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Biocomplexity in Coupled Natural–Human Systems: A Multidimensional Framework

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ABSTRACT

As defined by Ascher, biocomplexity results from a "multiplicity of interconnected relationships and levels." However, no integrative framework yet exists to facilitate the application of this concept to coupled human–natural systems. Indeed, the term "biocomplexity" is still used primarily as a creative and provocative metaphor. To help advance its utility, we present a framework that focuses on linkages among different disciplines that are often used in studies of coupled human–natural systems, including the ecological, physical, and socioeconomic sciences. The framework consists of three dimensions of complexity: spatial, organizational, and temporal. Spatial complexity increases as the focus changes from the type and number of the elements of spatial heterogeneity to an explicit configuration of the elements. Similarly, organizational complexity increases as the focus shifts from unconnected units to connectivity among functional units. Finally, temporal complexity increases as the current state of a system comes to rely more and more on past states, and therefore to reflect echoes, legacies, and evolving indirect effects of those states. This three-dimensional, conceptual volume of biocomplexity enables connections between models that derive from different disciplines to be drawn at an appropriate level of complexity for integration.

Key words: biocomplexity; biodiversity; heterogeneity; history; cross-disciplinary; integration; space; time; organization; metaphor.

INTRODUCTION

The term "biocomplexity" is a relatively new one (Mervis 1999; Michener and others 2001). There are two ways to conceive of its introduction into ecology—first, by analogy to the slightly older term "biodiversity" (Wilson and Peter 1988), and second, as a bridge to the abstractions of complexity in systems theory and other sciences (Auyang 1998). In both translations, the term is generally used primarily as a provocative metaphor. In an effort to apply this concept more effectively to the study of coupled human–natural systems, we have devised a framework that can help operationalize the metaphors and abstractions used in integrative studies.

The biodiversity pathway may seem to be relatively straightforward. However, it is less clear how the physical and mathematical sources can be used to build an empirical bridge between ecology and the social sciences. We propose a framework based on commonly recognized dimensions of space, time, and organization (Frost and others 1988; Cottingham 2002). By suggesting some potentially measurable ways in which complexity may vary along those three dimensions, we hope to identify features that ecologists and social scientists can use for cross-disciplinary integration.

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Although metaphor is an extremely useful tool for joining disciplines (Pickett and Cadenasso 2002), the framework we present shows how to move beyond metaphor in linking social and ecological disciplines. A framework is not itself a theory, but a skeleton to link the various components of theory (Pickett and others 1994) and to suggest the components that will ultimately be used in operational models (Cadenasso and others 2003). Frameworks specify the factors and processes that must be included in models to translate an abstract concept into particular cases.

DEFINITIONS OF BIOCOMPLEXITY

The concept of "biocomplexity" was first introduced by Colwell (1998) as a rather metaphorical means of adumbrating a new research initiative. She applied this new coinage to a wide variety of goals and phenomena: (a) links across the sciences; (b) the linkage of biological and physical processes; (c) the wide scope of various methodological approaches; (d) the inherent complexity of the Earth, including global scales and the human components of systems; (e) environmental problem solving; (f) a foundation in systems and chaos theories; and (g) the creation of order in nature. This sort of richness of connotations was echoed in subsequent analyses. In their discussion of biocomplexity, Michener and others (2001) highlighted emergence, space and time-scale changes, and synergistic mechanisms. They defined "biocomplexity" as "the properties emerging from the interplay of behavioral, biological, chemical, physical, and social interactions that affect, sustain, or are modified by organisms, including humans" (Michener and others 2001). Cottingham (2002) emphasized the diversity required of teams investigating biocomplexity, as well as the need for conceptual and scalar integration.

Two questions emerge from these characterizations of biocomplexity. First, is there an underlying core concept that can unify the diversity of ideas currently associated with the term? Second, is there a way to use the concept to achieve the integration of social and biogeophysical sciences (see, for example, Covich 2000) The general definition proposed by Ascher (2001) captures the essence of many of the characterizations and narrower definitions of biocomplexity: Biocomplexity is "the multiplicity of interconnected relationships and levels." According to this view, many of the specific technical features of biocomplexity emerge from these interconnected relationships. To promote the operational application of biocomplexity to coupled human–natural systems, we purpose a more focused, fully articulated definition that follows the spirit of Ascher's general concept. We define biocomplexity as "the degree to which the interactions in ecological systems comprising biological, social, and physical components incorporate spatially explicity structure, organizational connectivity, and historical contingency."

