Patterns of social self-organisation in cyberspace revealed by temporal correlations and co-evolving networks

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Online social interactions, supported by the present information technology, provide a suitable environment for collaborative problem solving, which can lead to the emergence of social values. Apart from their specific rules and design, each communication site provides a possibility for exchange of messages whose content (cognitive, emotional) can affect the course of events and potentially lead to a collective behavior of the actors in the process. Here, we consider two representative examples: i) Collective knowledge building in a Questions & Answers system (Q&A), which aims to transform the individual's expertise and tacit knowledge into a collective social value [1], and ii) Appearance of the collective emotional behavior in online chats with Bots [2]. In both cases, a plenty of data possessing high temporal resolution and identity of all users as well as contents of communicated messages facilitates the study of the underlying self-organized processes. To make sense of the data, we use modeling concepts of agent-directed dynamics, where the agents represent the actors in the process, and their relevant attributes are designed to match statistically the ones in the empirical data [3]. Moreover, in the simulations we vary certain parameters and the agent's attributes away from the estimated experimental values to explore their importance for the process and predict potential outcomes, which are not present in the experimental system. To quantify the emergent collective dynamics, we utilize the analysis of time series as well as the topology of the co-evolving networks, both suitably constructed from the sequence of events in the empirical and simulated data [4, 5]. Fig. 1 shows two types of networks evolving in the process, in particular a *monopartite network of the users* in emotion-driven chats [6] and a *bipartite network of the actors and their artefacts (questions)* in Q&A system Mathematics [1].

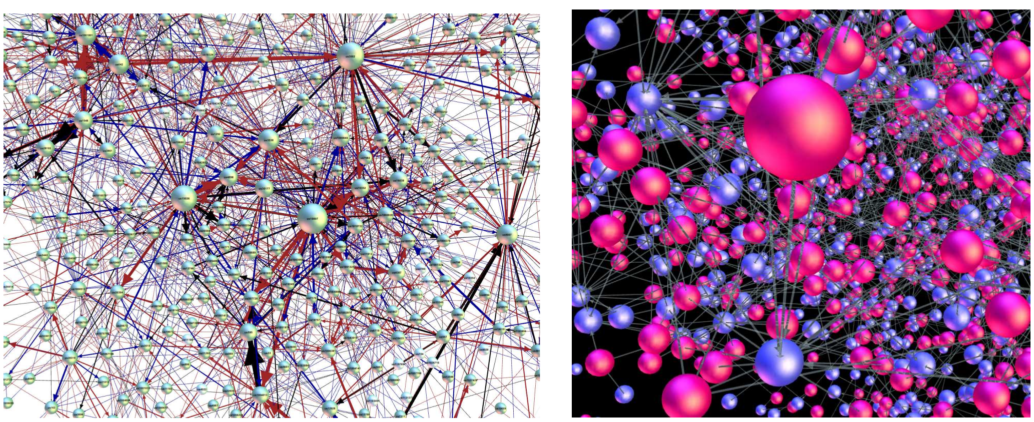

Figure 1: Left: Evolving network of actors in online Chats; colors along the links indicate emotional contents of messages (positive–red, negative–blue, neutral–black); Right: A bipartite network of users (blue) and questions (red) in Q&A site Mathematics.

Temporal fractal structures have been discussed within modeling the evolution of the Web [7] as well as in the empirical data analysis related to the use of the online social networks on the Web [8]. In the co-evolving networks of online communications, the network architecture and the temporal fluctuations of the relevant dynamical observables go hand-in-hand [4]. Thus, a network with communities emerges driven by a few very active users with broad expertise in the Q&A system [1], or a favorite post with excessive negative emotion in Diggs [5]. On the other hand, a hierarchically organized network with a core appears in Chats due to the dominance of a robot and active moderators [6, 9]. These sub-structures closely match with the temporal correlations and clustering of events in the underlying nonlinear dynamics. Assuming that certain attributes of the actors and artefacts affect the self-organizing process, we construct time series by selecting the events containing such attributes. For instance, apart from the

