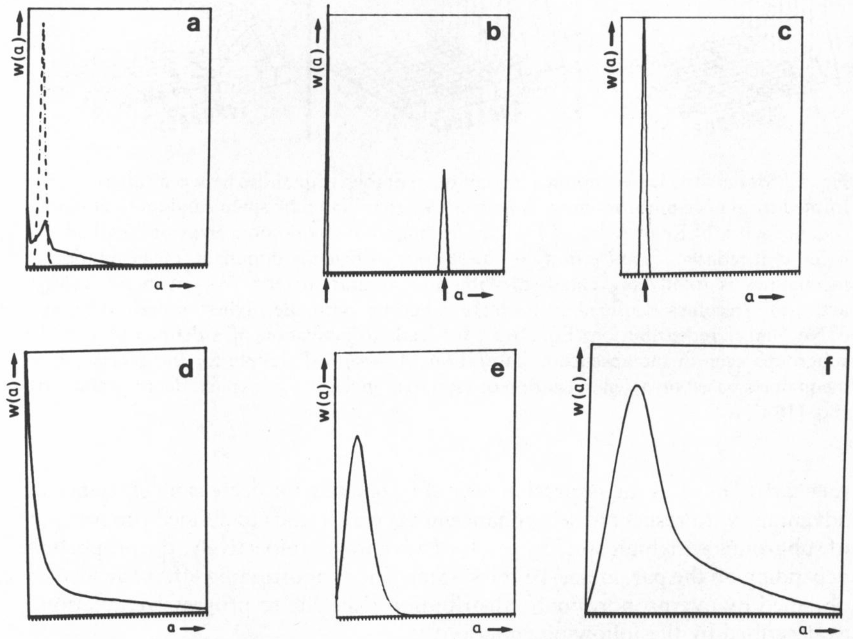

Fig. 3: Distribution of advantage $w(a)$ according to Eqs. (12, 14) based on the model Eq. (16 a, b) a) (---) initial (——) intermediate distribution. b) Final bimodal distribution (arrows), similar to Fig. 2 b ($d_a = 0$). c) Redistribution by a large term d_a prevents the development of inequalities (similar to Fig. 2 c). d) Randomizing redistribution of type Eq. (15) with ψ = const. $(1 + a)$ leads to a monotonous decrease of $w(a)$ for high values of a ($d_a = 0$). e) Parameters as in Fig. d, but with a large redistribution term d_a, the latter cancelling the self-enhancement effect. f) In addition to the distribution $w(a)$ as given in d) a basic advantage following a Gaussian distribution is assumed and the distribution for total advantage plotted.

Figs. 3 a–c show the generation of a stable unequal distribution on the basis of Eq. (16 a, b) (corresponding to the cases demonstrated in Fig. 2 a–c) in terms of advantage distribution $w(a)$: A bimodal distribution, giving rise to a privileged and underprivileged sector, develops from near-uniform initial conditions (Fig. 3 a, b). Introducing a strong redistribution term d_a (Eq. (10)) completely abolishes the generation of inequalities by self-enhancement (Fig. 3 c), because now the uniform solution is stable. Fig. 3 d shows that adding a random fluctuation (Eq. (15) with ψ = const $(1 + a)$, $d_a = 0$) smoothes out the pattern of Fig. 3 b giving rise to a wide continuous distribution of advantages extending smoothly towards high values of a. To demonstrate that this feature is due to self-enhancement, a large value d_a is introduced (as in Fig. 3 c) preventing the self-enhancing effects; the inequalities produced are now due to the randomizing term (Eq. (15)) alone (Fig. 3 e). They are much smaller than in Fig. 3 d and advantages do not extend towards high values of a.

Distribution of personal wealth and earnings

The distribution of advantages $w(a)$ provides a basis for modelling the distribution of personal wealth, income and earnings. One of the most interesting empirical features of such distributions is the shallow decrease towards higher values, deviating strongly from a Gaussian distribution. If a represents generalized wealth, including contributions to "human capital", wealth distribution would be a transform of $w(a)$ (possibly with some further randomizing because of the statistics of splitting into material wealth and other contributions such as "human capital"); in simple cases wealth may be proportional to a, and the distribution of wealth thus proportional to $w(a)$. The function $w(a)$ modelled in Fig. 3 d resulting from self-enhancement, depletion and redistribution shows the non-Gaussian characteristic of a shallow decrease of advantages towards high values of a.