Before presenting the framework, we will briefly outline the roots of the biocomplexity concept, as they motivate and lend context to the structure of our framework.

BIODIVERSITY AND ITS LIMITS

Biocomplexity has clear analogies with the slightly older concept of biodiversity. Both deal with numbers of entities and phenomena. The concept of biodiversity emphasizes the richness of the living world based on hereditary variation (Wilson and Peter 1988). "Biodiversity" was originally introduced as a metaphorical term that could engage the public and policy makers. Thereafter, technical definitions, such as the one proposed by Gaston and Blackburn (2000), codified biodiversity as "the study of number and difference." The term "biodiversity" was proposed to advance scientific understanding and to serve a societal function. Specifically, it was intended to improve the success of conservation (Noss and Cooperrider 1994). In that context, it engages personal and public values and acts as a vehicle for public discourse. In the public discourse, it remains a powerful metaphorical tool.

The concept of biodiversity now clearly applies to multiple biological realms, ranging from genes to landscapes. For each biological realm, three attributes of biodiversity exist: composition, structure, and function (Noss 1990). Composition is about what constitutes a complex. Structure is about how the components are assembled, and function is about what the complex does in a specified context.

In spite of the functional and hierarchical interpretation of biodiversity by Noss (1990), the concept, as it is usually used, has important limits. Because it was developed first for hereditary units, such as species (Wilson and Peter 1988), it has a legacy of focusing on the biological part of ecosystems. However, the physical environment may, as much as the organisms, drive the differentiation that is fundamental to biodiversity. In addition, the study of biodiversity has maintained a structural or compositional emphasis in practice.

A further limit to biodiversity is that the subject has been spatially inexplicit. In other words, the heterogeneities of the natural world are often lumped or averaged, rather than expressed in their full spatial richness. Another limit is that humans have either been excluded from analysis or considered to be external drivers to ecological systems.

Biocomplexity corrects some of the limitations biodiversity has met with in practice. Biocomplexity emphasizes the dynamics of systems and is explicit about the application beyond the focus on species. In addition, biocomplexity deals with multiple scales in systems dynamics. Thus, it clearly moves beyond the perception of number and difference as the static entities they have sometimes been considered under the rubric of biodiversity. However, it is important to resist merely substituting the newer and perhaps more fashionable term "biocomplexity" for "biodiversity", when it is the older term and its application to different criteria of observation in field studies that is meant (Carey and Wilson 2001: Amoros and Bornette 2002). Such substitution ignores the other root of biocomplexity—systems theory.

BIOCOMPLEXITY FROM SYSTEMS THEORY

The other root of biocomplexity is from systems theory, which deals with hierarchy, nonlinearity, the contingency of initial conditions, self-organization, and emergence (Lewin 1992; Krugman 1996; Bak 1996; Johnson 2001). Reflecting on this conceptual source, ecologists recognize that complexity appears in ecosystems because of the middle number problem (Frost and others 1988; Allen and Starr 1982). Both enormous and very small collections of interacting objects can be described simply, whereas intermediate-sized collections show complexity because although there are many interactions, there and not so many that individual behaviors can be subsumed in the aggregate. Within the scope of middle number systems, the causes of complexity include the large number of pathways that interaction between organisms and resources may take (Carpenter and Kitchell 1988) and the importance of indirect effects (Wootton 2002).

The issues raised by systems theory are at the base of biocomplexity applications in biology (Gunderson 2000; Bruggeman and others 2002; Wootton 2002). However, these highly abstract concepts may seem difficult to apply empirically to coupled human–ecosystem studies. The basic definition proposed by Ascher (2001) ties these abstractions together and suggests a way to proceed. According to this definition, biocomplexity is the state that exists when there is a multiplicity of relationships, and when those interacting relationships span multiple scales. The more abstract aspects of complexity, such as emergence and nonlinearity (Ascher 2001), result from these basic features. Therefore, a framework that enables us to address a multiplicity of interactions across multiple scales would assist in the study of coupled human–natural systems.