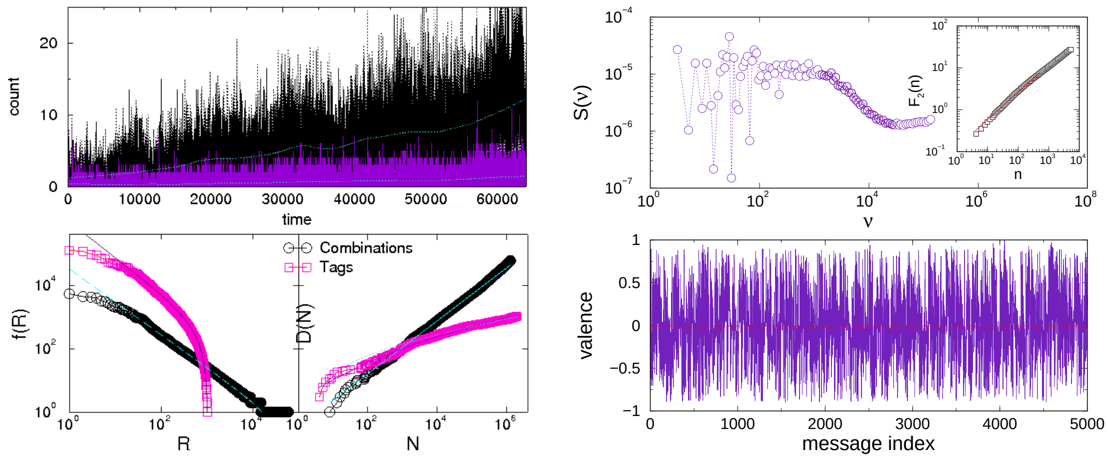

Figure 2: Left: Time series with a specified knowledge contents and the number of users (top) and measures of cooperation and innovation (bottom). Right: Temporal correlations of valence fluctuations time series in the emotional Chats (used with permission from [2]).

number of events per time unit, we collect the series of events that contain a particular knowledge or tag in Q&A. Fig. 2 shows that these time series typically exhibit an increasing trend with a long cycle. Using the proper methods [8], we remove trends and examine the nature of fluctuations, avalanches and temporal correlations by detrended time series analysis. Furthermore, we evaluate measures of *innovation* and *cooperation* that yield the scaling of the related Zipf's and Heap law in the frequencies of tags combinations. In Chats, we select and analyse the time series of positive/negative emotion and valence fluctuations in the network, cf. Fig2. The fractal analysis of these time series reveals [2] the occurrence of non-Gaussian relaxation (avalanche returns) and the long-range temporal correlations in the streams of events carrying positive/negative emotion valence. A set of quantifiers of these self-organized processes is readily computed both from empirical data and simulations. A similar, but more profound self-organization characterizes the cognitive-matching processes in Q&A system Mathematics[1].

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Algebraic Topology Analysis of Networks Emerging from Content-Driven Social Interactions

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High-resolution empirical data from online communication systems contain valuable information about user activity patterns as well as the contents (cognitive, emotional) exchanged among the users. In this respect, new IT is systematically developing to support the process of innovation and knowledge building. A prototypal example is Questions and Answers (Q&A) system devoted to a specified type of knowledge or science discipline. On these systems, a suitable subject tagging provides information about the use of particular contents contained in the artifacts that intermediate human interactions. On the other side, we have the online social networks, where a direct user-to-user communication often carries information that is heavily masked by emotional contents. In both cases, a particular content and human attributes of individual actors in the process and their expertise can crucially influence the course of events leading to the formation of communities, which share the emergent social value. For instance, by data analysis and appropriate modeling we have shown [1] that community forms around a few very active individuals who are possessing a high expertise. Similarly, posting an 'explosive' content on Blogs influence the appearance of communities that last for an extended period [2]. Quantifying the role of such individuals and finding the key subjects (cognitive contents) in streaming online data is a challenging problem, which requires network analysis beyond standard network measures. Recently, we have devised suitable quantifiers of nodes [3] within the algebraic topology analysis of graphs. In this approach, the geometrical objects can be identified such as triangles, tetrahedra, and higher-order cliques and their complexes in which a particular node participates. Here, we present the basic features of this methodology. We then analyze two types of networks suitably constructed from the empirical data with content-driven online communications. Specifically, we show how the influential individuals appear by building social capital in the communities on online social networks. Further, we analyze empirical data from the platform for scientific collaboration *Mathematics*, where we describe the topological spaces of key nodes representing the cognitive contents used in the Q&A communications among experts.