Models for income and earnings distribution require further considerations: In contrast to close-to-zero wealth, close-to-zero earnings are rare; one expects that there is a basic contribution e_b in addition to the contribution with self-enhancing features e_s to total earnings e, so that the distribution $W(e)$ for earnings is obtained by suitable folding of distributions for the basic and the self-enhancing components, $w_b(e_b)$ and $w_s(e_s)$. Whereas w_b may be expected to follow a Gaussian distribution, the self-enhancing distribution w_s is closely related to the advantage distribution $w(a)$.

In the simplest model one may assume that e_s is proportional to a, so that $w(a)$ represents directly $w_s(e_s)$, giving rise to a total distribution as shown in Fig. 3 f. Parameters can be adapted to resemble the empirical earnings distributions in the U.S. of 1971 (Fig. 4).

A simple relation between advantages and earnings implies however quite abstract meanings of production and removal terms p and r: a is an earnings-generating capacity; p is the production rate of this capacity, and r the removal rate due to outdating of education and other advantages contributing to a.

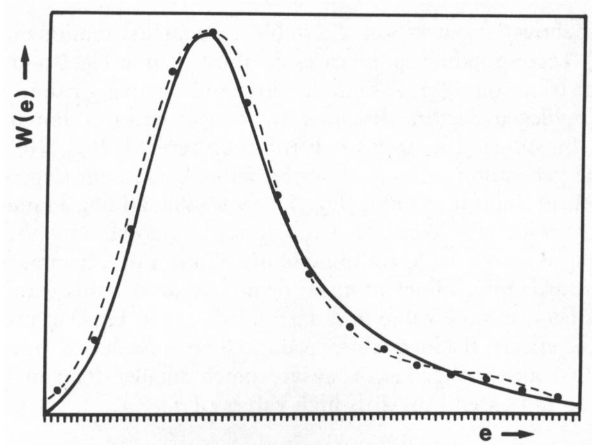

Fig. 4: Model for earnings or income distribution. Parameters are adapted to resemble the earnings distribution of the U.S. in 1971 (in arbitrary units) given by (···) (Source: US Bureau of Census, Current Population Report, No. 85, 1972, quoted in Atkinson (1975), p. 76)). Advantage distribution $w(a)$ is calculated on the basis of Eq. (12, 14, 16 a, b) with a randomizing redistribution of type Eq. (15) ($\psi \sim 1 + a$). The model thus incorporates self-enhancement of advantages as well as random steps up and down in the course of time. In one plot (——) earnings are taken as proportional to a, and an additive basic advantage with a Gaussian distribution is assumed (similar as in Fig. 3 f). In the other plot (---) it is assumed that earnings are porportional to the production term p (Eq. (17) with $\gamma = 0.75$). Advantage distribution is calculated on the basis of Eqs. (12, 14), the distribution $w_p(p)$ is derived and an additive Gaussian distribution of basic earnings is assumed.

Another approach gives production and removal terms p and r more direct economic interpretations: p is the production rate of generalized wealth (including "human capital"), r removal and depreciation, the reinvested difference $p - r$ the advantage gain which feeds back on future productivity in the generation of advantages p. Then income or earnings (depending on whether a includes also real or only "human" capital) may be taken as proportional to suitable functions p.

To model for a continuous distribution with respect to p, the function p should be chosen not to approach an absolute upper limit for high values of a. This suggests a minor generalization of Eq. (16 a) to

$$\frac{\mathrm{d}a_\mathrm{n}}{\mathrm{d}t} = p - \mu a_\mathrm{n}^\nu + d_a \cdot (\bar{a} - a_\mathrm{n}); \; p = \varrho_\mathrm{n}^0 + \frac{\varrho a_\mathrm{n} s}{1 + \left(\frac{a_\mathrm{n}}{A}\right)^\gamma} \tag{17}$$

with γ somewhat below 1 to avoid an upper limit of p, again combined with a random redistribution of the type Eq. (15). The distribution $w_p(p)$ of earnings proportional to p is obtained by transforming $w(a)$ according to the equation

$$w_p(p(a)) = \frac{w(a)}{\left(\frac{\mathrm{d}p(a)}{\mathrm{d}a}\right)}$$

$w_p(p)$ then represents the self-enhancing contribution to earnings $w_s(e_s)$; this is again combined with a Gaussian distribution of basic production $w_b(e_b)$, yielding the total earnings distribution $W(e)$. In Fig. 4, a distribution of this type is shown with parameters again adapted to resemble the US earnings distribution in 1971.

