Chaos, Solitons and Fractals 103 (2017) 177–183

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

Vaccination and epidemics in networked populations—An introduction

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ARTICLE INFO

Article history:
Available online 12 June 2017

Keywords:
Vaccination
Epidemics
Networks
Cooperation
Complexity

ABSTRACT

This is an introduction to the special issue titled “Vaccination and epidemics in networked populations” that is in the making at Chaos, Solitons & Fractals . While vaccination is undoubtedly one of the most important preventive measures of modern times, epidemics are feared as one of the most damaging phenomena in human societies. Recent research has explored the pivotal implications of individual behavior and heterogeneous contact patterns in networked populations, as well as the many feedback loops that exist between vaccinating behavior and disease propagation [1, 2]. Interdisciplinary explorations in the realm of statistical physics, network science, nonlinear dynamics, and data analysis have given rise to theoretical epidemiology, as well as to the theory of epidemic processes in complex networks. From classical models assuming well-mixed populations and ignoring human behavior, to recent models that account for behavioral feedback and population structure, we have come a long way in understanding disease transmission and disease dynamics, and in using this knowledge to devise effective prevention strategies. This special issue is aimed at helping the further development of these synergies. We hope that it contributes to enhance our understanding of vaccination and epidemics in networked populations, by featuring works related to vaccination and epidemics using techniques ranging from complex and temporal networks to network of networks and show-casing the possibilities of interdisciplinarity via complex systems science to tackle the challenges in our quest for a healthier future. Topics of interest include but are not limited to epidemiological modeling and vaccination, behavior-vaccination dynamics, reaction-diffusion processes and metapopulation models, evolutionary and game theoretical models in epidemiology, as well as to influence maximization and digital epidemiology.

1. Networks

During the past two decades network science has emerged as a central paradigm behind some of the most fascinating discoveries of the 21st century [3,4]. From the mathematical formulation of small-world properties and their omnipresence in seemingly diverse systems such as electric power grids, food chains, brain networks, protein networks, transcriptional networks and social networks [5], to universal scaling properties due to growth and preferential attachment that likewise pervade biological, social and technological networks [6], the field of research today known as network science has been going from strength to strength, as evidenced by the many reviews devoted to this field of research [7–14]. Network science has provided models, methods and algorithms that have revived not just statistical physics, arguably the nurturer to the field, but indeed many other fields of natural and social sciences, including of course research concerning vaccination and epidemics to which this special issue is devoted to.

In addition to static networks, network science allows us to study and take into account network evolution over time, for example due to changes in external factors, the onset of disease, targeted attack, or simply due to random failure. Such changes can be studied in the realm of temporal networks [11,15,16], where the theoretical framework accounts for the addition or removal of nodes, or similarly for the changes in the links between nodes, over time. A beautiful example of how changing links over time

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http://dx.doi.org/10.1016/j.chaos.2017.06.004