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Modeling The Dynamics of Knowledge Creation in Online Communities

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Exchange of knowledge contents supported by online communication systems can lead to the emergent behavior, where interacting communities share an accumulated knowledge. In this process, both the knowledge of individual actors as well as the patterns of their conduct over time play an important role. In Ref. [1], we have analyzed the emergence of collective knowledge in a modern Questions & Answers (Q& A) system *Mathematics*, where cognitive elements of each artifact are marked by several tags within the standard mathematical classification scheme. Here, we present a microscopic model of knowledge sharing, which correctly accounts for the detailed description of the process from the elementary to the global scale. Based on our experience in modeling online social communications [2, 3, 4], the knowledge-based interactions in this model are closely related to the dynamics observed in the empirical system [1]. Specifically, the interaction rules match the studied Q& A system, and the profiles of the actors in the model are statistically similar to the profiles of users in *Mathematics*. In addition, we assume that at least minimal matching occurs between the cognitive contents of the answered question and the actor's expertise, which can be expressed by a combination of tags.

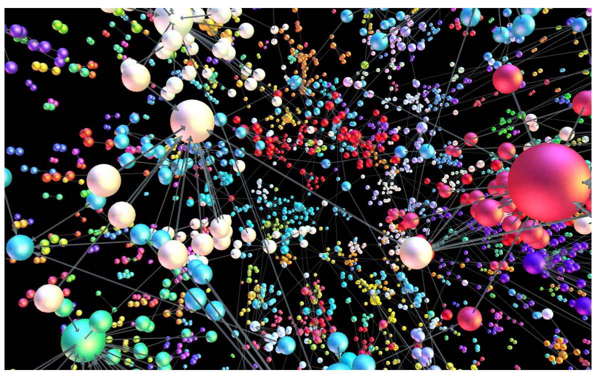

Figure 1: Community patterns in the bipartite network of questions and actors with an expertise limited to two tags.

Following the sequence of events in the simulations, we observe the growth of a bipartite graph of actors and their artifacts, and the appearance of network communities. The structure of communities reveals the principal actors (Fig.1) and the involved cognitive elements. We sample time series related to the integral activity in the network as well as the activity that is strictly involving a particular cognitive element or specified combinations of such elements. By analysis of these time series, we determine various indicators of the collective behavior and the related knowledge contents. Furthermore, we investigate how these indicators depend on the actors' profiles and the range of their expertise.

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The dynamics of collective knowledge building via questions and answers

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Collective knowledge building is a socio-cultural process which takes place trough self-organized dynamics of interactions among individuals [1]. In recent years, quantitative study of different collective social phenomena has been enabled by vast amount of empirical data in online communication systems such as Blogs [2], Digg [3], online social networks [4, 5, 6], online chats [8] and online games [7, 9]. Question and answers (Q&A) sites form excellent repositories of collective knowledge and provide a proper environment where dynamics of collective knowledge building can be studied. On these sites, interactions among users are conveyed by means of asking and answering or commenting questions. This kind of problem-solving collaborative dynamics gives rise to new social phenomena, for example, formation of cross-topic or cross-disciplinary groups of participants, popularity of particular problems, subjects, authors or their solutions.

We analyse the empirical data from Mathematics Q&A site of StackExchange network. The large dataset used for the analysis contains all user-contributed content on this site for the period of four years. We focus on quantitative analysis of collective phenomena arising in the exchange of cognitive contents that can be identified in the empirical data. We combine diverse methodologies that are illustrated by the results in Fig. 1.