Since several parameters have been adapted to obtain agreement between the empirical earnings distribution and the distribution generated by the model, the fit shown in Fig. 4 may not seem surprising. Many more studies would be required to give the model parameters an empirical basis. However, the correspondence of the general types of theoretical and empirical distribution functions showing the non-Gaussian "trail" toward high earnings and wealth is far from trivial and is not easily obtained by alternative models without complex assumptions. In the models proposed, it results from and depends on self-enhancement and depletion. By themselves, these effects would lead to a binary distribution as shown in Fig. 3 b. The random redistribution, preferentially though not exclusively between neighbours in advantage space (that is, by finite steps of gains or losses of advantages), leads to the smooth distribution of Fig. 3 d, f and 4. It is emphasized that this distribution is not just a superimposition of two Gaussian curves; it results from the combined effect of self-enhancement and redistribution on the dynamics of the distribution of advantages as given in Eq. (14).

Economic growth

The models described thus far lead to a stable unequal distribution of advantages which is near-independent of initial conditions and which forms even from random fluctuations of initially near-uniform distributions. These notions do not imply that initial and intrinsic inequalities between subgroups do not exist; they can be introduced into such models for instance as different $a_n(t = 0)$, ϱ_n^0, ϱ_n for various subgroups in equations of type (16).

Further, it is possible to include overall growth as function of efficiency of the economic system as a whole, e.g. due to technological progress. This can be done by introducing a factor F measuring the state of efficiency which may be assumed to increase slowly at a rate determined by average advantage $\bar{a}$, e.g.

$$\frac{\mathrm{d}F}{\mathrm{d}t} = \varepsilon\bar{a}\,;\; \bar{a} = \frac{1}{\mathrm{N}} \cdot \sum_{1}^{\mathrm{N}} a_n \qquad (18)$$

F may in principle affect any term in Eqs. (6, 7, 16) for advantages and depletion. Such models are based on a conceptional separation of system interactions generating inequalities, from superimposed system features affecting overall growth. They can be applied both to inequalities between subgroups within a society and to inequalities between nations and regions.

The effect of changes of efficiency factor F (Eq. (18)) on growth and inequalities depends strikingly on the particular choice of models. This will be demonstrated by a few simple examples. F is introduced into equations of type (16 a″, b) as follows:

$$\frac{da_n}{dt} = \left(\varrho_0^n + \frac{\varrho a_n s}{1 + a_n/AF^\gamma} - \sigma a_n\right) F^\alpha - \mu a_n^\nu - d_a(a_n - \bar{a}) \qquad (19\,a)$$

$$s = \frac{q_0 F^\beta}{\sum \frac{\varrho a_n F^\alpha}{1 + a_n/AF^\gamma}} \qquad (19\,b)$$

α describes an effect of F on the efficiency of self-enhancement of advantages (Eq. (19 a)) which feeds back on depletion (Eq. (19 b)). β accounts for the effect of F on the availability (or efficiency of use) of limiting resources s. γ accounts for the effect of F on saturation of advantages and is taken as equal to β in the model calculations. Fig. 5 a shows a mixed case $\alpha = \beta = ½$ leading to growth. If the effect of F on self-enhancement of advantages is not accompanied by an increase of availability, or efficiency of use, of limiting resources ($\alpha = ½$; $\beta = 0$), a nearly stable unequal distribution rather than growth results (Fig. 5 b). Figure 5 c demonstrates a case where F affects the efficiency of use (or availability) of limiting resources ($\beta = ½$; $\alpha = 0$) leading to growth. Whether growth is accompanied by a reduction of inequalities (as in Fig. 5 a) or not (Fig. 5 c) is strongly dependent both on the choice of the particular model (Eq. (19)) and the feedback of efficiency F on the model parameters. Figures 5 d–f show a calculation similar to that in Fig. 5 a, a mixed case with efficiency affecting various terms, for small (Fig. 5 d), medium (Fig. 5 e) and large (Fig. 5 f) redistribution terms d_a. The model is chosen so that advantages for all subgroups, including the least privileged one, are somewhat higher *in the long run* if redistribution is restricted and inequalities are high, in particular at intermediate stages. The example shows how an optimizing problem can be treated on the basis of the theory: If we demand that no subgroup should at any time fall below a certain level of advantage, an intermediate degree of redistribution such as that shown in Fig. 5 e would be optimal. It should be emphasized, however, that a long-term advantage of transient inequalities is a property of this particular model; other models lead to optimal development of the poorest subgroups for near equal distributions.

