

Biocybernetic and thermodynamic perspectives of landscape functions and land use patterns

Zev Naveh

Technion, Israel Institute of Technology, Haifa 32 000, Israel

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Abstract

This paper develops and applies two concepts which are fundamental to landscape ecology. These concepts concern biocybernetics, which is the theory of regulation of biological and ecological systems, and thermodynamics, especially the flux of energy and the production of entropy. The landscape state factors, including site conditions and fluxes of energy, materials, and organisms, are shaped by the biocybernetic and thermodynamic processes. This theory provides us a way of understanding and discussing complex human interactions with landscape systems, expressing our concept of the whole landscape system (what I have termed the Total Human Ecosystem), and linking landscape ecology with several of the most powerfully creative ideas in modern science.

Introduction

In this paper landscapes will be dealt with in their totality as physical, ecological and geographical entities, integrating all natural and human caused ('cultural') patterns and processes along spatial, temporal and conceptional scales. As has been explained elsewhere (Naveh 1982; Naveh and Lieberman 1984), landscapes can be considered as concrete, space/time defined holons of the Total Human Ecosystem with increasing complexity from the ecotope, the smallest and simplest landscape holon, to the ecosphere, the largest and most complex, global one.

Throughout evolution, physico-chemical and biological patterns and processes have shaped the structure and function of terrestrial landscapes and their subsystems. These landscape systems are dependent variables of landscape state factors, name-

ly initial geological, hydrological and physiographical site conditions and the external flux potentials of energy, nutrients and organisms reaching or leaving the site.

Following Jenny (1961), we can describe these factors by a natural landscape state factors equation:

$$l, s, v, b = f(L_0, P_x, t) \quad (1)$$

Where l, s, v, b are the internal properties of the landscape made up of soil, vegetation and other elements of the biotic community as dependent variables of the major state factors: L_0 is the initial geosphere state factor of the larger landscape holon at time zero; P_x is the external flux potential of energy, material, information and organisms, and t is the age of the landscape system.

Humankind from its early beginnings has used these functions for its own benefit and has in-

roduced new patterns and processes that modified the natural landscapes into semi-natural landscapes or converted them into agricultural and urban-industrial landscapes. In this way, the closely interlaced mosaics of our cultural landscapes were created.

For the human-caused or anthropogenic functions, the following general semi-natural landscape state factor equation can be used.

$$l s, v, b = f(H, L_o, P_x, T) \quad (2)$$

Where H is the human land use state factor as an additional driving force, and T is the duration of this land use pattern.

In the more far-reaching anthropogenic functions of the agricultural landscape, H has become a dominant state factor by adding cultural artifacts (a), and changing not only the dependent variable but also some of the other state factors through additional inputs of energy, material and cultural information, therefore:

$$l s, v, b, a = f H(L, P_x, T) \quad (3)$$

Finally, in the built-up landscape state factor equation the living systems of the landscape holon has been totally replaced by human artifacts, therefore:

$$l a = f H(L, P_x, T) \quad (4)$$

Tangible and intangible landscape functions

From the point of view of human land uses, and according to Dauvallier and Van der Maarel (1977), the most important landscape functions are production, carrier (transport), information and regulation. This classification served the Netherlands Ministry of Housing and Physical Planning as the central focus in the preparation of a general model for the planning process.

Actual values of these functions and their change are described in studies of air pollution and soil erosion in the USA, where, according to Borman (1976), each year at least 3000 km² of rural lands are converted to urban-industrial land and highways. Westman (1977) has estimated that the loss of the

foothill pastures by the construction of the San Bernardino freeway in Southern California has added 440 kg/ha of carbon monoxide which previously had been absorbed by these grasslands. The magnitude of the increase of erosion, sedimentation and loss of mineral nutrients after forest clearing for agriculture and urban land uses can be in the range of 10–100 (Leopold 1956). On a long-term, historical basis, Davis (1976) estimated a fortyfold increase in these losses in the first decades and a tenfold increase in the first century after clearing of a forested watershed in Southeastern Michigan.

