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14. ABSTRACT
The main aim of this research project has been to illustrate the close connection between swarm intelligence, criticality and the widely used principle of complexity management.

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Report Title

Final Report: From Complexity Management to Artificial Intelligence

ABSTRACT

The main aim of this research project has been to illustrate the close connection between swarm intelligence, criticality and the widely used principle of complexity management.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
05/05/2015 20.00	Paolo Grigolini, Dante Chialvo. Brain criticality, Chaos, Solitons and Fractals, (06 2013): 1. doi:
05/05/2015 21.00	P. Grigolini, M. Zare. Criticality and avalanches in neural networks, Chaos, Solitons and Fractals, (06 2013): 80. doi:
05/05/2015 22.00	Pensri Pramukkul, Adam Svenkeson,, Paolo Grigolini,, Mauro Bologna,, Bruce West. Complexity and the Fractional Calculus, Advances in Mathematical Physics, (03 2013): 1. doi:
05/05/2015 23.00	Adam Svenkeson, Malgorzata Turalska, Bruce J. West, Paolo Grigolini, Mirza Tanweer Beig. Fractional trajectories: Decorrelation versus friction, Physica A: Statistical Mechanics and its Applications, (04 2013): 5663. doi:
08/31/2012 12.00	Malgorzata Turalska, Paolo Allegrini, Bruce J. West, Paolo Grigolini, Nicholas W. Hollingshad. Erratum to “A new measure of network efficiency” [Physica A 391 (4) (2012) 1894–1899], Physica A: Statistical Mechanics and its Applications, (12 2012): 0. doi: 10.1016/j.physa.2012.07.035
08/31/2012 13.00	Elvis Geneston, Bruce J. West, Paolo Allegrini, Paolo Grigolini, Malgorzata Turalska. Cooperation-Induced Topological Complexity: A Promising Road to Fault Tolerance and Hebbian Learning, Frontiers in Physiology, (2012): 0. doi: 10.3389/fphys.2012.00052
08/31/2012 14.00	Paolo Allegrini, Elvis Geneston, Bruce J. West, Elisa Lovecchio, Paolo Grigolini. From Self-Organized to Extended Criticality, Frontiers in Physiology, (2012): 0. doi: 10.3389/fphys.2012.00098
08/31/2012 16.00	Nicholas W. Hollingshad, Malgorzata Turalska, Paolo Allegrini, Bruce J. West, Paolo Grigolini. A new measure of network efficiency, Physica A: Statistical Mechanics and its Applications, (2 2012): 0. doi: 10.1016/j.physa.2011.11.017
TOTAL:	**8**

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(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
08/30/2012	3.00	Malgorzata Turalska, Paolo Allegrini, Bruce J. West, Paolo Grigolini, Nicholas W. Hollingshad. A new measure of network efficiency, Physica A: Statistical Mechanics and its Applications, (06 2011): 0. doi:
08/30/2012	8.00	Luigi Palatella, Paolo Grigolini. Noise-induced intermittency of a reflexive model withsymmetry-induced equilibrium manifold, Physica A: Statistical Mechanics and its Applications, (03 2012): 0. doi:
08/30/2012	6.00	Elisa Lovecchio, Paolo Allegrini, Bruce J. West, Paolo Grigolini. Fromself-organizedtoextendedcriticality, Frontiers in Physiology, (04 2012): 0. doi:
08/30/2012	5.00	Malgorzata Turalska, Elvis Geneston, Bruce J. West, Paolo Allegrini, Paolo Grigolini. Cooperation-inducedtopologicalcomplexity:apromisingroadtofaulttoleranceandHebbianlearning, Frontiers in Physiology, (03 2012): 0. doi:
08/30/2012	4.00	Nicholas W. Hollingshad, Malgorzata Turalska, Paolo Allegrini, Bruce J. West, Paolo Grigolini. ERRATUM , , ( ): 0. doi:
10/01/2013	24.00	B. J. West, P. Grigolini, M. Turalska. Role of committed minorities in times ofcrisis, Scientic reports, (12 2012): 0. doi:
10/01/2013	25.00	Matjaz Perc, Paolo Grigolini. Collective behavior and evolutionary games – An introduction, Chaos, Solitons and Fractals, (06 2013): 0. doi:
TOTAL:		**7**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

Received		Paper
08/30/2012	2.00	Malgorzata Turalska, Bruce J. West, Paolo Grigolini. Complex Networks: From Social Crises to Neuronal Avalanches, IN PRESS on a a John Wiley book edited by Dietmar Plenz (05 2012)
08/30/2012	7.00	. Neural Dynamics: Criticality, Cooperation, Avalanchesand Entrainment between Complex Networks, John Wiley Book edited by Dietmar Plenz (05 2012)
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Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

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FTE Equivalent:
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Names of Post Doctorates

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

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NAME	PERCENT_SUPPORTED

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Total Number:

Names of Under Graduate students supported

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FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

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Names of Personnel receiving masters degrees

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Total Number:

Names of personnel receiving PHDs

NAME

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Names of other research staff

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Scientific Progress

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Technology Transfer

Report on grant W911NF-11-1-0478

From Complexity Management to Artificial Intelligence

The main aim of this research project has been to illustrate the close connection between swarm intelligence, criticality and the widely used principle of complexity management.