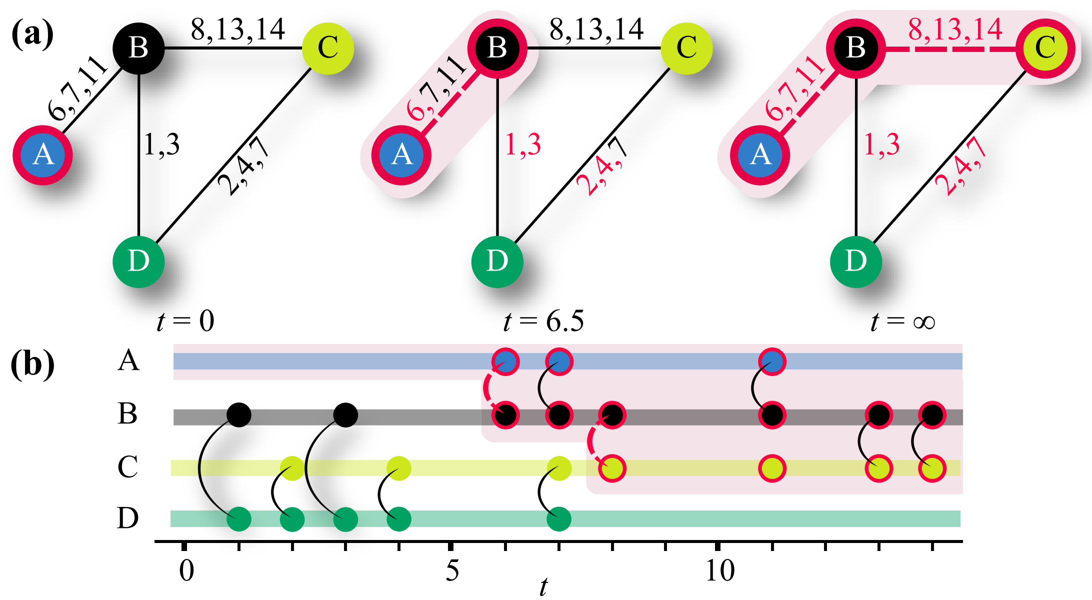

Fig. 1. The importance of temporal networks. Changes in the links between individuals A, B, C and D affect disease spreading. In the upper row, the contact times between the individuals are indicated on the edges. Let us assume that a disease starts spreading at individual A and spreads further as soon as contact occurs. This spreading process is illustrated for four different times from left to right. At $t = \infty$ the spreading stops as individual D cannot get infected. However, if the spreading starts at individual D, then all other depicted individuals would eventually be infected. Aggregating the edges into one static graph cannot capture this effect that arises from the time ordering of contacts. The lower row visualizes the same situation by showing the temporal dimension explicitly. This figure is reproduced with permission from [11].

between different individuals might affect disease spreading, reproduced from [11], is shown in Fig. 1.

Also of importance, networks exist between different layers of each studied system, and this is particularly apparent in social systems, where one person can be simultaneously member of many different networks that are to various degrees interdependent [17–21]. This can be accommodated in the theoretical framework of multilayer networks, or more generally networks of networks, which acknowledge that not only is the range of our interactions limited and thus inadequately described by well-mixed models, but also that the networks that should be an integral part of such models are often interconnected, thus making the processes that are unfolding on them interdependent [12,13,22–24]. From the world economy and transportation systems to the spread of epidemics, it is clear that processes taking place in one network can significantly affect what is happening in many other networks. From this point of view, the consideration of multilayer or interdependent networks is crucial for a comprehensive treatment of vaccination and epidemics in networked populations [25,26].

In addition to the theoretical coming of age of network science, technological breakthroughs in the acquisition and storage of vast amounts of digitized data have significantly aided the progress in our understanding of both vaccination and epidemic spreading. The data revolution has had a particularly deep impact on the social sciences, where social experiments in the past typically involved one-shot self-reported data on relationships and their outcomes in a small sample of people, while today the approach is to mine massive amounts of digitized data for both the structure and the content of relationships [27,28], which may in turn relevantly inform vaccination strategies [2] as well as the spread of epidemics [1].

In particular, the synergies between mathematical modeling and theoretical explorations and data-driven research, coupled with taking into account feedbacks between disease, behavior and vaccination, are likely the future of complex systems research aimed at a better understanding of vaccination and epidemics in modern human societies.

2. Vaccination

As already stated, vaccination is undoubtedly one of the most important preventive measures of modern times, unfolding on the planetary scale with the aim of preventing the spread of infectious diseases that have had a crippling impact on many human societies in the not so distant past. The 20th century, in particular, saw enormous progress in public health, especially in terms of preventing and treating infectious diseases. The use of vaccines was crucial to that effect. However, due to limited amounts of vaccines and knowledge, early studies simply assumed that vaccination should be done compulsively and/or randomly. Today we know that vaccination efforts on networks are more effective if random vaccination is combined with targeted vaccination and the vaccination of acquaintances [1,29–31]. While random vaccination of course does not require any information about the structure of the network, it needs in return a very broad coverage, and is thus very costly, in order to be effective [29,32]. More precisely, uniform vaccination is super inefficient for disease eradication in heterogeneous networks [29]. To offset this disadvantage, targeted vaccination according to the centrality indexes of individuals, like degree, betweenness and closeness [33–37] should be considered. For example, because large-degree nodes are known to be responsible for the spreading of disease, a degree-based targeted vaccination strategy was proposed to immunize the most highly connected individuals [34,38]. Compared with random vaccination, targeted vaccination thus greatly reduces costs, but since the identification of centrality-defined individuals usually takes a long(er) time, the practicability of targeted vaccination is doubtful in practice, especially in large populations [39]. There also exists inconsistencies in the definitions of some centrality indexes in more complex networks, especially in multilayer networks, which in turn restricts the universality of targeted vaccination [12]. Acquaintance vaccination is more suitable for practical applications in that a fraction of nodes is selected at random, and then random neighbors are vaccinated further [33,40]. This approach requires only partial knowledge of the network structure, and its variants have been studied