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Micro-level dynamics of the online information propagation: A user behavior model based on noisy spiking neurons

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HIGHLIGHTS

- We introduce a micro-level model of the online information propagation patterns.
- The online users' behavior is modeled as analogous to the dynamics of noisy spiking neurons.
- We incorporate internal and external, deterministic and stochastic sources of influence.
- The model qualitatively and quantitatively reproduces real information propagation patterns.
- The proposed method introduces a new framework for social simulations.

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ABSTRACT

We develop and validate a model of the micro-level dynamics underlying the formation of macro-level information propagation patterns in online social networks. In particular, we address the dynamics at the level of the mechanism regulating a user's participation in an online information propagation process. We demonstrate that this mechanism can be realistically described by the dynamics of noisy spiking neurons driven by endogenous and exogenous, deterministic and stochastic stimuli representing the influence modulating one's intention to be an information spreader. Depending on the dynamically changing influence characteristics, time-varying propagation patterns emerge reflecting the temporal structure, strength, and signal-to-noise ratio characteristics of the stimulation driving the online users' information sharing activity. The proposed model constitutes an overarching, novel, and flexible approach to the modeling of the micro-level mechanisms whereby information propagates in online social networks. As such, it can be used for a comprehensive understanding of the online transmission of information, a process integral to the sociocultural evolution of modern societies. The proposed model is highly adaptable and suitable for the study of the propagation patterns of behavior, opinions, and innovations among others.

1. Introduction

Online social networks have evolved into valuable sources of information and pervasive communication platforms where people, businesses, and organizations generate and share content, build relationships, and join public conversations. In this online ecosystem, ideas, opinions, news, habits and trends, taking the form of messages, hashtags, hyperlinks, images, or videos compete for the users' attention. As societies and the economy shift towards information and knowledge based services, the investigation of the micro-level dynamics underlying the formation of the macro-level propagation patterns of online information emerges as a major research target, inherent to the understanding of the online social dynamics and their role in the socio-cultural evolution of an increasingly interconnected world.

Several approaches to the conceptualization of information propagation processes are based on the analogy between the spread of infections, and the spread of ideas, rumors, news and behaviors in social networks (Daley & Kendall, 1964; Dodds & Watts, 2005; Goffman & Newill, 1964; Moreno, Nekovee, & Pacheco, 2004; Vespignani, 2012; Zanette, 2002). However, when it comes to explaining the difference between the susceptibility of people to particular diseases, such as influenza, and their susceptibility to online content and information, this analogy cannot be adequately justified. To explain this difference many

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studies rely on the concept of "complex" contagion suggesting that the transmission of ideas, social attitudes, behaviors and new products, requires social affirmation deriving from the interaction with multiple adopters, especially when an adoption decision involves risk (Centola & Macy, 2007). This process is described as "complex" contagion in contrast to the "simple" contagion, where the interaction with a single adopter can be a sufficient condition for the transmission to occur. There is evidence that "complex" contagion phenomena appear in the online social networks. Romero et al. studied the propagation of different types of information tokens (hashtags) on Twitter and observed that the exposure to multiple users exerting positive influence, was particularly critical to the adoption of political hashtags (Romero, Meeder, & Kleinberg, 2011). Goel et al. examined the information adoption patterns in online environments to discover that the adoption cascades are mostly narrow, contrary to what would be expected by the analogy between biological and social transmission (Goel, Watts, & Goldstein, 2012). Weng et al. found that the majority of internet memes propagate faster and farther in highly clustered assortative communities, wherein the social reinforcement is stronger due to the common interests of the interconnected individuals (Weng, Menczer, & Ahn, 2013).

From the above considerations, it becomes evident that the propagation of online information depends on the affirmative impact of social interactions with multiple adopters as well as on the users' interests. Nevertheless, the online social networks are open systems and the information propagation is affected by external sources of influence, such as mass media, socio-economic circumstances, advertising, or events, giving rise to time-dependent, non-stationary propagation patterns. To capture the macro-level characteristics of the online information propagation patterns, we propose a micro-level model of the online users' behavioral mechanics based on the dynamics of the *noisy, leaky Integrate-and-Fire (LIF) neurons* (Brunel, 2000; Dayan & Abbott, 2001; Gerstner & Kistler, 2002; Vogels & Abbott, 2005). A noisy LIF neuron can be thought of as an excitable element driven by an input current consisting of a deterministic and a stochastic part representing the unpredictable, noisy part of the input. When the excitation of a noisy LIF neuron crosses a firing threshold from below, an action potential is emitted imposing excitation or inhibition (but not both) on post-synaptic neurons depending on the type of synapses. The essential analogies enabling the application of the aforementioned mechanism to the modeling of a user's behavioral dynamics during the propagation of online information, can be summarized as follows:

