COMPLEX SYSTEMS

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1. Introduction

This article deals with the interactions between the two scientific communities of AI and Complex Systems Sciences (which will be briefly referred to as CSS[1]). The term "complexity" is used since the 80's to refer to a largely interdisciplinary endeavour, aimed at understanding common organizational and dynamical properties of nonlinear systems.

The interactions between the two communities of CSS and AI have been so far rather limited, although both might benefit from closer encounters. Recent developments in the context of agent-based modelling and simulation, which is receiving a growing interest in various fields from biology to social simulation, represent a new opportunity for further exploring and strengthening these interactions and connections, in particular between CSS and Multi-Agent Systems (MAS), a topic that is discussed also in another article of this special issue.

While of course there is no need to define AI here, we will present in section 2 a concise outlook of the CSS field. In section 3 we will provide some information about European and Italian activities. Section 4 outlines some major open problems in CSS, while the following section 5 is devoted to its relationships with AI. The final section discusses some applications.

2. What are complex systems?

The origins of CSS can be remotely traced back to the works of Maxwell, Boltzmann and others, who founded the study of statistical mechanics and kinetic theory, which bridged the gap between the microscopic description of a physical system (e.g., a gas described as a set of interacting molecules) and its macroscopic (i.e. thermodynamic) description. The other outstanding XIX century predecessor of complexity is evolutionary biology: Darwin, Wallace and followers were also able to relate macroscopic phenomena (the change of biological species in time) to microscopic mutations, a concept which received concrete support in the following century by genetics and molecular biology.

More recent ancestor of CSS (as well as of AI!) can be found around the mid of the XX century in cybernetics and in the "systems movement", inspired by theoretical achievements as well as by the development of sophisticated machines, whose properties resembled those of living beings. The search for common organizational principles in very different kinds of systems led to the major concepts of feedback and of measurable information, which raised enormous interests (try to think for example of modern biology without these concepts) and applications.

However, while control theory and informatics flourished, systems science lost its momentum as a general theory of complex systems (perhaps in part because of its own success, which promoted the birth of entire new fields).

The new "science of complex systems" later arose (starting in the late 70's and more vigorously in the early 80's) thanks to the contribution of different scientific disciplines, including physics, chemistry, biology, computer science, economics and social science.

While many leading thinkers of the early days were European, like Hermann Haken [1] and Ilya Prigogine, [2], in the US a strong impulse was given to CSS by the foundation of the Santa Fe Institute in the mid 80's, supported by well-known and respected researchers rooted in classical sciences, including Nobel laureates Murray Gell-Mann, Phil Anderson and Kenneth Arrow. From that time the interest has grown, and many new initiatives have been established.

Several disciplines are involved in complex systems research. Note that a common feature of those who take part in this effort is a strong tendency to break the boundaries of the disciplines and to establish cross-links. Nonetheless, let us quote for some major disciplines (without even attempting at completeness) some key topics which promoted the interest for CSS and benefited

[1] It is worth stressing that the word complexity is used here in a sense which does not refer to computational complexity.

from its development.

- physics: collective self-organization phenomena, like fluid flows and lasers, disordered materials (e.g. spin glasses). The interest of the physics community provided great impetus to the research on complex systems. Note also that there are some close links with topics which are familiar in AI, like neural networks
- dynamical systems: chaotic dynamics, fractal structures. Their discovery raised great enthusiasm, and provided a brand new understanding of nonlinear systems. While in the past most studies were concentrated on linear systems of differential equations, treating at most nonlinearity as a perturbation, it later became possible and rewarding to address fully nonlinear systems
- computer science: neural networks, genetic algorithms and genetic programming, discrete dynamical systems, distributed processing. The search for new computing paradigms, and the perhaps surprising discovery that very effective results were obtained by systems which imitated natural ones, raised the interest of many computer scientists for the science of complexity
- biology: evolution and development processes, origin of life, genome analysis, interpretation of gene expression data. Complexity research is largely inspired by biological systems, although the approach of classical biology has paid more attention to detailed descriptions rather than to the search for general principles. It is worth mentioning the birth of an entire new field, that of artificial life, concerned wih the abstract properties of systems which might be termed "alive" even if they differ from life as it is on earth
- social science and economics: nonlinear dynamical models, agent-based models. In these fields, quantitative approaches based on differential equations show some limitations which can be at least partly overcome by the use of agent-based models; the latter have been proposed as an alternative foundation of economics, with respect to the neoclassical one [3]. Of particular interest is the possibility to deal with the heterogeneity of the agent, and to introduce more realistic features to describe its behaviour
- urban planning: modelling and simulation of urban dynamics. Cellular automata [4], one of the key tools of complexity, and agent-based models have proven more effective than traditional approaches.

