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Predicting epidemics on directed contact networks

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Abstract

Contact network epidemiology is an approach to modeling the spread of infectious diseases that explicitly considers patterns of person-to-person contacts within a community. Contacts can be asymmetric, with a person more likely to infect one of their contacts than to become infected by that contact. This is true for some sexually transmitted diseases that are more easily caught by women than men during heterosexual encounters; and for severe infectious diseases that cause an average person to seek medical attention and thereby potentially infect health care workers (HCWs) who would not, in turn, have an opportunity to infect that average person. Here we use methods from percolation theory to develop a mathematical framework for predicting disease transmission through semi-directed contact networks in which some contacts are undirected—the probability of transmission is symmetric between individuals—and others are directed—transmission is possible only in one direction. We find that the probability of an epidemic and the expected fraction of a population infected during an epidemic can be different in semi-directed networks, in contrast to the routine assumption that these two quantities are equal. We furthermore demonstrate that these methods more accurately predict the vulnerability of HCWs and the efficacy of various hospital-based containment strategies during outbreaks of severe respiratory diseases.

Keywords: Epidemiology; Contact network; Directed graph; Infectious disease; Hospital transmission

1. Introduction

Many infectious diseases spread through direct person-to-person contact. Respiratory-borne diseases like influenza, tuberculosis, meningococcal meningitis and SARS, spread through the exchange of respiratory droplets between people in close physical proximity to each other. Sexually transmitted diseases like HIV, genital herpes, and syphilis spread through intimate sexual contact. Explicit models of the patterns of contact among individuals in a community, *contact network models*, provide a powerful approach for predicting and controlling the spread of such infectious diseases (Longini, 1988; Sattenspiel and Simon, 1988; Morris, 1995; Kretzschmar et al., 1996; Ball et al., 1997; Morris and Kretzschmar, 1997; Ferguson and Garnett, 2000; Hethcote, 2000; Lloyd and May, 2001; Newman, 2002; Sander et al., 2002; Keeling et al., 2003; Meyers et al., 2003; Meyers et al., 2005). This approach has provided insight into the impact of simultaneous sexual partners on HIV transmission (Morris and Kretzschmar, 1997) and effective public health strategies for controlling STDs (Kretzschmar et al., 1996) and mycoplasma pneumonia (Meyers et al., 2003), among others.

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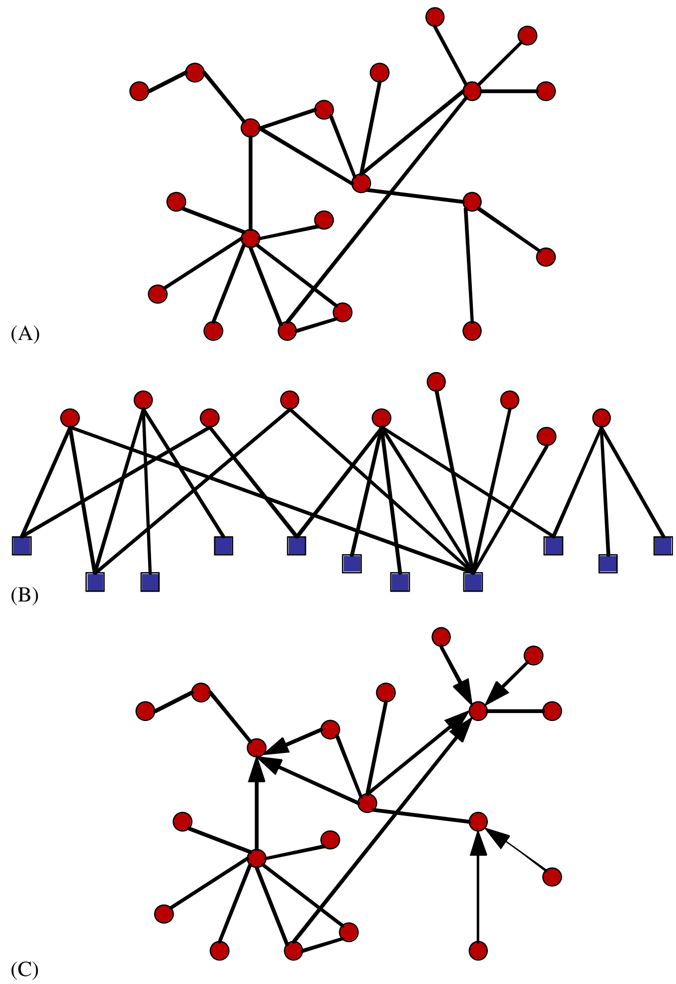

Fig. 1. Contact networks: (A) undirected network; (B) bipartite network; and (C) semi-directed network.

The simplest form of contact network model represents individuals as vertices and contacts as edges connecting appropriate vertices. The undirected network depicted in Fig. 1A assumes that if vertices i and j share an edge, then the probability that i infects j given that i is infective and j is susceptible is equal to the probability that j infects i given that i is susceptible and j is infective. There are many diseases for which this assumption does not hold. For example, there may be as much as a two-fold difference between male-to-female and female-to-male HIV transmission efficiency with females much more vulnerable than males (Nicolosi et al., 1994); health care workers (HCWs) and patients may have asymmetric transmission probabilities because, perhaps, patients are more likely to have immune deficiencies or caregivers are more likely to be exposed to bodily fluids during medical procedures; mothers can transmit blood-borne diseases to offspring in utero whereas there may be no opportunity for transmission in the reverse direction. We can model such asymmetries using bipartite contact networks in which there are two classes of nodes that transmit disease to each other at different rates (Fig. 1B). Mathematical methods for predicting the spread of disease on bipartite contact networks have been described in Ball et al. (1997) and Meyers et al. (2003).

Asymmetry in disease transmission may also arise if the disease influences individual behavior. During an outbreak, infected individuals may modify their typical patterns of interaction. In particular, they may visit a hospital or clinic at which they come into contact with HCWs and other patients. Individuals that are not infected, however, will likely have no contact with hospital personnel. Since we cannot know a priori which individuals will become infected, we cannot easily capture such conditional contacts in a simple network model.

Directed edges, in which transmission occurs only in one direction, provide a way around this difficulty (Fig. 1C). A directed edge leading from a member of the general population (P) to a HCW (H) reflects the following relationship: If P is infected, he or she will expose H with some probability; but if H is infected, he or she will have no contact with P. Thus, contact network models containing both directed and undirected edges (henceforth *semi-directed* networks) can be used to model community-based disease transmission in which there is a substantial one-way flow of disease from the general public into health care facilities. For respiratory diseases, predicting and controlling this flow is vital. Hospitals are