Westman (1977) estimated the 'replacement value' of some of the protection functions of the San Bernardino National Forest in southern California by the cost of removal of 200 cubic meter/ha/year of sediments, caused by erosion from steep slopes and siltation after the decline of the ponderosa pine forest from photochemical oxidant air pollutants. This would amount to \$122 million each year from an area of 4000 ha. Vester (1985) illustrated the multi-beneficial values of a single tree in the forests of the highly urbanized and industrialized society of West Germany. He also transformed these values into actual monetary terms and reached the amazing sum of 362,161 DM for a tree in the forest.

In addition to these tangible functions and their material benefits, landscapes can also fulfill social and cultural, spiritual, aesthetic, psychohygienic, scientific and other intangible functions. Therefore, in our studies on multiple use restoration of Mediterranean landscapes (Naveh 1978), we distinguished between production functions, which are transferable into market goods and can be expressed in monetary terms, and those producing noneconomic values which can be achieved by optimization of all intrinsic landscape values.

When landscapes carry out all these functions to their fullest ecological potential on a long-term basis, we can consider them as healthy, stable and attractive. However, in recent times, land uses have been devoted to the short-term exploitation of the production and transport or carrier functions and to the conversion of open landscapes into human habitation and the technosphere. At the same time, all other intrinsic landscape functions and values

have been taken for granted as 'free ecological services' (Westman 1977). They are therefore neglected and very often are not included in land use decisions and in cost/benefit calculations of environmental impact statements.

Presently, there is a growing awareness of the importance of such healthy, stable and attractive open landscapes and their ecological, socio-economical and cultural life support functions. But, the readiness of human society to apply ecological knowledge and wisdom in land use is lagging far behind its technological skills in exploiting these functions for short-term economic benefits. For this reason, the study of the interrelationships between landscape functions and land use patterns is not only of basic scientific interest but also of great practical importance.

Our goal should be to gain a deeper insight into these relations 'in order to arrive at some general laws with predictive value. If these laws could be used for the development of simple but meaningful indices for landscape health and stability, they might be able to counterbalance the one-sided economic determinism in land use planning and management, based on simplistic Gross National Income indices.

As a first step towards this goal, I will discuss these relations from a biocybernetic and thermodynamic point of view. These are probably the most generalized perspectives from which we can approach these complex relations and arrive at some isomorphic models, *sensu* Bertalanffy (1968). However, within the scope of this essay, I can provide only a broad overview, using some cybernetic and thermodynamic models by which these relations and their chief driving forces can be mapped and eventually quantified.

The biocybernetic regulation of natural and cultural landscapes

Biocybernetics is the theory of regulation in biological and ecological systems, enabling their self-stabilization and self-organization by feedback loops in which the output values are fed back into the input values. When the effect and countereffect operate in the same direction and therefore either

increase or decrease each other and act as a deviation amplifier, we talk – in the mathematical sense – about positive feedback couplings. But, if the effect and countereffect cancel each other and thereby act as a deviation reducer, we talk about negative feedback couplings. Sometimes positive feedbacks are very desirable, as in the case of our savings account in the bank which is growing in an exponential way together with the fixed interest in stable economic conditions; but in biological, ecological and social systems, unconstrained positive feedbacks can act as destabilizing 'run-away' feedbacks. This is the case in the vicious circle of positive feedback couplings between the uncontrolled, exponential growth rates of human populations and our growing need for more open land for housing and road construction, coupled with the resulting environmental degradation.

This approach is of relevance because the relations between landscape state factors, land use patterns and landscape functions are not determined by single, linear and sequential cause/effect reactions, but by much more complex inter- and cross-linked processes with mutual, causal related, positive and negative feedback loops. These latter can be grouped into two categories with opposing feedback regulations:

1. Biological production and self-organization functions, coupled by positive feedback loops between photosynthetic and assimilative growth processes of the biotic communities and the energy/material and information fluxes.

2. Ecological protection and self-stabilization functions, coupled by negative feedback loops between the moderating and attenuating processes of the biotic communities and these fluxes.

In natural landscapes, such as tropical forests and arctic and antarctic tundras, human disturbances are negligible and have not changed substantially the landscape structure and functions, their inherent capacities for self-organization and self-stabilization, and their production and protection functions. Therefore, the mutual balancing between positive and negative feedback loops has probably helped to maintain a kind of homeostatic steady state between the production and protection functions.

