Doctoral Dissertation
Doctoral Program in Electrical, Electronics and Communications Engineering
(36^{th}cycle)

Modeling Social Interactions in Complex Systems

A Journey from Opinion Formation to Epidemic Spread

By

Franco Galante

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Supervisor(s):
Prof. Emilio Leonardi

Doctoral Examination Committee:
Prof. Sara Alouf, Referee, INRIA
Prof. Anastasios Giovanidis, Referee, Ericsson Research & CNRS

Politecnico di Torino
2024

Declaration

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Franco Galante
2024

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

Modeling Social Interactions in Complex Systems

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Our society is undergoing profound change, shaped by the rapid progression of technological advancements, which are not only redefining the dynamics of interaction, education, and labor but also influencing all other aspects of our lives. One of the driving forces behind the current social changes is the advent of online social networks (OSNs). They changed interpersonal interactions, and are also redefining the way businesses, politicians, and media organizations engage with the wider public. A pressing challenge of our time is to understand how these changes affect our society and what potential dangers are associated with them. This thesis aims to provide a broad introduction to social modeling, highlight the connection between seemingly disparate domains, and introduce some of the fundamental tools of the *social modeler*. We will then focus on specific aspects of society, namely the mechanism of opinion formation and virus spread in a population.

On online social platforms, a few individuals, commonly referred to as *influencers*, produce the majority of content consumed by users and hegemonize the landscape of the social debate. Traditional opinion models do not capture this asymmetry in communication. In Chapter 2, we develop an opinion model inspired by observations on social media platforms with two main objectives: first, describing this inherent communication asymmetry in OSNs, and second, modeling the effects of content personalization. We introduce the concept of reference direction, i.e., the topic for which an influencer is known through the social media platform and which is used by the platform to suggest posts to users. Influencers are characterized by their popularity, which determines their reach on the platform and depends on the feedback the user gives for each post. This models the closed loop between users and influencers.

We derive a Fokker-Planck equation for the temporal evolution of users' opinion distribution and analytically characterize the stationary system behavior. This analysis is unfortunately non-constructive in that does not allow for direct computation of stationary solutions. Hence, we derive a first-order approximation, referred to as fluid limit, which allows us to obtain the stationary points through a fixed point approximation scheme. Analytical results, confirmed by Monte-Carlo simulations, show how strict forms of content personalization tend to radicalize user opinion, leading to the emergence of *echo chambers* and favor *structurally advantaged* influencers. As an example application, we apply our model to Facebook data during the Italian government crisis in 2019 and reproduce the sudden rise in popularity of Giuseppe Conte during the crisis, which provides an interpretative key to his success.

The new class of social media influencers plays a crucial role in shaping opinion. While we assumed in Chapter 2 that they have a fixed opinion on a topic, they actively compete for users' attention on social media. Through these targeted efforts, influencers seek to captivate users and build a loyal and engaged fan base, solidifying their position as an authoritative voice in the digital world and maximizing their impact on the population's opinion. The goal of Chapter 3 is twofold: first, we formalize the problem of maximizing social media impact, and second, we develop a game for competition between influencers. For the impact maximization problem where an influencer is considered in isolation, we develop a trellis-like solution to study the structure of the optimal solution. This suggests that the best strategy for the influencer is to first group users towards a common view and then drive them to the desired opinion. We show that the greedy solution, which maximizes the utility function at each step, is not always optimal. Then, taking inspiration from the optimal strategy, we design a game with two opposing players trying to maximize their influence on users' opinions. We characterize the Nash equilibria of the game in pure strategy and find that whenever an influencer is at a structural disadvantage, it has to compromise more on its target opinion by expressing a milder stance in order to align more with population opinion. We also consider the impact of the popularity and content personalization on the game.

Although it may seem far-fetched, the dynamics of belief and epidemics are described in very similar terms. In the last chapter of this thesis, we develop a SIR-like, stratified model to better understand the options available to policymakers in the case of an outbreak of a new pandemic. We consider a scenario where efforts are made to control the infection and focus on two control strategies. The first aims to control the rate of new infections; the second directly controls hospitalizations and intensive care unit (ICU) occupancy. Using a first-order analysis, we show that controlling the transmission rate can be difficult due to the lack of accurate information, leading to instability. Furthermore, we find that while hospitalizations and ICU occupancy are easily accessible and less noisy than the rate of new infections, a delay is introduced into the control loop that can endanger the stability of the system. We explicitly include the effects of vaccination in our model. We consider a two-dose system with different efficacy of each dose and administration intervals between the two doses. Our framework allows us to assess the joint impact of control strategies and vaccination campaigns on economic and social costs, taking into account: i) the heterogeneity of the population in terms of mortality rate and risk exposure, ii) the closed-loop control of the epidemiological curve, and iii) the progressive vaccination of individuals. We highlighted the trade-offs that exist between a suppression strategy, which aims to minimize the infection rate, and the "let it rip" strategy, which aims to achieve herd immunity, noting that the time horizon plays a crucial role. Finally, we considered a comprehensive scenario inspired by the actual evolution of the COVID-19 pandemic to assess the impact of different control and vaccination strategies deployed at the same time.