In the realm of coupled human–natural systems, the definition of "biocomplexity" and the related framework are antidotes to the metaphorical legacy of the term. This metaphorical tradition runs deep in many discussions of biocomplexity. In her introduction to biocomplexity, Colwell (1999) quotes John Muir: "When we try to pick out anything by itself, we find it hitched to everything else in the universe." This highly metaphorical image is compelling, but it is also somewhat dangerous. It is interpreted by some as a "law" of ecology: Everything is connected to everything else (Commoner 1971). However, a framework for biocomplexity selects key dimensions on which to consider connections—or, in Ascher's (2001) words, the multiplicity of interacting relationships—and it suggests some general ways to measure the differing degrees of complexity on each dimension.

A CONCEPTUAL FRAMEWORK FOR BIOCOMPLEXITY IN COUPLED HUMAN–NATURAL SYSTEMS

If the concept of biocomplexity is to be more useful, it must move beyond its metaphorical roots. To foster an operational approach to this subtle idea, we follow the precedent of identifying a conceptual volume within which components and degrees of complexity can be understood. A number of researchers have identified conceptual spaces that may promote the use of biocomplexity as an integrative tool in coupled human–natural systems. In their study of complex lake communities, Frost and others (1988) suggested that the dimensions of spatial and temporal scale, the resolution of system components, and the scale of experiments were fruitful descriptors of the choices that ecologists must make. A more general framework was proposed by Jax and others (1998) to address similar issues for ecology overall. They noted that to determine whether one was studying the same or a different system from time to time or place to place, the systems should be placed in a dimensional space described by (a) degree of system integration, (b) resolution of system components, and (c) system boundedness. These issues are relevant to biocom-

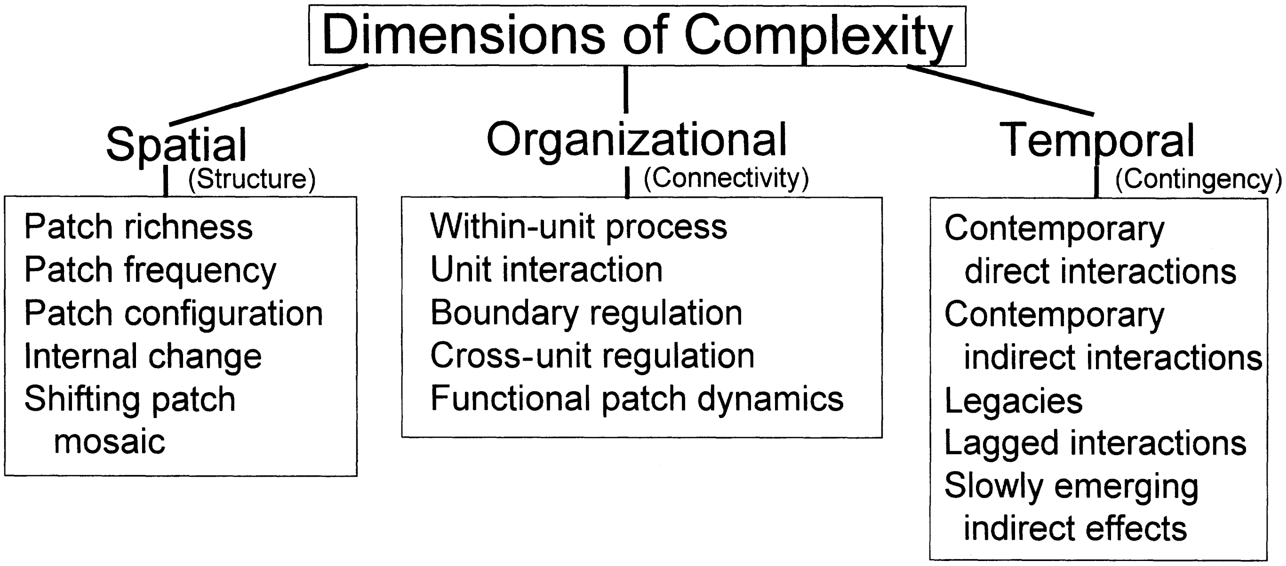

Figure 1. Dimensions of complexity. To ensure their applicability across many different disciplines, the three categories are cast in general terms. Spatial complexity represents increasing spatial explicitness in the structure and change in pattern within systems. Organizational complexity represents increasing connectivity and the influence of outside factors on individual units or discrete systems. Temporal complexity represents increasing historical contingency in the interactions within a system. How these general categories and their subcomponents are realized will differ in each discipline.