In semi-natural landscapes, pre-agricultural human land uses have disturbed the living community and have changed its structure and function by varying degrees. But if these landscapes are not exposed to too extreme human-caused perturbations to which they have not been adapted, and as long as their biotic communities are reproducing themselves spontaneously, we can assume that they have also retained their capacities for self-organization and self-regulation and their production and protection functions. Such landscapes make up the majority of our not yet spoiled 'natural' and 'wilderness' areas, nature reserves and parks. Many of these are studied by ecologists as 'natural ecosystems'. It is, therefore, important to clarify further their biocybernetic status.

Rindos (1984) has shown recently that the so-called neolithic agricultural revolution and the development of agro-ecosystems and of domestication should be regarded as the culmination of a very long process of reciprocal adaptation and coevolution, increasing the fitness of all. Westhoff (1983) claimed that the relationships between prehistoric and preliterate man and vegetation were mostly symbiotic and not antagonistic.

This seems to be especially true in the case of the evolution of the Mediterranean Total Human Ecosystem of Mt. Carmel and its landscapes from the Middle Pleistocene onwards (Naveh 1984). Another example is the sophisticated use of fire and the careful management of vegetation and wildlife resources by the California Indians (Lewis 1973) and the West Australian Aborigines (Hallam 1979). On one hand, the advanced food gathering and hunting techniques of these people acted as positive feedbacks on the production functions; but, on the other hand, the feedbacks were counteracted by cultural negative feedback loops of spiritual and religious beliefs, rituals and taboos and their intuitive, perceptual, and empirical ecological wisdom.

In this way, through repeated human perturbations of selective foraging and intentional burning, these pretechnological landscapes were probably not maintained in a state of homeostasis, preserving the landscape components at a constant value, but in a state of meta-stability by a dynamic flow

equilibrium or homeorhesis, (from the Greek, preserving the flow = rhexis). In this equilibrium the dynamic interplay of both natural and cultural regulative feedback couplings ensures that the system is kept altering in the same way as it has in the past (Waddington 1975).

All our present semi-natural landscapes, as well as those pastoral landscapes in which such a homeorhetic flow equilibrium has been ensured by periodic and regularly repeated natural and cultural perturbations of fire, grazing, and cutting should be considered as metastable, 'perturbation dependent' systems (Vogl 1980). In such landscapes it would be futile to attempt the restoration of the self-stabilizing and organizing processes of natural landscapes by simply stopping all human disturbances. On the contrary, we have to conserve and reestablish their homeorhetic flow equilibrium by continuing or simulating all ecological processes, including the defoliation pressures, to which they have been adapted throughout their long cultural history (Ricklefs *et al.* 1984; Naveh 1987).

In agricultural landscapes, humans have introduced new positive feedbacks to increase biological production by modifying the physico-chemical and biotic landscape state factors and especially the energy, nutrient and water fluxes. These fluxes are further enhanced by the impairment and/or replacement of the natural living community and its protection and regulation functions which could counteract these destabilizing feedbacks. If the natural protection functions are not replaced by cultural negative feedbacks of protective and regulative ecodevices such as terraces, living fences and shelterbelts, and the rotation of crops, these changes may lead to the loss of nutrients and the depletion of soil fertility, and to soil and water erosion.

As these agricultural land use patterns were shaped by long and diversified cultural traditions, there were great differences in their biocybernetic regulation. But in general, the more biological productivity was channeled into a single or a few agricultural crops, and the more powerful and efficient (from the short-term economic point of view) were the agrotechnological means developed for this purpose, the more pronounced were the de-

stabilizing positive feedbacks. Therefore, it became more difficult and costly to counterbalance the loss of the natural protection and regulation functions and the less were the farmers prepared to do so by introducing cultural negative feedbacks. It seems also that entirely 'rational' and utilitarian attitudes to nature were not sufficient to supply the cultural information for these ecodevices. According to Hughes (1975), who studied these relations in ancient civilizations, those societies in which the dominant myth was the conquest of chaotic nature by divine-human order were ultimately unsuccessful in maintaining their natural environment (and therefore their life supporting and protecting functions).

An example is Mesopotamia, the first great hydraulic civilization whose sustained agricultural productivity depended on the maintenance of irrigation ditches and canals controlled by the strong central political power. When this power was weakened and the society failed to cope with the accelerated erosion and siltation caused by the deforestation of the Armenian mountain watershed, the fertile plains turned into a salty sand desert and the whole system disintegrated.