It is worth emphasizing that there is no generally accepted definition of complexity (a situation which sounds familiar to those who were active in AI a few years ago). The case that a word from everyday language takes on a more technical meaning is not uncommon in science: in some cases the scientific community agrees on its use in a restricted sense (think for example of "work" in physics). There is presently no such agreement about the meaning of "complexity".

Science has largely to do with measure, so several different measures of complexity have been proposed, each one capturing some aspects of the concept. However no such measure has proven to be general enough to be accepted by the whole community. It is also likely that complexity be a multidimensional concepts, and that different kinds of complexity measures are appropriate for different dimensions.

For our purposes, we may define here a complex system as one composed by different elements, which change in time and interact in a nonlinear way. A general feature of these systems is that they can reach different states; moreover, the presence of positive feedbacks can lead to the amplification of small fluctuations, leading to very large effects.

A particularly effective way of describing these phenomena is by resorting to the language of dynamical attractors, i.e. states or sets of states which the system approaches in the asymptotic time limit. Neglecting transients, the different attractors correspond to different behaviours of the system. In nonlinear systems many different attractors can exist: depending upon the initial condition a system may tend to one attractor or another (the set of initial states which are mapped by the dynamics onto a given attractor is its "basin of attraction").

Attractors and their basins depend upon the value of some parameters which may be affected by the interaction of the system with its environment. By changing the value of one or a few control parameters the system may reach an instability point, where one of its attractors becomes unstable: new attractors appear, and the system undergoes a large qualitative change.

Moreover, in many cases, at the onset of instability two or more attractors appear, and one may observe spontaneous symmetry breaking [5]: while the overall equation system is symmetric with respect to some operation (e.g. the change of sign of a variable) the actual state which is reached by the system doea not have this property. In this case a random fluctuation at the time of the onset of instability may determine the "choice" of the system between different attractors [1, 6] (a property often referred to as "path dependency" in the economics literature).

A key notion is that of an emergent property [5], i.e. a macroscopic property which springs out of the interaction of microscopic elements, but which in turn constrains their behaviour: think for example to the relationship between a vortex and the water molecules, which is often christened as "reciprocal causation" between levels. Note also that the notion of emergent property is more general than that of a macroscopic semistable pattern: for example, in social systems one observes that recurrent interactions may give rise to new organizations which then play a key role in the further evolution of the system.

Another notion which ir receiving much attention is that of networks: all the systems may be given a network (i.e. graph) representation[2], where the relevant entities are associated to the nodes, and the links to the relationships. It has been discovered that there are some topological features of these networks which are common to very different systems, for example a metabolic network and the WWW [7]. Particular attention has been given to the distribution of degrees (i.e. number of connections per node). It has also been observed that many important properties of these networks, including their robustness and the way in which information spreads, are highly influenced by the topology.

3. European and Italian activities

Research groups and centres working on complex systems are growing in several European countries. Let us quote here two important Europe-level collaboration initiatives which have been launched by the EU Commission within the 6th Framework Programme (FP): IST-FET and NEST. They both have funded research projects and networking initiatives, promoting the creation of a European complex systems community, which holds annual meetings since 2004 (in Torino, Paris and Oxford). FET belongs to the ICT sector, and has therefore a strong emphasis on computation; since FET is in place, NEST does not support projects which are directly addressing IT issues, although of course computer science plays a major role also in NEST projects. The forthcoming 7th Framework Programme will further increase the emphasis on complex systems research.