plexity. Another dimensional approach to biocomplexity was taken by Cottingham (2002), who linked the basic idea to dimensions of (a) spatial complexity, (b) organizational complexity, and (c) temporal complexity. Although she emphasized the existence of spatial, temporal, and organizational axes in the description of biocomplexity, Cottingham (2002) did not elaborate on the kinds of operational differences the three dimensions might represent. Therefore, our aim was to develop the axes more fully and specifically to apply them to the unification of biogeophysical and social processes in coupled natural–human systems.

The concept of complexity clearly recognizes layers of feedbacks and nesting of system structure, but it expresses much more than increasing detail or resolution. Biocomplexity is still a relatively new topic, and its conceptual structure merits exploration in different domains and in different ways. We flesh out the three dimensions to refine and clarify the concept as a potential tool for the study of coupled human–natural systems (Figure 1). The framework may suggest empirical measures and comparisons that are useful in other systems as well.

DIMENSIONS OF BIOCOMPLEXITY

The first dimension is spatial complexity. *"Spatial complexity"* refers to increasingly subtle and comprehensive quantification of spatial mosaics or spatial fields. The key to understanding the increasing complexity of spatial structure of systems is to find a way to work with spatial heterogeneity where multiple interacting relationships are at play. Ecologists often describe spatial heterogeneity in terms of patches—discrete areas that differ from one another in structure, composition, or function. The ecological theory of patch dynamics has been an important explanatory and modeling tool in understanding and applying community organization, population dynamics, succession, disturbance, ecosystem function, and conservation (Pickett and Rogers 1997). Patch theory can readily support the evaluation of complexity in ecological systems, and it suggests that a clear understanding of complexity in spatial structure is a powerful first step toward the exploration of structure–function relationships (Fortin and others 2003). Statistical formulations that reflect the continuous nature of spatial data are equally appropriate (Csillag and Kabos 2002). Essentially, the complexity of spatial structure increases as quantifications move from the simple discrimination of patch types and the number of each type to the assessment of configuration and the change in the mosaic through time (Li and Reynolds 1995; Wiens 2000). Biocomplexity starts with number, as does biodiversity, but it progresses to spatially explicit assessments of the heterogeneity and difference within any ecological system. Note that "system" can refer to any level of the traditional ecological hierarchy.

We can summarize the spatial dimension of complexity as the following sequence: Patch richness → Patch frequency → Patch configuration → Internal patch change → Shifting patch mosaic. Patch richness, the simplest level of the spatial axis, describes the number of different patch types. Patch frequency adds complexity by describing the relative contribution of each patch type to the whole array of patch types. Patch configuration describes the explicit spatial pattern of patches, indicating the proximity of different patch types, boundary relationships, and other spatial characteristics of patches as they fit together in a volumetric mosaic. The fourth level of complexity recognizes that patches are not internally fixed through time. Internal patch change enables researchers to describe and account for the way that each patch changes or persists through time. The highest degree of spatial complexity takes into account both the spatial configuration of a set of patches, and the fact that individual patches and hence the entire array, can change through time. The spatial dimension of complexity lays out the possible and increasingly comprehensive ways that patches and arrays of patches can be described. This axis is relevant to the multiplicity of interactions that may occur over the diversity and array of patterns through time (Figure 1).

The second dimension is *organizational complexity*, which reflects the increasing connectivity of the basic units that control system dynamics. Within organizational hierarchies, causality can move upward or downward. Organizational complexity is a crucial driver of system resilience—that is, the capacity to adjust to shifting external conditions or internal feedbacks (Gunderson 2000; Holling 2001).

