systems: pp-pp, year
ISSN xxxx-xxxx
http://systems-journal.eu

Crucial role of creative elements in changes of exploration and exploitation with network position and during crisis

András London[1,2], Gábor Simkó[2,3], Ágoston Mihalik[2,4], Kristóf Kubina[2,5], Marcell Stippinger[2,6], Shijun Wang[7], Peter Csermely[2,1,*]

[1]*University of Szeged, Department of Computational Optimization, H-6701, Szeged, P.O. Box. 652, Hungary*

[2]*Semmelweis University, Department of Medical Chemistry, H-1444 Budapest 8, P.O. Box. 260, Hungary, e-mail: csermely.peter@med.semmelweis-univ.hu, Telephone: +36-1-459-1500*

[3]*Vanderbilt University, Nashville TN, USA*

[4]*University of Pécs, Department of Anatomy, H-7624, Pécs, Szigeti u. 12., Hungary*

[5]*Péter Pázmány Catholic University, Faculty of Information Technology, H-1083 Budapest, Práter str. 50/a., Hungary*

[6]*Budapest University of Technology and Economics, Institute of Physics, H-1111 Budafoki str 8., Budapest, Hungary*

[7]*National Institutes of Health, Clinical Center, 10 Center Drive, MSC 1182, Bldg 10, Room 1C224, Bethesda, MD 20892-1182, USA*

Abstract: *Significant changes in structure of a complex network reflect to the changes in stability and adaptation of the network. Inter-modular nodes, hubs and creative nodes play a key role in the crisis-adaptation of complex systems. Game theory has been shown as a useful model to study the topological importance and behavior of agents in complex systems. This behavior is well characterized by cooperativity of nodes in spatial social dilemma games. Creative behavior is crucial for maintaining network structure-independent cooperation in spatial game contexts. Hubs and inter-modular positions emerge as key determinants to maintain cooperation. Our findings suggest that optimization of exploitation/exploration, trade-off is reflected by an intermediate position between extremes of rigid, cumulus-like and flexible, stratus-like network topologies.*

Keywords: Adaptation, cooperation, creative node, crisis, network, network modules, Prisoner's Dilemma game, protein-protein interaction networks, spatial social dilemma games, stress, yeast

Acknowledgement: Authors thank members of the LINK-Group (www.linkgroup.hu) for their discussions and help. This work was supported by the EU (TÁMOP-4.2.2/B-10/1-2010-0013), by the Hungarian Scientific Research Fund (OTKA K-83314) and by a residence at the Rockefeller Foundation Bellagio Center (PC).

Network approach to study complex systems has become more and more important in recent years. The large number of high-throughput technologies made us available so many data while increasing storage capacities allowed us to collect and study enormous amounts of data on complex systems. The network approach may simplify this data structure to an extent that we may pick up the most important actors in the complex systems, and may also find their most important interactions. Networks not only give us a clear visual image of these systems providing an instant recognition of groups and important elements, but also have a number of structural features, which are general and important properties of biological, social and engineered networks. Real-world networks have many general and common properties such as the small-world character, scale-free type degree distribution which involves the existence of hubs; modules, hierarchical and nested toplology; the stabilizing role of weak links and many others are amongst these features (Csermely, 2009). Our highly multidisciplinary group (www.linkgroup.hu) uses networks as 'highways' making the transfer of concepts between various disciplines rather easy. The network approach allows the translation of the original concepts into the context of other scientific fields with entirely different linguistic, and helps to solve creativity deadlocks due to unexpected associations and solutions (Farkas et al, 2011).

Cooperation is a main concept helping the self-organization of complex systems. Understanding the evolution of cooperation is a key concept, since the selfish, competitive behaviour is often the only evolutionary stable pattern instead of cooperation. We used spatial games to show that the influence of the individual agents on the final level of cooperation is far from being equal. We also showed that the agents' influence on cooperation strictly depends on their network position. Thus network structure quite often determines function. On the other hand, networks often help us to discriminate between the local and global level. For example in our initial results a biological network in crisis produces just the opposite behavior in cooperation locally and globally, meaning that after crisis it cooperates more locally, but less globally. Such an opposite behavior is a characteristic feature of complex systems in general.

