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Complex agent networks: An emerging approach for modeling complex systems

Shan Mei[a,*,1], Narges Zarrabi[b,1], Michael Lees[b], Peter M.A. Sloot[b,c,d]

[a] College of Information System and Management, National University of Defense Technology, Changsha, China
[b] Computational Science, University of Amsterdam, Science Park 904, Amsterdam 1098 XH, The Netherlands
[c] School of Computer Engineering, Nanyang Technological University, Singapore 639798, Singapore
[d] National Research University ITMO, St. Petersburg, Russia

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ABSTRACT

Complexity and complex systems are all around us: from molecular and cellular systems in biology up to economics and human societies. There is an urgent need for methods that can capture the multi-scale spatio-temporal characteristics of complex systems. Recent emphasis has centered on two methods in particular, those being complex networks and agent-based models. In this paper we look at the combination of these two methods and identify “Complex Agent Networks”, as a new emerging computational paradigm for complex system modeling. We argue that complex agent networks are able to capture both individual-level dynamics as well as global-level properties of a complex system, and as such may help to obtain a better understanding of the fundamentals of such systems.

1. Introduction

Many of the worlds current problems can be described as *complex* [1,2]. Complexity science and complex systems provide new ways to study many natural phenomena, from protein–protein interactions [3,4] and the spreading of infectious diseases [5,6], to social interactions and socio-economics of modern megacities [7,8], all the way to the human brain itself [9,10]. A complex behavior can occur in any system that consists of large numbers of components, which interact in a non-linear way [11], such as molecular and cellular systems, organisms, ecosystems and human societies. A typical characteristic of these complex and adaptive systems is that the macroscopic emergent patterns feed back into the system and can impact the microscopic interactions. Therefore it is essential to capture the underlying mechanisms across all levels of the system. The study of complex systems provides means for understanding and predicting the behavior of such systems and therefore has the possibility of creating significant impact on understanding the complex world around us. Despite Complexity Science itself having no established theory [11,12], the methods commonly associated with the field have been applied widely and pervasively in solving problems in biology [3], economics [13,14], traffic [15], pandemics [6], computer science [16] and many other areas. Among others, complex networks and agent-based modeling are perhaps the most prominent examples of such methods that provide means to study complex systems.

Complex networks have provided insights and understanding of many complex phenomena [17–25]. A complex network forms when the components of a system are linked and have dynamic interactions. Many real-world applications can be described as a complex network, such as social networks [26], the network of protein–protein interactions [4,3] and the World Wide Web [27]. These networks are often huge, with some having thousands or millions of nodes. Besides their enormous size, what makes these networks complex is the dynamics of the interactions, which lead to a particular arrangement or topology of the network elements. A complex network can be described as a graph composed of a set of vertices and a set of edges. The number of edges that connect from a node to other nodes in the network is called the *degree* of the node. The frequency distribution of degrees over the whole network is an important characteristic of the network, called the *degree distribution*. The connectivity of all the nodes in the network is characterized by this degree distribution. There are various different forms of complex networks, including scale-free [28], small-world [29] and random networks [30]. A scale-free network is a form of network with a degree distribution that follows a *power law* of the form $P(k) \sim k^{-\gamma}$, where k is the degree, $P(k)$ is the probability of

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[*] Corresponding author at: College of Information System and Management, National University of Defense Technology, Changsha 410073, China. Tel.: +86 0731 84574538.

E-mail address: meishan.ann@gmail.com (S. Mei).

[1] These authors contributed equally to this work.

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a node with degree k, and γ is the *exponent* of the power law. A power-law distribution implies that the majority of nodes in the network have a low-degree, but also that there are a few high-degree nodes, known as *hubs* [31,32]. Power law distributions and scale-free networks occur in a wide range of phenomena [28,33]. Small-world networks are networks in which most pairs of vertices are connected through a short path. The small-world effect is not confined to social networks and is also observed in many other networks such as brain networks [9] and electric power grid networks [34]. Random graphs are the simplest form of complex networks, in which every pair of nodes are connected randomly with an independent probability p. The degree distribution of such a graph is then a Poisson distribution. There are also generalizations of random graphs such as exponential random graphs [23]. Random graphs however, typically do not produce the topological and structural properties of real-world systems observed in nature and society [35,36]. Much of the research in the area of complex networks focuses on examining real-world systems and understanding what form of network structure the particular natural phenomena maps to. The scale-free structure and power-law distributions are known to occur in many real-world networks. An example is the network structure of sexual contacts of homosexual males, which is known to be scale-free with a power law exponent value ranging between 1.5 and 2.0 [37,33]. Unfortunately the high-degree nodes in the sexual networks are usually the promiscuous individuals who may accelerate the spread of sexual transmittable infections in a population. Another example is the network of protein–protein interactions, which is also known to have a scale-free structure [38,4]. Highly connected nodes in such networks correspond to important proteins that play a major role in biological functions. To predict the behavior of a complex system, it is essential to start with a mathematical description of patterns observed in real-world data [8]. The definition of complex networks and knowledge of network characteristics provide such descriptions for many real-world systems. The degree distribution is an example of a mathematical formulation for the connectivity patterns in the network. Knowledge of network characteristics (i.e. degree distribution, average path length, centrality, clustering coefficient and community structure) provides insights on interconnectivity of components and global-level properties of a system [36].