Evidently, such models would have predictive or explanatory value only if substantiated by empirical evidence on the proper choice of parameters. Depending on conditions, productivity increases may contribute essentially to overall growth, or mainly to growth of some subgroups at the expense of others, and may lead to increased or reduced inequalities. Reduction of inequalities by redistribution can, but need not, decrease overall growth and the longterm development of the least privileged subgroup. Even at this stage of formal treat-

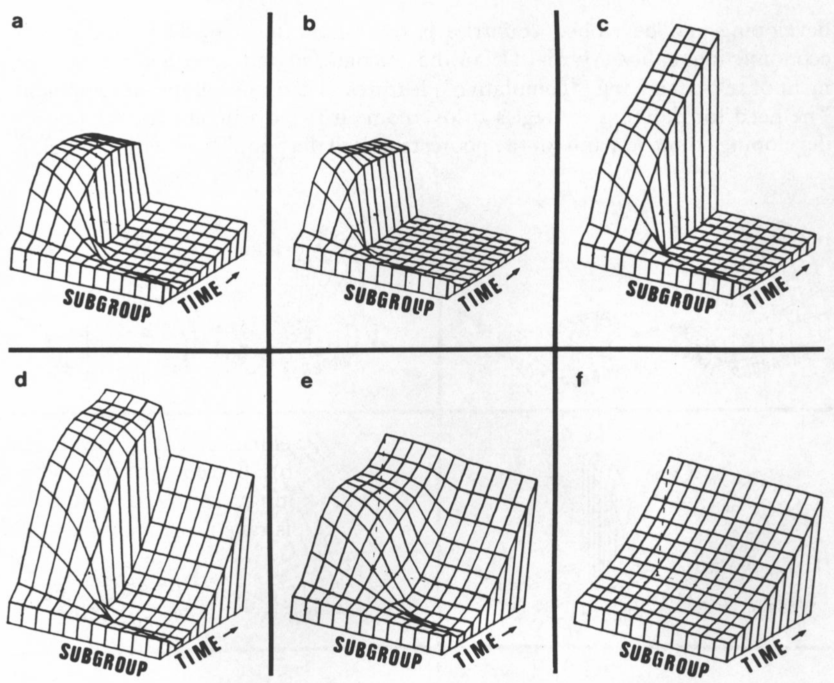

Fig. 5: Incorporation of overall growth into models for socioeconomic inequalities (Eqs. (18, 19)). a) Growth results if efficiency factor F is assumed to affect self-enhancement as well as efficiency of use of limited resources ($\alpha = \beta = \frac{1}{2}$ in Eq. (19)). b) No growth results if the efficiency of self-enhancement of advantages is increased, without an accompanying increase in availability (or efficiency of use) of limiting resources ($\alpha = \frac{1}{2}$; $\beta = 0$). c) Growth resulting from an effect of F on availability (or efficiency of use) of limiting resources ($\beta = \frac{1}{2}$; $\alpha = 0$) d–f). Effect of growth similar as in a) with redistribution d_a (Eq. (19 a)) increasing in the array d, e, f ($\alpha = \beta = \frac{1}{2}$).

ment, however, it is evident that in economic systems where self-enhancement and depletion matter, general overall statements on relations between growth and inequalities are to be considered with some caution: their validity is expected to depend on subtle and intricate interaction properties within the economic system, and may change more or less intentionally according to the political and economic boundary conditions set.

Issues of coupling and uncoupling (self-reliance) in development

As an example of application of the theory of inequalities resulting from self-enhancement and depletion some aspects of the relation between developing and developed countries will be discussed. The discrepancy of wealth between developing and developed countries is one of the most evident examples of economic inequality. Myrdal (1956) has recognized and described the involvement of self-enhancing ("cumulative") features as causes of under-development. The need for defining strategies to overcome it is most urgent for the poorest developing countries, and for the poorest parts of the population within develop-