Let us also mention the European networks of excellence: Exystence and its follower ONCE-CS (both funded by IST-FET, respectively in the 5th and 6th FP) which will in turn leave the role of stimulating and coordinating research at European level to the European Complex Systems Society, headed by Paul Bourgine.

Another European level initiative in the context of CSS that must be noted is the Research Year "The Sciences of Complexity", supported by the Center for Interdisciplinary Research (ZiF), of the Bielefeld University. This initiative provided a set of symposia and workshops on a variety of issues and topics related to CSS, ranging from the study of biological systems (and in particular the dynamics of the immune system), to the evolution of human societies.

In Italy there are several groups which are active in CSS, and it would be inappropriate to try to list them all. For the interested reader we have collected in a dedicated section of the reference list the website addresses of some italian groups and centres, limited to some of those which are closer to AI, either because they integrate methods and competencies from both fields, or because the problems they address are closer to those of AI (the choice of the groups to be included among those "closer to AI" is in part subjective and does not pretend to cover all the interesting research activities in complex systems in our country). We have not included groups working specifically in neural networks, genetic algorithms, genetic programming and robotics, which are covered in other articles of this special issue (but see section 5 for further comments).

An interesting series of workshops on Artificial Life (WIVA, Workshop Italiano sulla Vita Artificiale) is becoming an increasingly important meeting point for the Italian complex systems community (a special issue of the journal Sistemi Intelligenti [8] has been published, based on these conferences). Another activity worth mentioning is represented by the Agent Based Modelling and Simulation (ABModSim) symposium, which has taken place in the context of the 18th European Meeting on Cybernetic Science Research, with the patronage of the AI*IA.

It is particularly important to quote the series of conferences ACRI: they started in the 90's as Italian workshops and since 1998 they evolved to become important international conferences, dedicated to Cellular Automata.

Actitivities related to CSS and AI are supported and promoted by AI*IA (Associazione Italiana per l'Intelligenza Artificiale), Siren (Società Italiana Reti neuroniche) and AIRS (Associazione Italiana per la Ricerca sui Sistemi). The president of this last association has recently claimed that the future of systems science lies in a close tight with the "complexity" world [9].

The Italian industry has shown a certain (although limited) interest for applications of CSS, in particular cellular automata have been applied by Illy to study percolation of hot water through coffee, by Pirelli to describe the behaviour of rubber tyres and by Montedison to model the bioremediation of contaminated sites, as described in Section 6, where the proper references can also be found.

4. Open issues

While CSS has achieved many important results in the past, there are some major problems which still need to be addressed. Since the aim of this section is not that of providing a complete list of the most active and interesting fields of research in CSS, but rather to emphasize those areas which may attract the interests of the AI community, we restrict our list of "hot topics in CSS" accordingly.

[2] although sometimes this representation may hide some key features, like for example non-binary interactions