1. Creative network nodes

Inter-modular nodes, such as the extremely dynamic 'creative nodes' play an extraordinary role in network exploration (Csermely, 2008). Their presence plays a key role in the complex systems' potential for fast adaptation (called evolvability in biological systems). These elements bridge Ronald S. Burt's (1995) 'structural holes', and provide a key subset of Mark Granovetter's (1973) 'weak links'. Active centers and binding sites of proteins often occupy such a position in protein structure networks. As the complexity of the system increases, the mobility of creative elements expands, and covers more and more the entire network. Creative nodes emerge as crucial determinants helping crisis survival and evolution (Csermely, 2008).

2. Creative behavior is crucial for maintaining network topology-independent cooperation in spatial games

Biological and social interactions can be precisely represented as networks in which nodes represent agents and links stands for their relationships (Newman, 2010). Social dilemma games (their widely-known examples are the *Prisoner's Dilemma game* or the *Hawk-dove game*) show a behavioural dichotomy, because each agent has two choices (independently from the other agent's decision): to cooperate, or defect. Depending on the choices made, each agent gets profit (called payoff in game theoretical terminology) and the aim of the agents is to maximize the gained profit. The *payoff matrix* of a game describes the profit of each agent as the function of the decisions of both angnts. Table 1 shows the generic payoff matrix of a two-player game.

Table 1: Generic payoff matrix for the two-agent, two-strategies gemes (discussed in text)

	C	*D*
C	*R,R*	*S,T*
D	*T,S*	*P,P*

The set of strategies is $\{C,D\}$, where C denotes the cooperation and D means defection. In the payoff matrix R stands for the *reward* the two agent receive if they both cooperate, P is the *punishment* if they both defect. T is the *temptation* that an agent receives if he defects while the other cooperates getting the *sucker's* payoff S. For the Prisoner's Dilemma game these four payoffs have to satisfy the following two inequalities: $T>R>P>S$ and $T+P<2R$. In the Hawk-dove game $T>R>S>P$. Thus, in the Hawk-dove game, when both agents defect they each get the lowest payoff. We used $R=3$, $P=1$, $S=0$ and T was varied between 3 to 6 for (canonical) Prisoner's Dilemma game and $R=G/2$, $S=0$, $P=(G-1)/2$, $T=G$, where T was varied between 0 to 1 for the Hawk-dove game.

systems: pp-pp, year
ISSN xxxx-xxxx
http://systems-journal.eu

In spatial games, each node in the network is an agent, and each agent plays a social dilemma game only with its direct neighbours. Neighbouring agents play with each other repeatedly. This gives possibility for the players to change from cooperation to defection or vice versa. Let $s_i \in \{C, D\}$ is the strategy of agent *i* in a given round and *M* is the payoff matrix of the game. The average payoff collected by agent *i* at time step *t* is defined as:

$$\overline{\Pi}_i(t) = \frac{1}{k_i} \sum_{j \in N(i)} \sigma_i(t) M \sigma_j(t))$$

where k_i *and N(i) are* the number of neighbours and the set of direct neighbors of agent *i,* respectively, and $\sigma_i(t)$ is a vector giving the strategy profile at time *t* with *C=(1 0)* and *D=(0 1)*.