It is widely accepted that complex networks are characterized by the condition of scale-free distribution of links. We have derived this property from the cooperative interactions between the individuals of a society. Criticality generated by the cooperation between the individuals of a society with a strength large enough as to make a phase transition from the condition where the individuals are virtually independent the ones from the others to a condition where the dynamics of each individual are closely correlated to those of other individuals, yields renewal events, namely, temporary organization collapses, allowing the system to change mind, and long-range correlation between the individuals of the same society. A renewal event, in fact, is a "free will" state, or saddle point, where an extremely small bias can make the system either to keep or to change mind. We showed [1] that two individuals with no direct link, and no correlation when the control parameter vanishes, at criticality may have a correlation of intensity larger than the correlation between two individuals with a direct link. We made the Hebbian assumption that a strong, dynamically generated, correlation is turned into a direct link and we proved that this criterion leads to a network time evolution towards the condition of minimal cooperation effort. In fact, network topology moves towards the scale-free distribution of links, and the scale-free network generated by the Hebbian condition is characterized by the important property of generating consensus with a cooperation effort weaker than in the original network [1], this being a form of sociological benefit.

We have discussed which is the form of criticality generated by this theoretical approach and we have found that it is not an ordinary phase transition, which would require a fine tuned control parameter. It is not self-organized criticality either, but it is rather extended criticality [2]. We have studied the Leaky Integrate and Fire model, widely adopted by neurophysiologists [2], and we have derived out of it both temporal complexity and the neural avalanches, both properties being revealed by the experimental observation of brain dynamics.

Moving from physics to biology, from biology to sociology and from sociology to psychology generates the challenging need of supplementing the current theories of phase transition with ergodicity breaking and temporal periodicity, which emerge with compelling evidence from the observation of biological and sociological reality. Our theoretical approach fits very well this request, insofar as, for instance, the model of Leaky Integrate and Fire model, adopted by us as a paradigmatic model for neural networks, is shown to generate both temporal complexity, which is closely related to ergodicity breaking, and time periodicity, fitting the important concept of biological clock [3]. We have proved that the neural avalanches predicted by other investigators as a signature of criticality are instead a manifestation of super-criticality. This means that the control parameter making this form of time periodicity become predominant is closely connected with the epileptic condition [4]. We find that increasing the number of inhibitory links would have the effect of bringing back the neurophysiological system to criticality, thereby affording a powerful tool to cure epilepsy.

To establish a connection with complexity management, namely the very important property that a complex network is sensitive only to stimuli with the same complexity, we had to study first how to extend the conventional linear response theory to the case of systems at criticality [5]. This led us to prove that the mean field of a system at criticality is conveniently described by a non-linear Langevin equation [5], making it possible for us to explain the connection between criticality and ergodicity breaking. We proved that at criticality the mean field is allowed to evolve in time as a diffusion process generated by uncorrelated fluctuations, thereby making the return to the origin equivalent to a form of non-ergodic renewal process with the power law index mu = 1.5. To generate a form of temporal complexity different from that established by ordinary diffusion we have developed a model, of financial interest, proving that the inclusion of a form of intelligence based on the assumption that the investors makes conjectures on the decisions made by the other investors, yield a form of complexity with mu ranging from 1.5 to 2, in surprising agreement with the observation that brain dynamics are characterized by the latter form of complexity [6], namely, by the power index 2.

Moving from statistical physics to mathematics we have proposed a new form of generalized central limit theorem [7]. The complex systems at criticality are characterized by temporal complexity, which is a property referring to the time distance between two consecutive renewal events, going beyond Poisson statistics. The survival probability, namely, the probability that a renewal event does not occur up to a distance t from the last renewal event is not an exponential function, but it is very well described by a form of generalized exponential, called Mittag-Leffler (ML) exponential, which is known to afford a bridge between stretched exponential and inverse power law survival probabilities. The experimental and theoretical analysis of neural networks has shown [2, 3, 4] that at criticality the time distance between two consecutive firing events is very well described by the waiting time distribution density associated to the ML function. The paper [7] proves that this is a consequence of the fact that the event detectors have a limited accuracy. We have proved that observing a sequence of events described by an inverse power law, in the limiting case of a detector of smaller and smaller sensitivity yields a ML function. Paper [7] suggests also which form of fractional calculus in time to adopt to describe processes with criticality-induced temporal complexity.

Let us move now to describe the results of this research work on issues of sociological interest. The first paper of sociological interest is the study done in [8]. This paper shows that temporal complexity, which is essential for complexity management, is a finite size property, and that the time necessary to achieve consensus is significantly reduced moving from the thermodynamic limit to the condition of a society with a finite number of individuals. This paper suggests that a number of individuals, N, of the order of 50 may be the optimal value for the social benefit generated by a fast achievement of consensus. The important role of criticality-induced intelligence for sociological processes is discussed in [9]. This paper shows that the so called committed minorities can produce big sociological changes when they become active in the correspondence of criticality-induced renewal events. In fact, at criticality, on the one side, the long-range correlation between the individuals of the complex network allows the committed minorities acting on their specific and limited environment to transmit their directions to the

whole complex network, and, on the other side, the free-will condition of the social system allows it to select the small bias exerted on the system by committed minorities. This explain the surprising effect that a very small group of individuals may force the whole social community to adopt its choices.

The results of this research work is having an influence on the communities of neurophysiologists [10] and are attracting the attention of the community of evolutionary game theory to the important role of criticality [11]. The discovery of the connection between criticality-induced intelligence is fruitfully used by our group to turn complexity management into complexity matching. Complexity matching is the condition for the most efficient transport of information from one to another complex network, and is successfully used by an increasing number of experimental psychologists.

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