In contrast to this example other societies have been more adaptive and have compensated for the loss of their natural protection and regulation functions by invention of agro-ecological devices. This was the case in traditional mountainous agricultural systems in the Mediterranean, the Andes and Nepal, which combined the protection of the cultivated slopes from erosion by terraces and stone walls with highly sophisticated hydraulic devices for water conservation, regulation and irrigation. Here, severe topological limitations acted most probably as a negative feedback on the over-exploitation of the production functions of the living community and enforced the introduction of cultural regulation functions.

In other cases, severe climatic constraints acted in a similar way. In pastoral landscapes of the semi-arid subtropical and tropical regions with prolonged drought periods and unreliable rainfall distribution, lack of water and nutritious food in critical periods controlled the number of livestock and their movements. These acted as protection and

regulation functions and in closed negative feedback loops with human populations, ensured the long-term productivity of these pastoral landscapes.

However, in the process of so-called 'economic development' of these traditional semi-arid pastoral systems, cultural and natural negative feedbacks have been removed by the provision of supplemented food and water in critical periods. At the same time, most attempts to compensate these losses by the introduction of new cultural regulative feedbacks, such as modern management practices of controlled grazing according to carrying capacity and range conditions, have failed. In this way, well meant, but ill-advised, improvements have turned into vicious run-away feedbacks of pasture deterioration and population explosion. They were followed, in general, by more and more severe drought-starvation cycles, leading to desertification (Naveh 1966; Farvar and Milton 1972; Western and Finch 1986).

In the Mediterranean, such traditional agro-pastoral land uses modified most of the original mountain and hill landscapes into very heterogenous and attractive landscape mosaics which ensured high structural, floristic and faunistic diversity and metastability. During these long-lasting and periodically repeated disturbances a new dynamic homeorhetic flow equilibrium was established between the woody and herbaceous vegetation components and between the production and protection functions. This equilibrium is now disrupted, either by cessation of defoliation pressures and human disturbances or by the synergistic impacts of intensified traditional and neotechnological pressures, including mass recreation and tourism (Henry 1977; Naveh and Whittaker 1979; Naveh and Lieberman 1984).

Elsewhere, the modernization and intensification of traditional crop farming systems, aimed at greater short-term production and profits, has been achieved by the introduction of new, much more powerful and destabilizing, positive feedback loops between scientific and agrotechnological information and production functions, driven by huge, energy-demanding and costly machinery and by great inputs of chemical fertilizers. Most biological

and cultural ecodevices are replaced by chemical pesticides, herbicides and by technodevices of engineering installations. These not only accelerate the energy/material fluxes but induce far-reaching and detrimental changes in all other landscape state factors.

Thermodynamic relationships between landscape functions and land uses

As we have seen, human land uses have far-reaching impacts on the fluxes of energy/material and thereby also on the cybernetic relations between production and protection functions. These processes can be expressed also by thermodynamic parameters used in information theory. In this theory, the rate of entropy production is considered as a measure of homogeneity, randomness, uncertainty and disorder and its opposite, negentropy, as the measure of certainty, predictability, order and organization. Information is defined as the measure of uncertainty of an event and its removal by a message or a physical or biological effect. Therefore, any additional piece of information increases the negentropy of the system (Brillouin 1964). Phipps (1981a; 1981b; 1984) has applied these concepts to the measurement of the ecological-topological order of natural and agricultural landscapes.

In natural landscapes high-quality potential and chemical energy (and therefore low entropy producing energy) is derived from solar energy by photosynthetic production functions. Part of this energy is dissipated into low quality metabolic heat and respiration, and high organizational order and information is built up in the landscape by structural and species diversity in food chains and food webs. Simultaneously, entropy production is also minimized by the protective function of the living community, reducing the rates of kinetic energy and heat flows and their destructive and destabilizing impacts on the landscape. Thereby, a steady state of high negentropic order and information is maintained.

As has been described in detail elsewhere (Naveh and Lieberman 1984), in semi-natural, perturbation-dependent landscapes, not only their bio-

cybernetic regulation, but also their thermodynamic ordering principles are very different. These are nonequilibrium systems and until recently were treated as temporary disturbances of equilibrium. But the findings on nonlinear thermodynamics of irreversible processes by Prigogine and the 'Brussels group' showed that nonequilibrium may be a source of order and organization (Prigogine 1976; Nicholis and Prigogine 1977).

