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CITATION – NETWORKS, SCIENCE LANDSCAPES AND EVOLUTIONARY STRATEGIES*

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The construction of virtual science landscapes based on citation networks and the strategic use of the information therein shed new light on the issues of the evolution of the science system and possibilities for control. Citations seem to have a key position in the retrieval and valuation of information from scientific communication networks. *Leydesdorff's* approach to citation theory takes into account the dual-layered character of communication networks and the second-order nature of the science system. This perspective may help to sharpen the awareness of scientists and science policy makers for possible feedback loops within actions and activities in the science system, and probably nonlinear phenomena resulting therefrom. In this paper an additional link to geometrically oriented evolutionary theories is sketched and a specific landscape concept is used as a framework for some comments.

Introduction - Citation and science landscape

Spatial visualization of scientific development using different techniques of mapping has its own tradition in quantitative studies of science (cf. Refs 1-4). New achievements in the development of computer tools allow to produce interactive maps as well as an animation of their dynamics.[5,6] At the Sixth International Conference of the International Society for Scientometrics and Informetrics (ISSI) in 1997 in Jerusalem, *H. Small* took the audience on an excursion through a virtual science landscape. Navigation above this landscape showed the overall structure of science or scientific disciplines on a macro-level; by zooming into its structure, subdisciplines, research fronts and even individual articles on a micro-level were revealed. How is this landscape constructed? The space and the neighborhood of objects (like disciplines or research fronts) are determined by co-citation links between documents, whereby

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specific methods of clustering and ordination algorithms are applied. The structures obtained are marked by circles in a two-dimensional representation or by spheres in a spatial, three-dimensional representation.[7] As reported in Ref. 8, researchers at the *Sandia National Laboratory* (USA) also "developed a computer tool that shows up scientific trends as ripples, flows, peaks and gorges" in a "citation landscape"[9,10] (note a). Based on an entirely different visualization method, also here documents are positioned in a space and the density of documents is used as a landscape over this space. Researchers of this lab emphasized clearly the strategic goal of such tools: "The landscape shows the dynamics of the evolution of science, and ultimately may help us improve our ability to invest in leading areas"[11] (note b).

Citations are the basis of such impressive, vivid, and suggestive landscapes and maps. These show the state and the dynamics of scientific development—from the perspective of an international scientific community, of course. Citations have this fundamental role because of their indisputable objective nature[12] as components of a "worldwide expert system" represented by the *Science Citation Index.*[13,14] Right at the outset of citation analysis, a discussion started about the extent and the character of this objectivity[15] (note c). Regardless of whether a theory of citation ever could or should come about, the discussion on it should be extended and continuously referred to. This is of particular significance because of the strategic, science policy oriented use of citation data in different circumstances (e.g., for personnel management decisions influencing individual scientific careers, the evaluation of research institutes, or as basis for investment strategies and funding policies worldwide).

The question arises to what extent newly developed theoretical insights in other scientific fields can improve the understanding of the structure and function of citations inside as well as outside the science system. In this context *Leydesdorff's* paper (L. L.) attempts to incorporate different methods of thought ranging from science history and sociology to systems theory, cybernetics and self-organization theories with the aim to find a new perspective on theorizing about citations. His reference to modern systems theory could perhaps help to clarify the boundaries of the different systems (e.g., scientists, papers, citations, institutions) or contexts (social, cognitive, information-theoretical), and to structure the relationships between them. The science system is, in the sense of an autopoetic system,[16] at the same time relatively autonomous in terms of system-inherently determined rules and mechanisms, but it is also embedded in various socioeconomic contexts and structurally coupled with them.