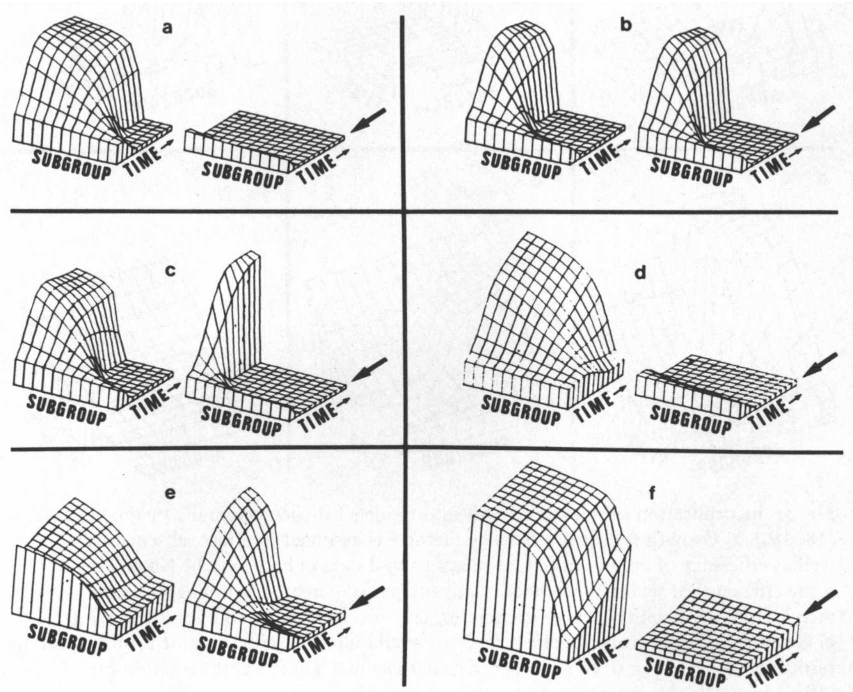

Fig. 6: Model for the effect of coupling and uncoupling of developing from developed countries. Effects of coupling and uncoupling between privileged and underprivileged half of an array on the distribution of advantage, modelling for strategies of uncoupling between developing and developed countries. Calculations are based on Eq. (16 a, b). Initial advantage (ϱ_n^0 in Eq. (16 a)) are slightly graded decreasing from left to right. In each computer diagram, the right half represents the underprivileged half (sector) and its right edge the time course of development for the most underprivileged subgroup. The arrow of type ↙ points to the state reached by the poorest subgroup of the underprivileged sector. a) complete coupling between privileged and underprivileged sectors, b) complete uncoupling, c) partial uncoupling of redistribution of limiting resources. d–f) Inclusion of technological progress effect: d) with uncoupling of technological progress advantage, but coupling of self-enhancement and depletion. e) After different states of technological progress are reached as described in d), further development is calculated with complete uncoupling of advantages and depletion as well as technological progress, whereas (f) depicts further development with complete coupling (including complete coupling with respect to further technological progress).

ing countries. One of the proposals currently being discussed emphasizes a policy of "self-reliance", which would imply a partial uncoupling of the economies of the developing and developed countries. While such dissociation might disturb some present beneficial interactions, it is often argued that on the whole developing countries would gain by such strategies.

The above models might offer some insight into this problem by emulating the dynamics of inequalities which are based on self-enhancement and depletion effects. As a crude model, countries are represented by one or several equally sized subgroups, arranged according to initial advantages, which therefore follow a slightly graded distribution. Let us then divide the array into two sectors according to higher and lower intial advantages, and follow their development according to Eq. (16). Uncoupling implies that the parameters representing averages in Eq. (16 a, b), namely $\bar{a}$ and s, are averaged over each section separately, whereas coupling corresponds to averaging a and s over both sections. With complete coupling between the sectors, advantages are confined to the privileged sector (Fig. 6 a). With complete uncoupling each sector would develop internal inequalities; the richer part of the poor sector would benefit from uncoupling at the expense of a poorer part of the rich sector, but the poorest part of the poor sector does not significantly gain by uncoupling (Fig. 6 b) unless increased redistribution of advantages within the underprivileged sector is introduced. Partial uncoupling of depletion leads to a small portion of the underprivileged sector becoming rich, but again there is no improvement for the poor part of the poor section (Fig. 6 c).