The following sequence describes organizational complexity: Within-unit process → Unit interaction → Boundary regulation → Cross-unit regulation → Functional patch dynamics. At the simple end of this axis, the functional connectivity between units is low, and the processes within a unit are determined by structures or other processes within that unit. Increasing complexity yields unit interaction, in which processes in one system or patch are affected by processes from elsewhere. If units interact, then boundary regulation is the next level of complexity. At this level, the structure of the boundaries between units determines the influence of one unit on another. Cross-unit interaction means that two neighboring or distant units can affect one another. At the highest level of complexity, a mosaic of units interacts through fluxes of matter, energy, organisms, or information, and the structure and dynamics of the mosaic can be altered by those fluxes. The most complex case is therefore most highly connected (Figure 1).

Temporal complexity, the third axis, refers to relationships in the system that extend beyond direct, contemporary ones. Therefore, the influence of legacies, or the apparent memory of past states of the system, the existence of lagged effects, and the presence of slowly appearing indirect effects constitute increasing temporal complexity. The mere passage and scaling of time, although crucial for interpreting ecological systems (Frost and others 1988), is distinct from temporal complexity, where the effect of history and legacies is the concern.

The temporal axis of complexity can be summarized by the following sequence: Contemporary direct interactions → Contemporary indirect interactions → Legacies → Lagged interactions → Slowly emerging indirect effects (Figure 1). Strictly contemporary interactions dominate in ecological interactions that depend only on the immediate state of the system. One example is a predator–prey interaction that is dependent only on the current densities of each of the two interacting populations. Legacies affect the system when a past state determines the current interactions. A hypothetical example might be the difference in predation risk in a population that has experience with predators compared to a population that had no prior experience with predators; in this case, the legacy of the inexperienced population would be a higher rate of predation. Past conditions may not yield an immediate or continuous effect on an ecological process. In other words, legacies may have lagged effects. For example, a system may react to a current stress differently if it has experienced past stresses or disturbances. Trees that have been injured by insects in the past may be more susceptible to a contemporary wind disturbance. The effect of insect damage is lagged in this case. Indirect effects, those by which one ecological entity affects another ecological entity through the effects on a third party, are often encountered in ecology. We expect them to be common in coupled systems as well.

SIMPLICITY AS THE NULL MODEL: HOW MUCH COMPLEXITY IS ENOUGH?

The study of biocomplexity must determine how well analyses using different degrees of complexity capture the dynamics of coupled systems. Simplicity is the null point on each axis of complexity. A practical goal of broad significance in the design and management of sustainable systems is to discover the simplest models capable of explaining and visualizing relationships in coupled natural–human systems.

Basic science can also be advanced by working with integrative models of an appropriate degree of complexity. For example, the use of maximally complex models will likely emphasize the differences among systems rather than identifying their common features (Cadwallader 1988; Jax and others 1998). Thus, analyses based on the most complex models may reduce comparisons to a series of special cases. Furthermore, questions of scale focus on homogeneity within patches to highlight coarse contrasts, rather than focusing on within-patch heterogeneity to examine fine-scale spatial dependence.

Likewise, scenarios developed for managers and planners based on the highest degree of complexity are likely to require too much, or unavailable, data, and delay crucial decisions. Finally, the degree to which model uncertainty increases with model complexity is an important practical limit to the marginal gain of increased complexity. Therefore, the ability to identify the analyses that are just simple enough to provide an effective explanation is one motivation for understanding the dimensions of complexity. Are there definable levels of complexity that maximize our ability to understand coupled system dynamics relative to the effort required and uncertainty resulting from the greater data demands and feedback specifications? Is the relationship improved by integrating across disciplines?

Complexity can also emerge by linking disciplines important to coupled systems. As analyses reflect increasing complexity by integrating different disciplines, do those analyses acquire greater explanatory power? In other words, to what extent are the relationships in a system better or more poorly represented by increasing disciplinary scope across the spatial, temporal, and organizational axes? The framework we have presented can support research that will ultimately provide the answers to such questions.

THE URBAN CASE: A HYPOTHETICAL EXAMPLE

To illustrate the role of complexity in understanding coupled systems, we will use urban systems. Urban systems are unarguably complex and necessarily coupled. Hence, they provide an ideal example to test the role of complexity in coupled systems. In urban environments, we can divide the system into three related, but usually separately conceived and separately managed, components: (a) ecological structures and processes, (b) social structures and processes, and (c) hydrological structures and processes. We will outline a hierarchy of organizational complexity for an urban system from the disciplinary perspectives of ecology, hydrology, and social science. In all of these examples, the core definition of organizational complexity as the degree of connectivity in a spatially structured mosaic holds.