There are several different rules for updating the strategy of the agents. The most commonly used update rule is the *best takes over* rule (or "*imitating the best*" rule), where an agent *i* adopts the strategy of that player selected from *i* and its neighbours, who had the highest average payoff in the previous round. We used this rule in our simulations as a basic model and then we changed it with the Q-learning (Watkins et al, 1992) strategy adoption rule which is a random model. In this model agents learned an optimal strategy maximizing their total discounted expected reward in the repeated game. An agent chose action at from a finite set of actions at time step *t.* In repeated multi-agent games, the state of each agent was affected by the states of its direct neighbours. The reward of the agent *i* after taking the action $a_t(i)$ is defined as:

$$r_t(i) = \frac{1}{k_i} \sum_{j \in N(i)} S_t(i) M S_t(j)$$

where *M* is the payoff matrix, $S_t(i)$ was a column vector indicating the state of agent *i* at round *t* (the values of elements of $S_t(i)$ are 0 or 1, and 1 indicated that agent i was in the corresponding state), k_i and *N(i)* are the same as before. Learning means that each agent try to optimize its total expected reward in the repeated game. For each agent the selection probability of a state a_i in time step *t* can be given by any discrete probability distribution. This parameter gives the randomness (i.e. creativity) for an agent.

Network structure heavily affects cooperation, and agents in key network positions have a major influence for spreading either cooperation or defection. Cooperation level of spatial games, such as that observed in Prisoner's Dilemma game is very sensitive for network topology. However, if strategy update rules contain both 'learning' (i.e. memory of payoffs in previous rounds of the game) and 'creativity' (in form of a low level of randomness to switch defection back to cooperation, if cooperation becomes extinct) the level of cooperation will not only high, but will also became rather independent from the topology of the complex network (Wang et al, 2008). Figure 1 shows that if the strategy update rule is not a simple imitation of a neighbouring node, but combines learning and innovation, cooperation is stabilized at a high level, irrespectively of the network structure. Thus creativity is important to maintain cooperation not only at the level of network position (in form of creative nodes; Csermely, 2008) but at decision patterns, too.

systems: pp-pp, year
ISSN xxxx-xxxx
http://systems-journal.eu

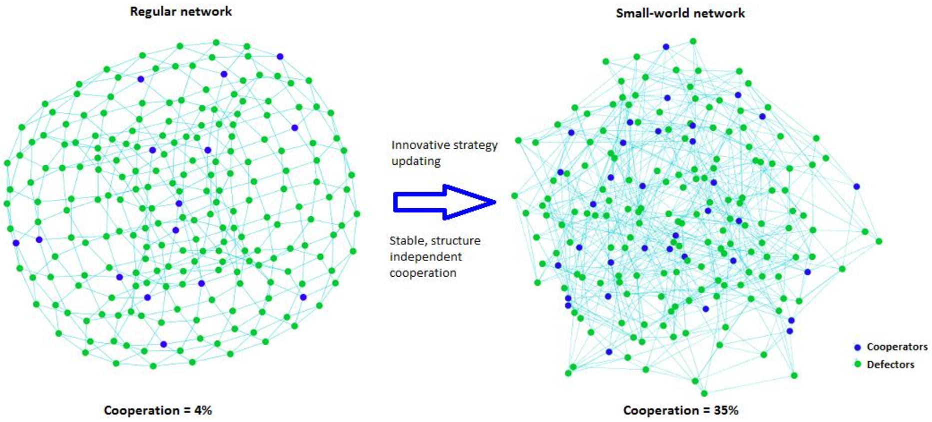

Figure 1: Learning and innovation (i.e. creativity) maintains and stabilizes cooperation in spatial Prisoner's dilemma game independently from the network structure. The first network is a regular graph and the second network is a Watts-Strogatz small-world network obtained by the first graph by rewiring a small fraction of network nodes. Stable cooperation means, that the ratio of cooperators independent form the fraction of rewired nodes.

Learning and innovative elements when applied together allow cooperation in a large number of model networks, including regular networks, random networks, Barabasi-Albert scale free networks and small-world networks. The simulations showed that learning strategy adoption rules promote cooperation, while innovative elements make the appearance of cooperation less dependent from the actual network structure in two different games (Prisoner's Dilemma and the Hawk-dove game). This is good news: we are not victims of our social environment but may develop cooperation even in a cooperation unfriendly network environment using a long-term memory and creativity, i.e. optimizing exploitation and exploration at the same time.