Further, effects of technological progress may also be introduced as factors (Eq. (18, 19)). For demonstration purposes the continued effect of efficiency factor F on parameters ($\alpha = \beta = 1/2$ as in Fig. 3 a, d–f) was assumed. F is taken as indicator of the state of technological progress increasing at a rate depending on average advantage $\bar{a}$ (Eq. (18)). The resulting distribution of advantages then depends on whether F increases as a function of overall advantage averaged over both the privileged and the underprivileged sectors, or whether the inrease of F is uncoupled leading to a greater increase in the privileged sector according to the higher internal average of a. In the latter case, the privileged sector acquires a higher efficiency F than the underprivileged sector (Fig. 6 d). Taking this as representing the present state in the world, we may compare a further strategy of complete uncoupling wherein the underprivileged sector depends on internally generated technological progress (Fig. 6 e), with a strategy of complete coupling including, from the present onward, full participation of the underprivileged sector in further technological progress (Fig. 6 f). The comparison reveals that uncoupling may be beneficial for part of the underprivileged sector, but can nevertheless be disadvantageous for the poorest subgroups.

This qualitative model already suggests that the consequences of uncoupling policies are subtle and do not lend themselves to dogmatic conclusions. Partial uncoupling could be beneficial for the development of the poorest subgroups of the underprivileged sector when redistribution of advantages within the underprivileged sector is increased and when participation in technological progress from the privileged sector persists, but otherwise it may be harmful for the poorest members of the sector. Detailed studies will require relating systems parameters a and s to specific entities, such as capital, resources etc. It should be emphasized that the model will not have predictive value, unless further developed in quantitative empirical terms. Nonetheless the concepts of self-enhancement and depletion effects which have been introduced may be useful for an adequate discussion of the problem even at the level of intuition and qualitative verbal consideration.

Multi-dimensional models: Inequalities between nations and social classes or subgroups

Similar models as for the distribution among nations can be made, with respect to coupling and uncoupling, for distributions among social classes or subgroups within a society. Ideally, one would like to model simultaneously in two dimensions for nations n as well as classes or subgroups m. The models for the generation of inequalities can be formally extended in a straightforward manner to the distribution of advantage in more than one dimension. The metric is again chosen such that each element is equally sized. Generalized equations for the generation of inequalities of type (6, 7, 16) in two dimensions then read

$$\frac{da_{mn}}{dt} = \varrho^0_{mn} + \frac{\varrho\, a_{mn}\, s_{mn}}{1 + a_{mn}/A} - \mu\, a^{\nu}_{mn} + \mathfrak{D}^{M}_{a}(a_{ik}) + \mathfrak{D}^{N}_{a}(a_{ik}) \tag{20a}$$

$$\frac{ds_{mn}}{dt} = q^0_{mn} - \frac{\varrho\, a_{mn}\, s_{mn}}{1 + a_{mn}/A} + \mathfrak{D}^{M}_{s}(s_{ik}) + \mathfrak{D}^{N}_{s}(s_{ik}) \tag{20b}$$

$$(m, i = 1 \ldots M; \qquad n, k = 1 \ldots N)$$

Redistribution operators $\mathfrak{D}^M_a$, $\mathfrak{D}^N_a$, $\mathfrak{D}^M_s$ and $\mathfrak{D}^N_s$ refer to the redistribution in the two dimensions of parameter space; the inequalities formed and stabilized, in two dimensions, depend on preferential redistributions in one or the other dimension. Technological progress (eq. (18)) may be introduced as functions of advantage averaged over nations, or subgroups, or combinations of both. Simple examples for asymmetric distribution functions have been given elsewhere (Gierer, 1979).

Discussion

In the preceding sections it has been shown how a theory of biological pattern formation can be adapted and applied to the generation and assessment of models for socioeconomic inequalities: If self-enhancing advantages are redistributed relatively little, whereas the depletion of limiting resources is widely distributed, stable unequal distributions of advantages are produced even from near-equal initial conditions. The distribution attained is mainly due to the dynamics of the interacting system determined by self-enhancement, depletion and redistribution rather than by the degree of initial variations. The dynamics of self-enhancement can be introduced into calculations of the distribution function of advantages. Models constructed on this basis for the personal distribution of income and wealth show the empirically observed non-Gaussian characteristic with a shallow decrease toward higher values. Overall growth, e.g. due to technological progress, as well as differences in efficiency among subgroups can be incorporated into the models. Socioeconomic inequalties can be studied with reference to subgroups within societies as well as between nations and regions; in particular, the models allow the study of the development of the least privileged subgroups. While in some applications it may be sufficient to consider advantage as a system parameter for economic factors in the usual sense of the word (such as wealth, the economic benefits of education etc.), the inclusion of social and psychic factors of self-enhancement (such as personal connections and self-confidence) is expected to yield, in other cases, a better approximation despite the methodological difficulties of including psychic components into a mathematical scheme.