- Agent-based models of social and economic processes (including dynamics of traders, foundations of economics, [3], etc.) This is particularly interesting as it is at the border with AI (the term "agent" is used by both communities with different but overlapping meanings). In CSS particular attention is paid to the emergence of new phenomena by the interaction of many microentites, which are often modelled in a very simple way. But what happens if the agents are sophisticated and rich in information processing capabilities as those used in AI? Much effort is still necessary to investigate this point in depth
- artificial life [8, 10]: this discipline deals with generic properties of "living" beings, irrespective of their actual physico-chemical makeup. The similarities with artificial intelligence are obvious. A topic which has raised much interest also in the AI community is that of the relationship between physical organization and information processing (cfr. the debate on the embodiment of intelligence [11]). Alife activities can broaden the cases and open new perspecitves on this problem
- emergence of new levels and interaction between levels: most complex systems display a hierarchical structure which at some point gets in place. While some forms of development of hierarchical levels are reasonably well understood, there are many unsolved questions [12], including the sandwiched emergence of levels in-between existing ones, the dynamics of tangled hierarchies and the relationship between the hierarchical structure and the functionalities it supports and permits
- top-down vs. bottom-up design: classical AI is inspired by a top-down approach of engineering flavour, while CSS is mainly bottom-up oriented. In designing complex systems (either physical or social ones) the possibility of integrating the strengths of the two approaches appears particularly interesting and calls for extensive "experimental "attempts. A closely related, although not identical topic concerns the control of distributed systems
- co-evolution and evolvability: some systems are able to change adapting to an environment which they jointly create, therefore giving rise to interesting co-evolution phenomena. In simpler cases the environment is prescribed, not influenced by the system itself. In both cases it is very important to estimate how much the system can still evolve. A particularly interesting issue is the search for conditions which allow open-ended evolution
- complex networks [7, 13]: as it has been observed in Section 2, some new topologies are widespread in existing biological, social and technological networks, including the Internet and the WWW. Effective tools to locate the relevant information should benefit both from AI methods and from knowledge of the network structure. Moreover, a very intriguing question concerns the interactions between topology and dynamics. Indeed, a dynamical system can be considered as a network, where the nodes are associated to the variables, and there is a directed link from node A to B if the variable associated to A appears in the equation which rules the evolution of B. But what happens, in large systems of interacting variables, when the topology of the interactions change from regular, or random, to e.g. scale free? While some interesting cases have been investigated [14-16], a general theory is still lacking
- genetic networks: the wealth of experimental data made available by the various genome projects and by extensive use of DNA microarrays calls for intelligent data mining and learning tools [17, 18], which may be complemented by a study of the complex dynamical properties of genetic networks [19, 20]
- synchronization: a very striking phenomenon displayed by nonlinear coupled oscillators is synchronization [21], which can be observed in some physical and biological cases, but also in artificial systems. Synchronization may be at the core of the way in which biological neurons operate, and may provide very interesting ways to code and process information
- visualization of complex data sets and networks: this is becoming more and more crucial, and AI and man-machine interface methods can help in overcoming the limitation of existing visualization tools

Other "hot topics" in CSS like self-organization in biology (morphogenesis, synchronization, origin of life) and in artificial systems (e.g., recent efforts in the context of Artificial Immune System, but also in autonomic systems in general), scaling, universality, and others, presently seem less close to the interests of the AI field.

5. Relationships with other AI fields and with other disciplines

Neural networks, genetic algorithms and genetic programming are often regarded a part of CSS, or at least their origins have a tight relationship with CSS.

Indeed a possible way to introduce neural networks [22] is to consider them as artificial systems which use the self-organizing properties of a nonlinear dynamical system to perform classification and recognition tasks (this is a common property of most neural models, which is particularly apparent in the Hopfield and ART ones). However, neural networks have come to a maturity level which allows them to be recognized as a field of their own, largely separated by the CSS one. Of course, the study of the topological properties of complex networks and the study of the dynamics of nonlinear systems with many degrees of freedom are important overlap areas.

Similar remarks apply to the field of genetic algorithms [23]. In this case however the two communities are somewhat closer: it is worthwhile to remember that John Holland, the inventor of genetic algorithms, has been one of the most active researchers at the Santa Fe Institute. He also introduced classifier systems, which were first described in a famous paper [24] which appeared in one of the classical books on machine learning. Recall that classifier systems (as well as the more recent methods of genetic programming) make extensive use of self-organization properties. For further information, we refer the interested reader to the article on neural networks and evolutionary computation in this special issue. Similarly, we will not consider here robotics, which is however an area where AI and complex systems largely interact [10] but which is described in another article of this special issue, as well as the MAS paradigm, that is a growingly adopted modelling approach in the context of CSS.

6. Applications

Complex systems are widespread, so applications are in a sense ubiquitous. It is however not easy to define the borders of this approach, as it largely overlaps with that of other disciplines. We will omit here, for reasons detailed in section 5, to describe applications of neural networks, genetic algorithms and genetic programming, and we will also omit to describe applications of nonlinear dynamical systems. We will rather concentrate on cellular automata and agent-based models, limiting our summary to applications developed by Italian groups.