3. Creative nodes in crisis adaptation – an example of yeast cells

Biological systems offer an easy way to model crisis. The importance of inter-modular creative nodes in crisis adaptation was demonstrated on the systems level crisis responses of a yeast cell. When the community structure of the protein-protein interaction network of yeast cells was studied using our recently developed method, ModuLand (Kovacs et al, 2010 www.linkgroup.hu/modules.php), the overlap of protein communities decreased, and protein-protein interaction modules became partially disintegrated as an initial response to stress. The stress-induced decrease of inter-modular connections was beneficial, since it

1. allowed a better focusing on vital functions, and thus spared resources
2. localized damage to the affected modules
3. reduced the propagation of noise
4. allowed a larger 'degree of freedom' of the individual modules to explore different adaptation strategies
5. helped the 'mediation of inter-modular conflicts' during a period of violent intra-modular changes.

Modular reorganization emerged as general and novel systems level way of cost-efficient adaptation (Mihalik and Csermely, 2011).

systems: pp-pp, year
ISSN xxxx-xxxx
http://systems-journal.eu

4. Changes of exploitation in crisis – cooperation-changes in Prisoner's Dilemma games of protein networks

Determining the cooperation level of the network is also very useful for prediction of key nodes of biological regulation. We have examined various ratios and starting positions of cooperators in the protein-protein interaction network of normal and stressed yeast cells using the NetworGame program package developed by Gabor Simko (Farkas et al, 2011; www.linkgroup.hu/NetworGame.php). In case of multiple defectors at the starting position we observed a smaller final level of cooperation in Prisoner's Dilemma games in stressed as compared to normal yeast networks. On the contrary, if a single defector was introduced, stressed yeast cells displayed a higher cooperation than that of normal cells (Stippinger and Csermely, unpublished observations, Figure 2). We observed, that biological crisis breaks global cooperation, but stabilizes local cooperation of the yeast protein-protein interaction network. Therefore, it is assumed that this fact is caused by isolation of local network communities in stress.

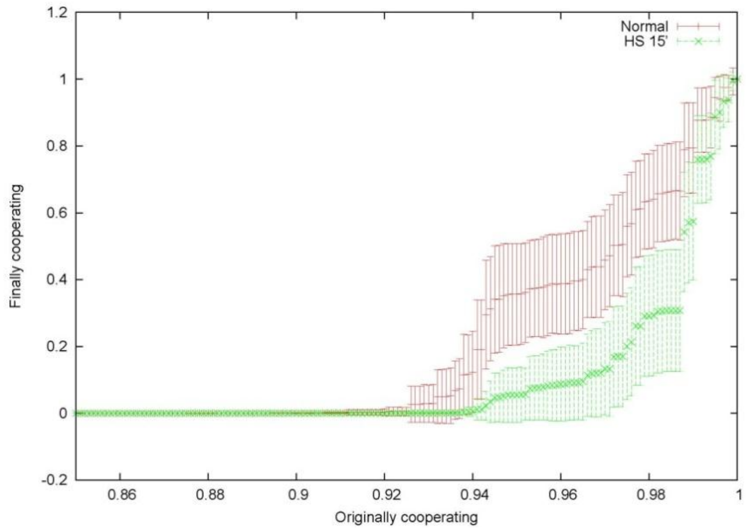

Figure 2: Many initial defectors eventuate less cooperation is stress, because isolated communities remain defectors. In contrary, in the case of only a few nodes initially defect, the cooperation still remains in stress, because isolated defecting communities may not invade others.

5. Inter-modular positions have a key importance to maintain cooperation in spatial games

When single defectors or cooperator pairs were introduced to various starting positions of real world networks in repeated spatial Prisoner's Dilemma games using the NetworGame program (Farkas et al, 2011; www.linkgroup.hu/NetworGame.php), a large variability of influence was observed on the final level of cooperation.Encouraged by these results we defined defective and cooperative game centralities as novel measures of the dynamic influence of individual nodes or node-pairs on network behavior. Examinations of various biological, engineering and social networks showed that hubs, hub-hub cores, and inter-modular nodes play a crucial role in the maintenance of cooperation of complex systems (London, Simko & Csermely, unpublished observations).