Another popular method for understanding complex systems is that of agent-based modeling [39,40]. Agent-based models (ABMs) consist of large numbers of heterogeneous entities, known as agents, that interact with each other according to some rules; through the interactions of the agents, system level phenomena are said to emerge. In the past 20 years ABMs have been used to investigate a number of different complex systems, from traffic and parking within cities [41,42,15] to cellular interactions and immune system dynamics [43–45]. ABMs are especially useful for simulating the dynamics of those systems that are driven by human behavior, such as social systems [46], crowd dynamics [47,48], financial markets [39,49] and economics [50]. Depending on the system under consideration the agent can be defined through a simple set of rules, or a more sophisticated entity with many interacting rules governing its behavior. In a complex social system, the definition of autonomous decision-making agents can be an abstraction of human actions in the system. ABMs are often built by first specifying the system components, compiling relevant information about entities at a lower level of the system and formulating theories about their behavior. The theories are then implemented in a computer simulation and the emergence of system-level properties can be observed [51]. Agent-based modeling provides a means to incorporate individual-level dynamics in studying complex systems.

As two of the most prominent methods of complexity science, the fields of ABM and complex networks have both had significant impact on many areas of science. However, each of the two methods shed light on understanding complex systems behavior from one particular perspective. ABMs are built based on individual-level behaviors (also known as micro-level dynamics), while complex networks provide global-level properties (or macro-level dynamics) of the system. Therefore, to understand the multi-scale nature and complexity of many systems, such as epidemic outbreaks, information spreading on the Internet and transportation and mobility in new socio-technological systems [52], moving towards more comprehensive modeling techniques is necessary. Recent years have witnessed the emergence of a new area of work that relates to both agent-based modeling and complex networks. Essentially, researchers have explicitly (and implicitly) started to combine techniques from both fields. That is using groups of agents that are mapped to complex network structures, to describe physical systems [53]. Such an approach is attractive to modelers as it provides a new and highly expressive way to describe complex systems. [53] presented the active attempt to unify ABM and Complex Networks, since then others have looked at different ways of capturing the dynamics on networks using for instance automata [54].

This paper has two emphases on complex systems research, both related to the area that combines complex networks and ABM. Firstly, we attempt to describe in Section 2 a form of modeling that unifies agent-based modeling and complex networks, which we term *complex agent networks* (CANs). We argue that CANs are able to capture both individual-level and global-level dynamics of a system and can naturally express the multi-scale properties prevalent in complex systems. In the CAN concept, we take advantage of both (1) structure and interaction patterns in complex networks and (2) agency and individual-level dynamics in ABM. CANs, as an emerging paradigm for complex systems modeling, incorporate data from different spatio-temporal scales and therefore have wider implications beyond that of either ABMs or Complex Networks. Secondly, the paper brings together existing work from epidemiology, ecology and economics that have in some way utilized the CAN concept. We present a detailed example (in Section 3) that uses CANs to study infectious disease spreading, as well as other examples of existing work (in Section 4) that use the CANs concepts for understanding complex systems. The paper concludes with a summary of significant research issues related to CANs in Sections 5 and 6. To the best of our knowledge this paper is the first attempt to formalize and consolidate the research area of CANs.

2. Formal definition of CANs

We are surrounded by autonomous and adaptive agents. These agents interact with each other and thus complex collective behavior emerges. To define complex networks of interacting agents, or a complex agent network, we start with the definition of a standard complex network. A standard complex network can be defined as a graph $G=(V,E)$ where V is the set of vertices or nodes and E is the set of connecting edges. The form of network, scale-free, small-world, etc. is then determined by the arrangement of the edges E. Given a particular form of network there are well-established mathematical properties and tools that we can use to reason about the network and its structure [35].

We define a complex agent network in the same way as a standard complex network, where vertices are replaced by agents. The edges in the network represent the interactions, or relationships, between agents and can change over time. We define a complex agent network model as Eq. (1) based on graph theory notation.

$$G_{\text{agents}}(t)=(\mathbb{V}_{\text{agents}}(t),\mathbb{E}_{\text{agents}}(t)) \tag{1}$$