The state of nonequilibrium is brought about by the effects of increasingly powerful environmental constraints, imposing a continuing change in entropy and removing the system further from equilibrium. Such ordered structures are called dissipative structures. As opposed to those in equilibrium, they are maintained and stabilized only by permanent energy/matter and entropy exchange with the environment. With their help, the system maintains its inner nonequilibrium and this, in turn, maintains the exchange processes. Driven by positive feedbacks of environmental and internal fluctuations, the dissipative structures move to new regimes which generate the conditions of renewal of higher entropy production. Thus, they create 'order through fluctuations' as nonequilibrium, but metastable systems.

In such systems during a regeneration phase, after periodically repeated perturbations by fire, grazing, cutting and other defoliation pressures with sufficient rest periods, negentropy is not only imported through intensified photosynthetic growth processes, but the system can actually use free energy to reorganize itself with increasing structural complexity, biological diversity and productivity. But if these perturbations are too frequent and severe or are stopped completely, then the external entropy exchange may become more and more positive and structural complexity and organization deteriorate until the system loses its self-stabilization capacities and thereby its homeo-rethic metastability. This is illustrated in Fig. 1 which describes, diagrammatically, three different Mediterranean landscape structures. In each graph the change in entropy (**S**) and disorder (**D**) are contrasted with change in negentropy and order; under different perturbation regimes. Disorder grows at the rate ds/dt :

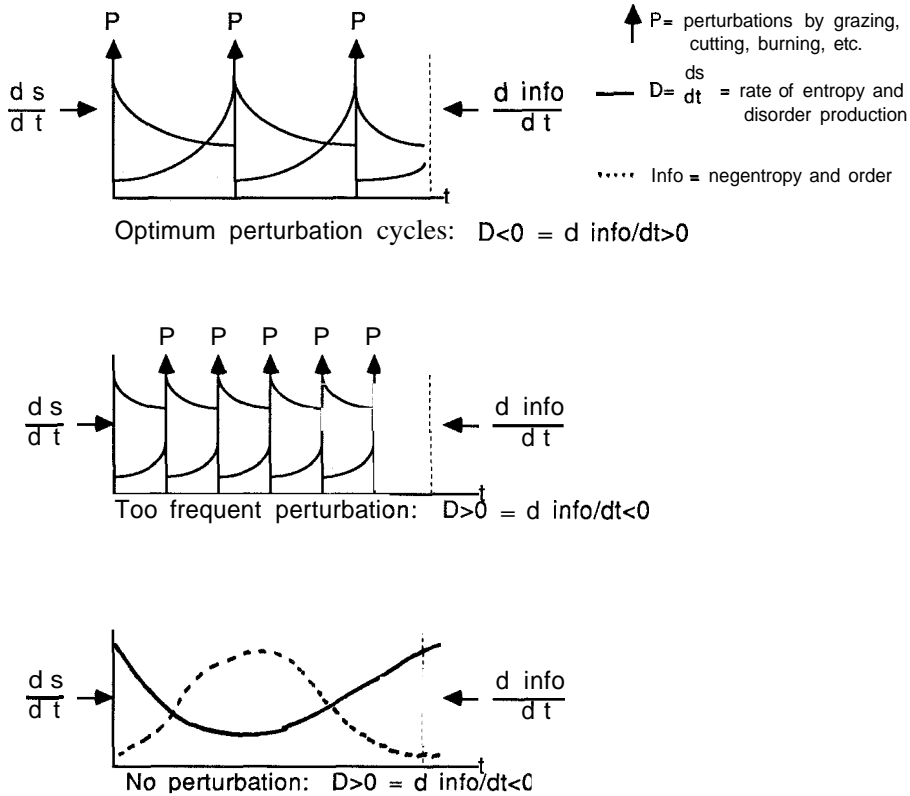


Fig. 1. Mediterranean landscapes as perturbation dependent dissipative structures.

$$D = ds/dt$$

where D may be positive, negative or zero. If D is zero, the system is in a stationary state. If it is possible ($D > 0$), the system is in a state of progressive disorganization. But if it is negative ($D < 0$), the system is in a state of progressive organization, increasing negentropy and information. In the figure, the natural state is shown at the bottom where order and disorder cycle over long time periods under natural environmental and biotic interactions and responses. In the center panel, disturbance is repeated at short intervals and disorder remains at a high level. In the top panel, the natural pattern has time to develop, but it is then interrupted by human management and is repeated. I have termed this the optimum perturbation cycle. A fuller explanation of the thermodynamic theory underlying these ideas is presented in Naveh and Lieberman (1984, p. 30).