To illustrate the power of spatial games analysis and to show the important role of inter-modular, creative nodes, and bridges between different communities that connect key network nodes, we analysed Zachary's karate club network. In the 1970's, Zachary studied a university karate club, where over the years the two most influential members of the club (the administrator and the instructor, see Figure 3) developed a conflict, and the club was split into two fractions following them. Applying the Hawk-dove game to this karate club network with a randomly distributed 50-50% cooperation and defection as a starting strategy distribution, the two fractions were recovered as separated cooperators

systems: pp-pp, year
ISSN xxxx-xxxx
http://systems-journal.eu

and defectors. Applying the Prisoner's dilemma game, the four nodes with the highest betweenness centrality (Freeman, 1977) (i.e. the nodes forming a part of the most paths between any two nodes) could be determined as the most influential nodes to spread defection to an otherwise fully cooperating community. Initial defection of these 4 nodes broke the cooperation of the whole network. These four nodes contained both the instructor and the administrator causing the split of the club.

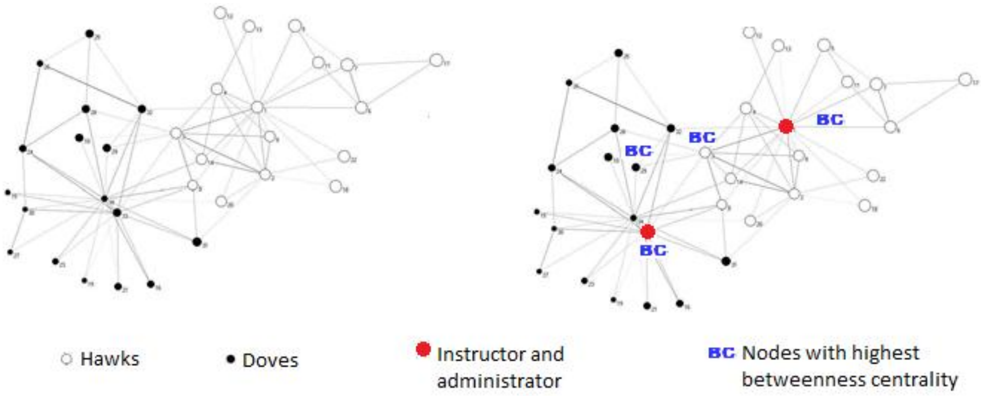

Figure 3:Hawk-dove game with random 50-50% starting defection/cooperation recovered network modules (left). Prisoner's dilemma game determined the most influential network nodes (highest BC), including the administrator and instructor causing the split of the club (right)

6. Optimization of exploitation/exploration trade-off is reflected by an intermediate position between extremes of rigid, cumulus-like and flexible, stratus-like network topologies

As we summarized recently (Csermely et al., 2012) networks seem to segregate to two basic conformations, the stratus- and cumulus-like network topology. As introduced first by Batada et al (2006) stratus-type networks are similar to flat, dense (dark) low-lying clouds, while cumulus-type networks are similar to puffy (white) clouds. Networks with a cumulus topology have a rather disjoint, multi-centered modular structure. Such a structure has a rather limited overlap between the modules, which implies a higher cohesion and rigidity of the individual modules. Networks with a stratus topology have a rather coalescent structure resembling that of stratus clouds. Such networks have a large overlap between their modules to the extent that modules cannot be readily distinguished from each other. This implies a high flexibility of the entire network. As we showed earlier stress induces a stratus cumulus transition in yeast protein-protein interaction networks (Mihalik and Csermely, 2011). Cumulus-type networks are optimized to the exploitation of their current behavior, and (in their extreme form) are rigid to the extent that they are unable to change, i.e. they are unable to learn. On the contrary, stratus-type networks are optimized to the exploration of alternative options, and (in their extreme form) are flexible to the extent that they are unable to get a stable state, i.e. they are unable to remember.