In the social realm, the abstraction of organizational connectivity is expressed through increasing complexity of decision-making structures. Decisions that affect a particular ecological process can be made by simple units, such as individuals. Increasing complexity arises as more points of view, values, sources of information, potential outcomes, and calculations of cost and benefit must be account for. Households are a more complex decision-making system than individuals. The complexity hierarchy increases through neighborhoods, municipal structures, and state and federal entities, Feedback across these different scales of organizational decision making is an important research topic.

In ecology, connectivity can be illustrated by controls on plant community dynamics in the urban matrix. Complexity increases as more processes must be accounted for. Internal patch processes, such as competition, may be sufficient in some cases to drive succession. However, ecologists are increasingly discovering that influences from adjacent patches alter the rate of succession. Boundaries can be significant in determining successional processes in adjacent communities. We expect this finding to widely apply to adjacent green spaces and urban developments (Drayton and Primack 1996). Finally, the complete suite of connections, based on physical processes, animal movements, dispersal of plants, the movement of nutrients and pollutants, and the spread of disturbance agents, leads to a complex, spatially integrated, and dynamic mosaic of successional patches.

Hydrology is a discipline that has long been well integrated. Therefore, examples of complexity actually have to pull apart entities that hydrologists usually consider well connected. However, the ideal sequence of control of hydrological flow begins with simple, in-channel control and increases as, by turns, control of floodplain processes, hillslope structure, small catchment dynamics, and finally large catchment source and sink connections are considered. Different levels of hydrological complexity can be the target of urban water management and restoration. Because urban systems modify the hydrological hierarchy and rearrange connections based on infrastructure, organizational complexity is very relevant to urban hydrology.

These examples based on different disciplinary perspectives, are abstract and hypothetical. But they point to the variety of hierarchical models, that might have to be built before we can understand complexity in its various dimensions. Ultimately, the goal is to construct models that incorporate biological, social, and physical perspectives in integrated models (Groffman and Likens 1994). The challenge is to determine the degree of complexity these models must represent to be useful to managers, successful in linking disciplines, and productive of new, tractable hypotheses.

CONCLUSIONS

The concept of biocomplexity appears to have originated as a metaphor intended to foster synthesis, integration, and multidisciplinary analysis in biology. It has roots by analogy in biodiversity and systems ecology. We have defined "biocomplexity" as "the degree to which interactions in ecological systems comprising biological, social, and physical components incorporate spatially explicit structure, organizational connectivity, and historical contingency through time". We have further proposed that clear operational frameworks are needed to support its use in various integrated studies. The study of biocomplexity has the advantage of explicitly integrating biotic and abiotic variables. It also emphasizes the functional aspects of biological systems, in addition to the structural and compositional foundations of those systems usually targeted by biodiversity studies.

Without frameworks to apply it in specific realms, biocomplexity remains abstract and nonoperational. The three dimensions of biocomplexity we have articulated constitute one kind of framework that can help to implement the concept and point the way toward operational models. We recognize axes of biocomplexity that are appropriate for coupled human–natural systems. We have articulated the kinds of differences that can exist along three dimensions of biocomplexity: (a) spatial complexity, (b) organizational complexity, and (c) temporal complexity. These three dimensions indicate the kinds of descriptions that models of complex coupled systems can include. Any specific model must choose from among the factors appearing in the framework. In essence, complexity is the interaction between model structure and the structure of the system itself (Allen and Hoekstra 1992).

Once the three dimensions of complexity are adopted as a framework, the goal of cross-disciplinary integration can be pursued. The first step is to link the various models generated by different disciplines, using appropriate levels of complexity for each of the dimensions represented by these models. The second step, still a distant goal, is to build integrated models from the start.

Finally, to return to the metaphorical and societally useful level, we still need to address the issue of how best to represent operational models of complex, coupled systems. The familiar models of isolated disciplines, which focus on a single dimension of complexity or on low levels of complexity, are often readily represented as maps. How should the multidimensional complexity of systems, as revealed by the three axes of complexity in space, organization, and time, be represented in public discourse? As this question suggests, the successful development and implementation of this new concept will require equal attention to its metaphorical, definitional, and modeling aspects.

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