In this paper I would like to focus primarily on *Leydesdorff's* consideration of the communication network as an evolving system. This perspective includes the historical dimension of citation networks and the importance of their dynamics or changeability, as well as the understanding of dynamic mechanisms like feedback leading to nonlinearities and the question of the emergence of the new. I would like to elaborate my comments with reference to a geometrically oriented evolutionary theory that describes evolution as a collective search by competing populations for locally improved solutions in an adaptive but unknown landscape. In light of this theoretical framework, scientific activity can be seen as a search in an unknown knowledge landscape, producing "mountains of research"[17] (note d). Because of increasing diversification and specialization it seems, especially today and more so than in the past, that it is impossible for individuals or institutions to have an overview about the knowledge landscape or even parts of it. Of course, it would be useful to have a perspective that would allow us to see the mountain peaks already reached, to anticipate the mountains yet hidden in the distance, or to see the passages or trails leading to unexplored knowledge territory. This is one reason for the attractiveness of virtually constructed science landscapes, which – at least in part – reflect the actual state of knowledge. The science system seems to be in the same situation as many complex systems: it is confronted with the task of providing good solutions to (or resolutions of) problems, in a reasonable length of time, with economic and efficient use of resources. Therefore, it would seem to be reasonable to try to find out whether the understanding of complex optimization and search processes can produce useful models or frameworks for the analysis of the science system. In this way the landscape picture of science will be used in yet another dimension – i.e., not only in terms of an empirical description, but also as a framework for theoretical explanations.

Evolution and optimization - landscapes and strategies: possible implications for the science system and science studies

Before discussing in greater detail some links between empirically constructed science landscapes, models of evolutionary search processes in an unknown knowledge landscape, and "recursive operations in a dual-layered network" (L. L.), let me consider briefly the background of the ideas which are used in the following.

Landscapes, in the sense of fitness landscapes, are widely and extensively studied in the fields of evolutionary algorithms, complex optimization, and evolution (cf. Ref. 18). Energy landscapes in disordered semiconductors (cf. Ref. 19), fitness landscapes of RNA-molecules (cf. Ref. 20), and the valuation criteria in complex optimization problems (cf. Refs 21, 22) are examples for the use of such a landscape picture in different contexts. Mathematical models for evolutionary search processes in a continuous phenotype-space[23,24] may serve as an example of a resulting interdisciplinary knowledge transfer. For earlier discussions of the relevance of these concepts for the development of knowledge and science see, e.g., Refs 25-28. Recently, the potential of this kind of modeling tool for describing evolutionary dynamics – also in social systems – has been reviewed,[29] and applications to technological and economical search processes have been proposed.[30]

Geometrically oriented evolutionary approaches describe evolution as a search process of competing individuals or populations in an unknown fitness landscape. Usually such approaches start with a spatial representation of characteristics of the considered participants (elements of the system) in the search process or, alternatively, with a set of system states that can be used to define a search space. In the first case, the dimensions of this space are related to a set of relevant, quantifiable variables or characteristics of elements of the system. A point in this abstract characteristics space thus reflects a certain combination of such characteristics. If the dimensions are labeled by continuously changing variables, a metric and thus a distance or neighborhood of objects can be easily defined. Concerning the science system, in an initial attempt, we could assume that classification schemes of disciplines or problem contexts can be linked to dimensions of a "problem space". Then, a specific problem (*qua* point in space) could be characterized in terms of the shares of different problem contexts within it. But, it is quite clear that problem contexts, i.e., the taxonomy of the system, and therefore, the dimensionality of the space changes in time. Consequently, an approach that starts from operations linking different states of the system might be more appropriate for the consideration of the science system. This is the second approach mentioned above. In this case, the search space is defined as a set of possible states of the system, and their neighborhood results from the accessibility of one state from another. The accessibility of states is described by means of a mutation operator and can be formulated in terms of a graph with certain properties.[31] In this way, the dynamic rules of the system define and change the actual search space. Links to the construction principles of empirical science maps seem to exist, but there is a complicated relationship between the two representations of the search space (and it is not the aim of this paper to elaborate the analogy further). For the time being, let us assume that an abstract search space (problem or knowledge space) can be constructed by whatever technique. In this space, the scientific problems under investigation at any given time represent the set of occupied points. The occupation of the space (intensity of research) can be described, e.g., by means of a density function. But not all possible problem configurations in this space are occupied. Certain areas – marked, e.g., by networks of articles or networks of (co-)citations – are preferred at a certain time. The empirically constructed science landscapes – if they use the density of documents as the landscape function over the space – seem to describe just this structured or clustered occupation. From an evolutionary point of view, the dynamics of the occupation can be described in terms of (evolutionary) search algorithms (i.e., in the sense of simulation rules for individual behavior and decisions) or by analytical models (partial differential equations). Independent of the method and the concrete form of the mathematical description, any evolutionary search follows two principles: selection and mutation. Mutation ensures the variety of the populations and the exploration of unknown territory. Selection entails a comparison of locations and the acceptance of better solutions. The comparison implies the existence of a valuation of locations, which can be formulated by means of a value function over the search space. This function – understood as an objective function in optimization problems or as a generalized fitness function – is characteristically linked to dynamic properties of the search. The valuation or fitness function forms a second landscape over the space which can be viewed from the evolutionary perspective as the original one. Usually, we will assume that the searching populations will be concentrated around the maxima of this function, so that the "occupation landscape" can be considered as a mirror of certain parts of the in general unknown "valuation landscape". The coupling between them is caused by selection. This is in agreement with a view of citation networks which define the occupied problems as selections in several contexts (L.L.). In evolutionary models the selection mechanism is often formally described by linking fitness values of locations to their reproductivity in terms of occupation. Reproduction as a continuing redistribution of citation patterns by publications (L. L.) maintains and changes the science landscape (as visible, occupied landscape). In general, selection will lead to a concentration of the occupation at the maxima of the fitness landscape; mutation ensures the spreading of the population. Then, evolution can be understood as hill-climbing in these mountains. One way to escape the problem of the explicit theoretical definition of the fitness function and the determination of its concrete shape is to consider the landscape as an unknown random, but correlated function with certain statistical properties. For complex systems we can assume that several optimal solutions exist, so that the function will be multimodal. Multimodality can be understood as the result of frustrating conditions which contradict each other. Specialization in science and the co-existence of different research fields seems to reflect such features. The framework of a geometrically oriented evolutionary approach represents a conceptual reference base by means of which the emergence of different patterns of occupation and their changeability can be explained. To illustrate the usefulness of this framework for the subject of this volume and possible strategic implications, two problems will be considered: the co-evolution of exploration and valuation; and the effectiveness of the selection as well as sources of innovation.