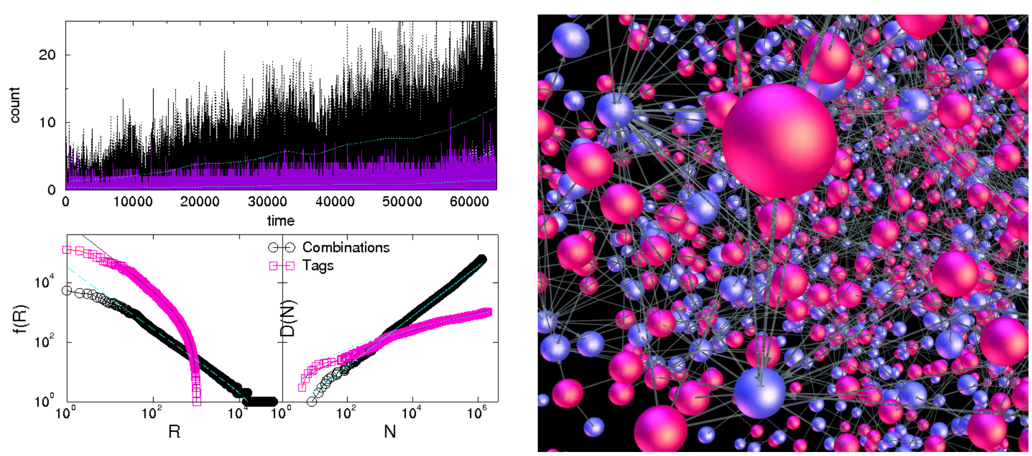

Figure 1: An example of time series with a specified knowledge contents and the number of users, exhibiting an increasing trend (top left); two measures of cooperation and innovation (bottom left) and a part of the network of connection between users and questions (right).

In particular, in our analysis, we map the data onto suitable *bipartite networks* of users and questions; using the appropriate methods of complex networks theory we analyse these bipartite graphs and their projection. Specifically, using the spectral analysis method for community detection [10], we identify user communities and examine dynamics of their formation in relation with tags (categories) of asked questions and answers. We consider *time series* of the number of events (questions, answers, comments) per time unit as well as the series of selected events that contain a particular knowledge or tag. As the Fig. 1 shows, these time series typically exhibit an increasing trend with a characteristic long cycle. Using the proper methods [4], we remove trends in these time series and examine the nature of fluctuations, clustering of events and temporal correlations by detrended time series analysis. Furthermore, we estimate two measures of *innovation and cooperation* that, according to ref. [11], can be described by the appearance of power laws in the related Zipf's and Heap law. In the present data, we demonstrate the occurrence of such functional relationships in the frequencies of each tag but also in tags combinations that develop in the sequence of events.

To further understand the dynamics of knowledge exchange from the microscopic to the global level, we introduced a model of interacting agents and performed simulations for varying parameters. The simulated results confirm the occurrence of collective knowledge as observed in the empirical data.

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SOCIAL STRUCTURES EMERGING IN ONLINE COMMUNICATIONS: ROLE OF CONTENTS AND UNDERLYING MECHANISMS

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What kind of social structures may emerge in *ad hoc* contacts on Blogs, Internet Relayed Chat channels and in 'friendly' online social networks communications? Are these structures stable and what holds them together? In this lecture, we attempt to address these questions by means of empirical data analysis and agent-based modelling approach. In the first part, we present quantitative analysis of large empirical datasets combining the methods of physics of complex systems and machine learning methods for analysis of the texts of communicated messages. Using the network mapping of the high resolution data we recognize and characterize several types of social structures and explore their resilience with respect to the contents of the messages communicated along the network links [1,2,3].

Furthermore, using the agent-based modelling where the agents exchange emotional messages on the appropriate evolving network structure, we explore the underlying mechanisms which lead to the appearance of these structures [4,5]. Owing to the self-organize nature of the dynamics, we explore the potentials to influence the course of the dynamics at the microscopic level by varying the relevant control parameters and by utilizing chat Bots of predefined characteristics [5].

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Can online chats with Bot affect your behavior: Agent-based simulations with emotional Bots

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Exchange of information in online communications has both knowledgable and social dimension. In the online chats on IRC channels, often Bots are involved to serve different objectives. Now days versatile Bots can be designed; they can make use of a variety of prepared data as well as dynamically changing knowledge about the entire system, which is beyond the limits of human users. The issue of their capability to have influence over a large number of users still remains controversial.