No claim is made that socioeconomic inequalities are entirely due to self-enhancement and depletion. However, a theory based on these effects can be supplemented to deal with intrinsic differences between subgroups, whereas theories based primarily on such intrinsic differences can hardly incorporate the self-generating effects that are expected to contribute to the generation of inequalities.

The theory discussed might be helpful at several levels: One would be to introduce the formalism into schemes of quantitative systems analysis to allow for the self-generating and self-stabilizing aspects of inequalities. It must be stressed that many more empirical studies would be necessary to give models of this type any predictive value. However, even in the present state some non-trivial qualitative system features emerge, and attention can be focussed on those systems properties which depend sensitively on self-enhancement, depletion and redistribution. Acquaintance with these features is useful for semiformal and non-formal procedures as well which underly most policy decisions combining objective information, verbal discussions, and intuition. The quality of the latter depends on the insight into the qualitative properties and characteristics of dynamic systems.

A further aspect of this work is in the recognition of general isomorphisms between generation of structures in various domains. Self-enhancement in conjunction with inhibitory or depletion effects, as proposed to explain biological pattern formation, are evidently involved in the inorganic domain: Autocatalytic effects are essential to understand the generation of structures such as stars and galaxies, crystals and dunes, waves and clouds. In social and economic systems the accumulation of capital, urban congestion, or the generation of traffic jams are obvious examples for self-enhancement. In pattern recognition, activation in conjunction with lateral inhibition plays a major role, too, as in the effect of "edge enhancement" in vision, based on the cooperation of activating and inhibiting synapses in neural networks (Kuffler, 1952; Kirschfeld and Reichardt, 1964).

The results described above indicate that the generation of socioeconomic inequalities has some properties isomorphic to the production of structures in other fields including biology. The approach of this paper, written by a biophysicist, presumes that understanding of processes, models and results in one such field may be helpful for understanding the other.

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Summary

Socioeconomic inequalities are functions not only of intrinsic differences between persons or groups but also of the dynamics of their interactions. Inequalities can arise and become stabilized if there are advantages (such as generalized wealth including "human capital") which are self-enhancing, whereas depletion of limiting resources is widely distributed. A recent theory of biological pattern formation has been generalized, adapted and applied to deal with this process. Applications include models for the non-Gaussian distribution of personal income and wealth, for overall economic growth in relation to inequalities and for effects of uncoupling strategies between developing and developed countries.

Zusammenfassung

Eine Theorie für die Erzeugung räumlicher Ungleichheiten bei der biologischen Gestalt- und Musterbildung wurde zur Anwendung auf sozioökonomische Ungleichheiten adaptiert und weiterentwickelt. Ökonomische Ungleichheiten können durch Selbstverstärkung von Vorteilen (z. B. von verallgemeinertem Kapital einschließlich „menschlichen Kapitals" in der Form von Ausbildung usw.) entstehen, wobei die begrenzte Verfügbarkeit allgemeiner Ressourcen zu stabilen Ungleichheiten führen kann; Voraussetzung ist, daß die Umverteilung von Vorteilen relativ gering ist. Wachstum sowie Unterschiede der Effizienz von Untergruppen können in derartige Modelle eingebaut werden. Es wurde gezeigt, wie auf Grund der Dynamik der Selbstverstärkung die Verteilungsfunktion von Vorteilen (z. B. von Wohlstand oder Einkommen) darstellbar ist. Auf dieser Grundlage läßt sich die empirisch gegebene Abweichung von einer Gauss-Verteilung in relativ einfacher Weise erklären. Solche Modelle lassen sich auf die personale Verteilung innerhalb einer Gesellschaft ebenso wie auf ökonomische Unterschiede zwischen Ländern oder Regionen anwenden. Einige Aspekte von Entkopplungsstrategien ("Self-Reliance") zwischen Entwicklungs- und Industrieländern werden diskutiert. In der Hauptsache stellt die Arbeit die Systemaspekte der Erzeugung von ökonomischen Ungleichheiten auf Grund von Effekten der Selbstverstärkung, der Verknappung und der Umverteilung dar, wobei die Isomorphie mit Strukturbildungen in den Bereichen der Biologie und Physik von besonderem Interesse ist.

Professor Dr. Alfred Gierer, Max-Planck-Institut für Virusforschung, Spemannstr. 34, 7400 Tübingen, W.-Germany.