A class of models which are typical of complex systems science are cellular automata (for a review see [4 Bandini, Mauri and Serra, 2001] and further references quoted therein]. Important applications which have been developed in Italy concern

- prediction and control of lava flows and landslides [25]
- scale-up from the laboratory to the field of interventions of bioremediation of contaminated soil [26]
- prediction of properties of rubber tyres and design optimization [27]
- modelling of percolation in coffee machines and optimization of the mixture [28]
- modelling of cell cultures [29]
- modelling the movement of entities in physical environment, for instance in order to simulate traffic or crowd dynamics [30]

Agent-based models have been applied to describe innovation processes [31], showing interesting emergent phenomena, as well as to several social and economic processes, including dynamics of partnership among firms and generation of networks of firms [32], and in general to study how aggregate behaviours of entities acting according to a local point of view can generate complex macro level dynamics. However, agent-based models have also been successfully applied to other domains, such as modelling and simulation of logistic networks, and are growingly considered as computational modelling approach that supports both the representation of spatial aspects of a simulated environment and the entities which inhabit it. MAS approaches can provide a clear separation between the latter and the environment in which they are situated, and thus it represents a natural way of modelling and representing heterogeneous systems in which agents may also have a not necessarily simple behavioural specification. In this framework, they are currently being applied in scenarios in which CAs were previously adopted, such as crowd modelling and simulation [33], but also offer a completely novel instrument for social sciences for investigating social cognitive aspects.

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Websites

Websites of Italian research groups

1. Bologna University: (a) http://www.physycom.unibo.it; (b) http://www.cs.unibo.it/~babaoglu/
2. Bologna Arpa: http://www.intermed.it/istbiotech/index_it.htm
3. Calabria University at Rende: (a) http://www.mat.unical.it/pers/docenti/digregorio/digregorio.html; (b) http://galileo.cincom.unical.it/pantano/pphome.htm, http://galileo.cincom.unical.it/bilotta/bilotta.htm;
4. Florence University: (a) http://www.ino.it/~arecchi/; (b) http://www.complex.unifi.it/
5. Milano-Bicocca University: (a) http://www.lintar.disco.unimib.it/; (b) http://www.fislab.disco.unimib.it/; (c) http://bioinformatics.bio.disco.unimib.it/;
6. Modena and Reggio Emilia University: http://www.iscom.unimo.it;
7. Pavia University: http://www.unipv.it/webpsyco/personale/paginedocenti/pessa.htm ;
8. Pisa University: (a) http://www.cissc.unipi.it; (b) http://www.lem.sssup.it;
9. Rome, CNR: (a)http://www.isc.cnr.it; (b) http://www.istc.cnr.it;
10. Rome University http://chimera.roma1.infn.it/GIORGIO/indexhome.htm;
11. Salerno University: http://www.dise.unisa.it/docenti/salzano.htm;
12. Siena University : http://csc.unisi.it;
13. Torino University : (a) http://www.biomolecular_complexsystems.unito.it/ ; (b) http://web.econ.unito.it/terna/; (c) http://www.isi.it/;

14. Trieste University : http://www.sissa.it, http://www.ictp.trieste.it;
15. Venice University: (a) http://www.protocell.org/PACE; (b) http://www.ecltech.org

Websites of networks and associations

Santa Fe Institute: http://www.sfi.edu
Exystence: http://www.complexityscience.org
ONCE-CS: http://www.once-cs.net
European Complex Systems Society: www.open.ac.uk/ecss
ZiF Centre for Interdisciplinary Research, "The Sciences of Complexity": http://www.physik.uni-bielefeld.de/complexity/
AIRS: www.airs.it
Workshop Vita Artificiale (II e III): http://gral.ip.rm.cnr.it/giva-aisc/ws2va/, http://laral.istc.cnr.it/wiva3/date.html
International Symposium on Agent Based Modelling and Simulation (ABModSim): http://www.lintar.disco.unimib.it/ABModSim

Websites of EU initiatives and projects

There are several ongoing projects: we quote here only a few, information about other projects can be found in the FET and NEST websites

IST-FET (Future and Emerging Technologies): http://www.cordis.lu/ist/fet/
NEST (New and Emerging Science and Technology): http://www.cordis.lu/nest/home.html
Iscom project: http://www.iscom.unimo.it
Delis project: http://delis.upb.de
Bison project: http://www.cs.unibo.it/bison
Pace project: http://www.protocell.org/PACE
Cetra project: http://moodle2.ktk.nyme