Optimization of both exploitation and exploration helps cooperation and makes it independent of network structure. Key network nodes having a high influence on breaking (or making) cooperation can be predicted in biological and social systems Optimization of exploitation/exploration trade-off is reflected by an intermediate position between extremes of rigid, cumulus-like and flexible, stratus-like network topologies (Csermely et al., 2012).

References

Batada, N. N., Reguly, T., Breitkreutz, A., Boucher, L., Breitkreutz, B. J., Hurst, L. D. & Tyers, M. (2006) Stratus not altocumulus: a new view of the yeast protein interaction network. *PLoS Biology, 4*, e317.

Burt, R. S. (1995) *Structural Holes: The Social Structure of Competition*. Cambridge: Harvard University Press.

Csermely, P. (2008) Creative elements: network-based predictions of active centres in proteins, cellular and social networks. *Trends in Biochemical Sciences, 33,* 569-576.

Csermely, P. (2009) *Weak links: The Universal Key to the Stability of Networks and Complex Systems*. Heidelberg: Springer.

Csermely, P., Sandhu, K.S., Hazai, E., Hoksza, Z., Kiss, H.J.M., Miozzo, F. Veres, D.V., Piazza, F. & Nussinov, R. (2012) Disordered proteins and network disorder in network representations of protein structure, dynamics and function. Hypotheses and a comprehensive review. *Current Protein and Peptide Science, 13*, 19-33.

Farkas, I. J., Korcsmáros, T., Kovács, I. A., Mihalik, Á., Palotai, R., Simkó, G. I., Szalay, K. Z., Szalay-Bekő, M., Vellai, T., Wang, S. & Csermely, P. (2011) Network-based tools in the identification of novel drug-targets. *Science Signaling, 4*, pt3.

Freeman, L.C. (1977) A set of measures of centrality based on betwennes. *Sociometry*, 40, 35-41.

Granovetter, M. (1973) The strength of weak ties. *American Journal of Sociology, 78*, 1360-1380.

Kovács, I. A., Palotai, R., Szalay, M. S. & Csermely, P. (2010) Community landscapes: a novel, integrative approach for the determination of overlapping network modules. *PLoS ONE, 7*, e12528.

Mihalik, Á. & Csermely, P. (2011) Heat shock partially dissociates the overlapping modules of the yeast protein-protein interaction network: a systems level model of adaptation. *PLoS Computational Biology, 7*, e1002187.

Newman, M. (2010) *Networks: An introduction*. New York: Oxford University Press

Wang, S., Szalay, M.S., Zhang, C. & Csermely, P. (2008) Learning and innovative elements of strategy update rules expand cooperative network topologies. *PLoS ONE, 3*, e1917.

Watkins, C. J., & Dayan, P. (1992) Q-learning. *Machine learning*, 8, 279-292.

About the Authors

András London is a PhD student of Computer Science of the Szeged University, Hungary. Ágoston Mihalik, Gábor Simkó and Marcell Stippinger are PhD students of the Pécs University (Pécs, Hungary), Vanderbilt University (Nashville TN, USA) and the Eötvös University (Budapest, Hungary), respectively. Kristóf Kubina is an MSc student of the Pázmány University (Budapest, Hungary). Shijun Wang is a staff member of the National Institute of Health (Bethesda MD, USA). In October 2012 the LINK group had 45 members (www.linkgroup.hu/members.php) from 8 universities, research institutions and 2 R&D firms in Hungary, as well as from the Centre for Integrative Biology in Trento, ETH in Zürich, Max Planck Institute in Sanghai, National Institutes of Health in Bethesda, the Universities of Beijing, Dalian, Hong Kong, Nashville (TN), Oxford, Sevilla, Sanghai, St. Paul (MN), and Strathclyde, as well as an additional 139 loosely attached cooperators.