Adaptive landscapes – the co-evolution of the exploration of the landscape and the fitness landscape itself

In the simplest models of evolutionary searches the fitness landscape is considered to be time-independent and as a scalar function of the search space. As explained above, the occupation or exploration of the search space is driven by the valuation landscape (Fisher-Eigen-type models). In social systems often a co-evolution between the evaluative environment and the system seems to be relevant. Then, the fitness function will change in time. This change can be caused exogenously or endogenously and can be modeled correspondingly in different ways. In mathematical models of continuous evolutionary search, e.g., a feedback between the occupation and the valuation of the occupied places can be expressed by means of a Lotka-Volterra dynamics. In this case the fitness function depends on the occupation density, it is a functional over the space (a so-called adaptive landscape). As a result, the occupation landscape (first landscape) will move in accordance with the shape of the fitness landscape (second landscape) and, at the same time, will reshape the fitness landscape during this movement. This feedback probably corresponds to the "dynamic perspective of selection operating upon selections" (L. L.) when citing at different points in time is being taken into account. If the occupation can be expressed by co-citation networks of documents, further citations of these documents can be understood as a source of the reformation of these networks in the sense of a changing occupation. If citations are related to a valuation of networks of documents, the reproduction of citation networks can also include a change in the valuation landscape. For continuous models with adaptive landscapes analytical results are hard to obtain. But, one can argue that processes of differentiation and, in particular, processes of merging of occupied centers or trajectories can be better described by means of adaptive landscapes than by stationary landscapes. It seems to be reasonable to attribute such an integrating function to the "selections upon selections" operation (L. L.), which will probably lead to trails between different semi-optimal solutions and perhaps to a creation of a new overlapping hill to climb on.