In other landscapes, the reduction of the natural production and protection functions of the living community through human land use and destabilizing positive feedbacks increases the rate of entropy production and disorder and conversely reduces the rate of negentropic order and information in the landscape. This impairs their self-organizing and self-stabilizing capacities. In traditional agricultural landscapes, these losses were at least partly compensated for by increasing the photosynthetic (agricultural) production and replacing some of the natural protection and regulation functions by low energy demanding ecodesigns.

However, in modern, intensively used agricultural landscapes, this agro-ecological order and organization is deteriorating and the heterogeneous, fine-grained and metastable landscape patterns are converted into homogeneous, coarse-grained and high yielding but unstable monocultures. However, the recent increase in agricultural production is not

the result of a direct rise of negentropic photosynthetic efficiency, but of high inputs of fossil energy and chemicals, followed by their entropic degradation into kinetic energy, heat and waste products. Entropy production and pollution are further enhanced by the loss of the natural landscape protection and regulation functions not only from intensively cultivated land but also from the remaining degraded and denuded natural landscapes.

Discussion and conclusions

At the present stage of our knowledge, there seems to be a general consensus about the far reaching global implications of the biocybernetic and thermodynamic interrelations between landscape function and use. This has been shown recently in an advanced workshop dealing with climate-vegetation interactions (Rosenzweig and Dickinson 1986). Because of the overwhelming effect of vegetation denudation on the albedo, evapotranspiration and surface roughness, there are strong positive feedback effects between the removal of the vegetation canopy and climate. Therefore, human-caused changes in vegetation may have a significant influence not only on local rainfall and on the process of desertification, but also on the long-term climatology of the earth (Sud and Molod 1986). The same is true also for the rise in atmospheric carbon dioxide, acid rain and other destabilizing changes in atmospheric chemistry driven by positive feedbacks with industrialization, land clearing and agricultural intensification. Although, according to the Gaia hypothesis (Lovelock 1982), the biosphere has great homeostatic self-regulating and self-cleansing capacities and can even change over to homeorhetic regulation, we are far from being able to predict at what stage these human-caused changes in the atmospheric physics and chemistry and in the over-all thermodynamic balance will cause a breakdown of the entire system.

In general terms, the more far reaching the human interference in natural landscape processes and in energy/matter and information flows, and the greater the impairment of self-stabilization and organization capacity of the ecosphere landscapes,

the more will our natural landscapes resemble controlled servo-mechanisms, such as our air-conditioned buildings. In these, the constant state of low entropy can be ensured only by inputs of energy from a larger system, namely the electric power station and, in our case, from a higher landscape system. But even if all this entropy producing and destabilizing energy could be harnessed, and all gaseous and solid waste products could be captured and recycled by mechanical and physico-chemical and engineering means, this would be not only very costly, but demand even further inputs of entropy producing and polluting processes. Therefore, it should be realized that such techno-devices cannot restore the negentropic order and information lost in degraded landscapes. This would be achieved, at least partly, by low energy demanding ecodevices and chiefly by those based on the direct use of solar energy. Herein lies the great importance of the bioecological, multifactorial restoration of degraded landscapes with living, self-organizing and self-stabilizing plant material of green shelterbelts, and grassed waterways and roadsides, in addition to the long-term conservation of the remaining natural and semi-natural landscapes.

The main conclusion to be drawn is that the life-supporting production and protection functions of our open landscapes are closely related to biocybernetic regulation of self-stabilization and organization and negentropic order and information. These landscapes are now exposed to growing neo-technological degradation driven by complex and powerful destabilizing feedbacks. For us, the crucial question is whether human society will be ready and able to counteract these trends by more powerful cultural regulative feedbacks and ecodevices and what role new insights and innovative methods of landscape ecological appraisal, conservation, management and education can play in this process.

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