In this work, we analyse the problem of online chats with Bots from the viewpoint of theory of complex dynamical systems and networks. Specifically, using the agent-based method [1, 2, 3], we simulate several circumstances where Bots favouring specific emotional contents maintain contact with emotional agents. The action rules and several parameters of the model are motivated by an empirical chat system [4]. Analysis of the simulated results implies that the Bot may polarize mood on the entire chat-network. The Bot's effectiveness depends on the structure of contacts among agents as well as the fractal character of the underlying stochastic process.

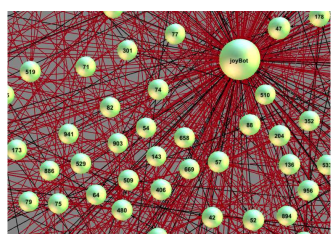

Figure 1: Presence of positive-emotion Bot polarizes positively the links among agents.

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COLLECTIVE CHARGE FLUCTUATIONS IN MONOLAYERED STRUCTURES EXHIBITING COULOMB BLOCKADE TRANSPORT

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Key words: *Cellular Networks, Single-Electron Tunnelings, Culomb Blockade, Collective Charge Fluctuations, Cunducting Paths.*

Structured arrays of metal nano-particles (NP) have non-Ohmic conduction properties with a nonlinear current–voltage $I(V)$ characteristic above a threshold bias voltage. In these capacitative-coupled NP systems, the mechanisms of single-electron tunnelings (SET) are provided by Coulomb blockade transport between adjacent nano-particles along a conduction path [1, 3]. The $I(V)$ dependence was shown to be strongly correlated with the geometry of the array: a larger topological disorder induces a larger $I(V)$ nonlinearity [2, 3]. The origin of this phenomenon lies in the collective charge fluctuations along different conduction paths between the electrodes that are dynamically established through the system [3]. Recently, a similar conduction properties were reported in chemically reduced graphene oxide sheets [4], where isolated graphene domains are surrounded by insulating oxide area, through which SET occur between the adjacent conducting domains. Another interesting material with Coulomb blockade transport represents a “necklace” of Au NP which are nano-cemented with CdS [5]. In contrast to NP films studied in [2], these systems have strictly monolayered structure; this imposes additional constraints to the topology of conduction paths and, thus, to the charge transport in these materials. In this work, using simulations of SET processes on nanonetworks [6], we study collective charge fluctuations in nanoparticle assemblies that are modeled by planar graphs with varied structure. The planar graphs are grown by aggregation of cells of various sizes [7]. In Fig. , we show an example of a cellular network with a scale-free distribution of cell sizes.

Firstly, we briefly describe two key elements of this modeling approach: (i) mathematical structure and implementation of the SET processes through the nanoparticle assembly of arbitrary structure represented by the adjacency matrix of a nanonetwork; (ii) quantitative analysis of the emergent collective dynamics. Then, by performing simulations of SET in

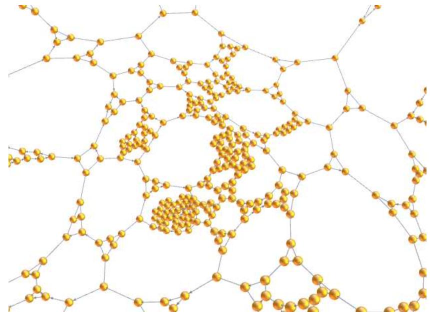

Figure 1: An example of cellular network structure grown by cell aggregation described in Ref. [7].

different nanonetworks, we give several quantitative measures of the emergent collective dynamics. We determine the nonlinear $I(V)$ curves for each particular structure, and study temporal correlations in the underlying stochastic process which gives rise to the observed nonlinearity. Specifically, we analyze the persistence in the charge fluctuations time series, avalanches of tunneling events, avalanche correlations and entropy as well as experimentally observable non-Gaussian current fluctuations in these nanonetworks.

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