Search strategies - the effectiveness of the selection and sources of innovation

The relationship between selectivity and mutability plays an important role in models of evolutionary searches. A well-known effect is the mutation catastrophe, i.e., the existence of a critical mutation rate. Beyond this limit the processes of structure formation end for the reason of undifferentiability. For concrete search problems, sometimes it is possible to formulate optimal relations between selection and mutation rates, or at least to design search strategies with changing strategic parameters in dependence on the current search experience. The importance of this questions is related to the lack of knowledge about the shape of the valuation function, the location of relatively high maxima, or even a useful direction for the search process in most of the complex problem solving tasks. In general, evolution effects a local optimization. However, the problem is not only how to achieve a certain maximum, but also, in the long run, how to leave this maximum for a new one. For fitness landscapes in biological evolution, *Wright* (1932) wrote: "... selection will easily carry the species to the nearest peak, but there may be innumerable other peaks which are higher but which are separated by 'valleys'. The problem of evolution as I see it is that of a mechanism by which the species may continually find its way from lower to higher peaks in such a field" (Ref. 32, p. 358). There seems to be a similar problem in the science system for which already *Bush* as early as 1945 stated: " There is a growing mountain of research. But there is increased evidence that we are being bogged down today as specialization extends " (Ref. 17, p. 101). From the point of view of continuous evolutionary models one can argue that the search starts at the periphery of the occupied locations. A strict orientation towards improvement can be a successful strategy for short periods of time but, in the long run, it will be counterproductive. Concerning the progress of science, this problem touches the question of the function of the tails in skew distributions, e.g., scientific productivity. This leads ultimately to the debate surrounding the Ortega hypothesis. Confronted with the use of citations for valuation in a strategic dimension – regardless of extent or level – it seems to be useful to consider this problem in an evolutionary context again. Even if citations were an indicator of quality beyond all shadow of a doubt, and a citation landscape above the problem space could be constructed in the sense of a fitness landscape, it is nevertheless not to be recommended that this landscape be used as an exclusive selection criterion. It is well known that niches may have strategic importance (note e). Given the necessity of competition and selection for obtaining better solutions, experiences gained from different evolutionary strategies in complex optimization problems can also be regarded as an argument for maintaining a sufficient level of variety.

So far, the adaptive landscape concept and the problem of variety versus selectivity have been used to illustrate the possible explanatory potential of geometrically oriented evolutionary approaches for problems of the development of science. One advantage of this framework is that relations between the topology of the fitness landscape and search algorithms can be expressed by means of mathematical models. Formal models permit one to formulate features and conditions of the search process – for example, the definition of a rate of progress. Of course, such statements depend on the concrete nature of the problem: the search space, the features of the valuation landscape, the search populations and their dynamic properties. It would go far beyond the aim of this paper to elaborate such a model for the evolution of science in any concrete form. Nevertheless, the landscape picture seems to be an interesting concept for knowledge transfer between a geometric representation of knowledge systems and a theoretical description of their dynamic properties, as well as for an integration of such approaches into an evolutionary framework.

Summary – Science: continuous extension, storage and consultation

Virtually constructed science landscapes make hidden or distributed information visible and facilitate the orientation and navigation in the existent knowledge landscape. New methodological approaches, such as simulations of scientific activities in artificial science systems, can provide some insight into the mechanisms for the formation and reshaping of such landscapes, starting from elementary rules of scientific behavior.[33] The perception of the dual-layered character of scientific communication and the perception of the function of dynamic, nonlinear feedback in such networks make it easier to understand the formation and reshaping of the landscape as the result of our own scientific activity and the role of structural couplings to environments of science. Links to theories of evolutionary search in complex adaptive landscapes and to evolutionary strategies can probably help to better understand the conditions for successful and effective search. Inversely, they may help us to determine "no-go" principles.

For a further clarification of such links manifold questions (empirical, methodological and theoretical) must be discussed. For example: What types of shifting, merging and differentiation of structures or objects in the science landscape can be observed empirically? How do different construction principles of document networks, of the concrete search space, and the landscapes in it influence the character of observable processes? What are the time constants for changes in the landscape, and can different time scales be observed (note f)? Can a co-evolution of valuation and occupation be made visible? Which quantitative indicators could be chosen for constructing a valuation landscape? Despite of the wide range of open questions, attempts to integrate geometrical representations of science in terms of virtual science or citation landscapes and formal models that give a theoretical explanation of the emergence and evolution of such structures are useful.

Regardless how successful such integrational attempts might be, all these tools and considerations would not be possible without the existence of citation indexing. This leads us back to the beginning of this comment and the subject of this volume. The question is not whether to use or not to use citations, but rather to understand *what* is being used and to ensure that it can also be used in the future.