(i) The online users and the noisy LIF neurons are both excitable interconnected entities whose excitation is regulated by stimuli originating from their self-dynamics, the interaction network, and the external environment.
(ii) In both cases the incoming stimulus can be described by a deterministic, average term and a stochastically fluctuating part.
(iii) The sharing of information by a user through a message is equivalent to the emission of an action potential by a noisy LIF neuron when its excitation crosses a firing threshold.
(iv) A message generated by an online user may have a positive or negative impact on the receiving users' excitation about the message content, much like an action potential delivers excitatory or inhibitory current to post-synaptic neurons, thus increasing or decreasing their membrane potential.

Modeling the propagation of online information as the outcome of an excitation process, resembles the mechanism by means of which the popularity of content disseminated on online social networks thrives, stagnates or perishes, as this lifecycle boils down to an emotional state defining the users' information sharing attitude: *Like* or *dislike*. Indeed, social interactions are complex processes, since human communication transfers not only information but also emotions, feelings and individual perceptions (Mainzer, 2007), which can either intensify or lessen one's excitement thereby affecting the propagation of online information. Emotions evoked by ideas, behaviors, and products, are considered to be one of the most important determining factors of contagiousness, inasmuch as things activating the proper emotions are shared more frequently (Berger, 2013). Also, studies on the fields of behavioral economics (Kagel & Roth, 1995), and behavioral finance (Shleifer, 2000) indicate that the human decision process is substantially influenced by the individuals' emotional states.

The approach that we introduce through this study aims to accomplish the following objectives:

(i) To model the micro-level dynamics of the online information propagation by incorporating endogenous and exogenous, positive and negative, deterministic and stochastic influences affecting the online users' behavioral state, while also considering the interaction network, the interaction mechanism, and the users' heterogeneity.
(ii) To capture the characteristics of the online information propagation patterns emerging from the micro-level interactions that are driven by the dynamically changing internal and external influence.
(iii) To establish a proof-of-concept of the ability of noisy spiking neural networks to constitute platforms of social simulations and agent-based modeling allowing the investigation of various social dynamical processes.

To the best of our knowledge, our method is the first to combine all the aforementioned aspects, thus introducing an overarching approach to the modeling of the online information propagation in a way that accurately captures the time-dependence and variability of the information propagation patterns. Also, it is the first to use the dynamics of noisy spiking neurons in the users' behavior modeling, thereby introducing an effective and highly flexible method for social simulations capturing the stochastic and non-equilibrium nature of human dynamics. The user behavior model introduced by this study extends the work on the modeling of the online social contagion through the dynamics of networks of Integrate-and-Fire neurons (Lymperopoulos & Ioannou, 2015) by adding signal transmission delays and stochasticity induced by noisy stimuli. In doing so, we more accurately capture the fluctuations in the users' activity patterns due to the asynchronous activation of online users, by considering not only the irregularity of their behavioral characteristics, their connectivity inhomogeneity, and the strength of the external influence, but also the noisy characteristics of the stimuli they receive. Through this approach we qualitatively and quantitatively reproduce stationary and non-stationary online information propagation patterns, thereby providing experimental evidence of the suitability of the noisy, leaky Integrate-and-Fire neurons for the modeling of human behavior. The model proposed by this study is based on methodological frameworks treating online social networks as Complex Adaptive Systems, whereby the global activity patterns emerge through the conditional action of the system elements which interact in parallel through the exchange of signals, while adapting to environmental influences (Lymperopoulos & Ioannou, 2016; Lymperopoulos & Lekakos, 2013).

To validate the model we use two datasets containing sequences of hashtags extracted from public Twitter messages. The suitability of this data for the study of the online information propagation is based on the premise that Twitter hashtags have acquired a symbolic meaning representing emerging discussion topics connecting people, ideas, news and events (Huang, Thornton, & Efthimiadis, 2010). Another reason for using this type of data in the validation of the model relates to the real-time nature of