In a classic paper already mentioned[17] *Bush* wrote: "A record, if it is to be useful to science, must be continuously extended, it must be stored, and above all it must be consulted." (Ref. 17, p. 102). This sentence is relevant for the aim of this volume in several respects. Let us consider the discussion on *Leydesdorff's* paper, "Theories of Citation?", as a second-order communication phenomenon (or a communication about communication).[34] Insofar as we participate in this discussion, a reproductive occupation of a particular problem area in the science landscape is performed, and the topic is kept alive in public. The second (and probably even more important) dimension of relevance of the above quotation concerns the first-order system – the scientific communication itself. New media, like the Internet, will certainly influence and probably radically change the production of scientific knowledge, the appearance of scientific results, and the methods used to communicate them. In the light of electronic publishing, virtual libraries and information networks built by hyperlinked web-pages, *Bush's* claim that the construction of effective information storage and retrieval systems in science is of strategic importance gains new relevance. Obviously, despite or because of the splendid possibilities of electronic databases and networks, the question arises how the "world-wide expert system" can be maintained and extended. Reproducing knowledge, handing it over to the next generations may help to maintain certain standards even in a world in continual flux. And, only these standards – in the sense of knowledge about the construction, use, and meaning of citation indexing and analysis as a mirror of an international, globally linked scientific community – can ensure that an ethics for the use of citations and other bibliometric information can be formed.

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Notes and comments

[a] According to the presentation of the method by the laboratory, supercomputers and special tools (V_X*Insight*$_{(TM)}$) (see Refs 9–11) are used to extract information from large databases. In the case of the science system, *ISI* data are used. Virtual reality techniques are used to "fly over the landscape to see subareas appearing, others merging or separating in perhaps unknown ways".

[b] For the strategic aim the following quotation is interesting: "He (program manager, *C. Meyers*) says the landscape could provide new insights for policymakers, corporations and even intelligence agencies wanting a better understanding of unfolding trends in science".[8]

[c] The body of literature on the citation debate is overwhelmingly large. To follow earlier roots of argumentation, sometimes repeated in the present, one might just take a look at any of the volumes of the *Essays of an Information Scientist* by *Garfield.*[15] It is not the aim of the present paper to review this extended discourse; this has been done, e.g., in *Leydesdorff's* paper and elsewhere (see also Ref. 35, 36). Let me just make a few remarks here. The objectivity of citations as measurable, quantitative representation of certain features of the science system is linked to the analysis of *large* systems. It is not accidental that *Price* with his famous metaphor of the "molecule called George" referred to statistical physics, the physics of many-particle systems. To a certain extent, discussions about the relevance of citations can be related to the field of conflict between the analysis on a micro level and the analysis on a macro level; and sometimes these levels seems to be confused with one another. Is it not fascinating that despite the speed of scientific production, the diversity of individual behavior (reading, writing, referencing, publishing and so on), the uniqueness of the historical moment, and the irreversibility of time we can observe nevertheless different patterns, order and structure – stable and reproducible – in publications and citations?

[d] Geographic metaphors are widespread in science studies. They are used in conceptual frameworks (cf. Ref. 37) or they are linked to empirical analysis (cf. Ref. 38). In addition to the literature on science mapping already mentioned, further I would like to refer to an article of *Braun* and *Schubert*[39] and an article of *Noyons*[40] both of which recently used the landscape picture explicitly: *Noyons* in the context of mapping techniques developed by the *CWTS*, and *Braun/Schubert* with respect to a three-dimensional representation of bibliometric indicators. The landscape picture extends or specifies the spatial representation of science by emphasizing one dimension. This distinguished dimension is of relevance in particular from an evolutionary perspective, in which the shape of the landscape is correlated with a valuation of spatial locations and the dynamics of the system. This will be discussed in greater detail later on.

[e] For the role of dynamic niches for innovations under hyperselective conditions see Ref. 41. For the role of intermediate states for scientific search processes from the point of view of evolutionary strategies cf. Ref. 25. So-called "generic instruments" seem to be another example for innovations starting in valleys or at peripheries of current developments. They are technical instruments or methodological systems that are not only design for one special field of application, but which are flexible for different

uses and which are being redesign locally. Generic instruments seem to have a linking and path-finding character, and the biographies of their inventors stand for singularities and non-adaptivity.[42]
Concerning the changeability of virtual (or digital) landscapes *Noyens* and *van Raan* wrote: "A drawback of this approach for bibliometric evaluation purposes is, however, that the structure is too dynamic. The contents of a mountain changes every year, but also the elements defining the structure ... changes every year. Therefore, a reliable trend analysis is impossible because the structure in year I is not comparable to the structure of year I-1."[5] The question seems to be whether a stable reference space can be found, whose dimensions are relatively stable over some periods in time and in which changing positions of dynamic networks can be compared to each other.

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