Bando
Fondazione di Sardegna – 2018-2020 e 2021
Progetti di ricerca di base dipartimentali

Dipartimento

Dipartimento di Scienze Economiche e Aziendali

Titolo del progetto di ricerca

Modeling and Simulation of Dynamical Processes and Agent Behavior on Networks

Settori Scientifico Disciplinari del progetto di ricerca

SECS-S/06, FIS/02, FIS/07

Referente scientifico del Dipartimento

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Abstract del progetto di ricerca (Max 5.000 caratteri)

A remarkable number of real-world systems correspond to networks of entities that dynamically interact though relationships of various nature. Such systems are encountered in the physical world or technological infrastructures, as well in the social sciences, in economics and finance.
Genes and proteins have functioning that depends on their relative positions and interactions in the gene regulatory network; species coexist in ecosystems through food-webs of prey–predator relationships; information, opinions and rumors diffuse through real or virtual social networks; infectious diseases spread through interpersonal contacts; financial distress propagates due to direct or indirect exposures between financial actors; power grids undergo system-wide failures due to the complex pattern of interconnections between the system's components; our economies rest on complex networks of interdependencies corresponding to flows of goods and capitals.

Real-world networks often exhibit complex topologies, long-range correlations, strong heterogeneity, large fluctuations and clustered structures. Some general organization principles have been identified and similarities between very different phenomena have been recognized, allowing to adopt similar frameworks in some cases. For instance, information and rumors propagate through the connections between individuals in a population; this is similar to the diffusion of an infection, but the specificities of the two dynamical phenomena can lead to different evolutions. Investigation of dynamical processes on networks has clarified that complexity can break theoretical models assuming homogeneity;

different and rich dynamics are produced depending on the complex features of the network, like the effects of hubs and authorities, or those due to a clustered structure.

Careful investigation of how topology affects the properties of equilibrium and non-equilibrium systems is a crucial step and modeling the system's dynamics must rely on basic yet realistic assumptions about the structure of the specific system and interactions between its constituents. Among others, statistical physics has recently emerged as a legitimate approach to pursue such goals. Understanding the dynamics of these systems is of paramount importance if we are to redesign them, or influence their behavior to meet specifications. It also represents a condition for effective supervision and policy making by regulators.

While it is well understood that topology affects dynamics to a great extent, in many cases it is the dynamical process itself that can shape the network. The popularity of individual webpages impacts the creation of new links and thus the topology of the World Wide Web. Financial agents have the ability, to some extent, of anticipating future events and take advantage of that, which can alter the network's connectivity pattern. An interplay between dynamics and topology through feedback effects can be expected and, more generally, real networks are not static entities but more often change with time.

Moreover, real networks are often characterized by different kinds of links between their vertices. Each class of relationship corresponds to a network "layer" and the different layers are in general interdependent. In this so called *multiplexes* the collective behavior of the system cannot be fully understood unless we consider the dynamics of all layers and how each single-layer dynamics interacts with the other layers.

A further difficulty is represented by incomplete information about the connectivity pattern of the network, which is often the case for networks deduced collecting or sampling empirical data. Proper methodologies have to be used for network reconstruction in order to draw reliable conclusions about such systems and make sensible predictions.

This project integrates in the field of the study and modeling of complex dynamical networks. Investigation and modeling efforts will address systems of practical interest due to their implications for the society, the economy and the environment:

- Financial networks and infrastructures;
- Ecological and compartmental networks;
- Social and contact networks;
- Networks of mission-oriented organizations like non-governmental organizations;
- Healthcare systems and subsystems like patient–physician networks or physician–physician networks.

We will address the evolution of dynamical processes on such networks, with emphasis on financial distress propagation, information and infectious diseases diffusion, opinion and consensus formation, emergence of biased behaviors from strategic interactions in presence of defensive mechanisms (e.g. defensive medicine practice).

We will focus on modeling approaches to represent network dynamics, with an attention to temporal multiplex networks, and on network reconstruction problems. Exact or approximate analytical developments will be complemented by large-scale agent-based simulations, starting from the modeling of the individual interactions and linking them to emergent and collective behaviors in the system.

Obiettivi che il progetto si propone di raggiungere (Max 5000 caratteri)

The project is aimed at:

- Providing representations of networks of interest if not already available;
- Improving existing partial representations of real-world networks through the use of network reconstruction techniques;
- Developing improved algorithms to infer network structures or properties from partial information;
- Describing in mathematical terms the interactions between constituents of selected networks and derive the equations that govern their evolution;
- Developing a consistent framework to describe the coupled dynamics of multi-layer temporal networks;
- Characterizing the effects and implications of constraining strategic interactions in a game-theoretic approach to a static or time-varying network structure to understand, for example, how play in a game depends on the network connectivity pattern;
- Providing game-theoretic foundations to the structure and evolution of holdings networks like asset-portfolio or consumer-product networks;
- Building analytical and computational models that properly take into account the interplay between the dynamical processes unfolding on the network and its topology and characteristics, as well as its temporal variations due to the interactions with the external environment;
- Deriving exact or approximate analytical solutions of the dynamical equations for the probability distribution function of the systems or its projections over selected variables of interest;
- Studying processes of network formation and growth to better understand why they exhibit certain connectivity patterns and complex features;
- Characterizing the effects of network topology and characteristics on dynamical evolution, and identifying "safest" configurations with respect to suitable measures of resilience or robustness;
- Providing extensive characterization of the macroscopic properties and collective behaviors of the networks under the study through agent-based simulations of the dynamics at the microscopic level;
- Identifying conditions for the dynamical system to be in equilibrium or out of the equilibrium and to detect critical phenomena and phase transitions;
- Comparing results from agent-based simulations with analytical solutions (if available) to track the degree of accuracy of the latter;
- Assessing quantitatively the robustness of real networks with respect to the propagation of exogenous or endogenous shocks, node failures or perturbations to the structure of mutual interactions between the agents; in particular, testing for the effects induced by herding behaviors or agents similarities in terms of characteristics, behaviors and preferences;
- Studying and simulating avalanche processes and identification of conditions for systemic collapse;
- Contributing simulations of realistic scenarios of dynamical evolution in real-word networks, particularly for diffusion processes of information or infectious diseases, propagation of distress in financial networks, emergence of cooperative or antagonistic behaviors in social networks;
- Establishing explicit connections between model parameters and macroscopic, measurable characteristics of the networks, and studying the implications of each parameter with respect to ESG dimensions (Environmental-Social-Governance) and in terms of policy-making and regulation.
- Contributing to identify the most relevant parameters through comparative statics analysis;
- For networks that are amenable of external intervention like regulation or that are human engineered, selecting optimal configurations or control parameters by solving optimal control problems.

Stato dell'arte (Max 8.000 caratteri)

Many real-world networks exhibit a complex topology. Their systematic investigation has identified common characteristics and general organization principles [1–5]. In particular, high heterogeneity, large-scale fluctuations, scale-free properties, clustering and hierarchical ordering are typical signatures of such systems. While early empirical research focused on the study of their static properties, many systems of interest are dynamic in nature, both because the network size or connectivity pattern change with time, and because dynamical processes take place on them [6]. Typically, vertices represent dynamical entities, like people in a social network, and have state variables that vary with time due to the local interactions with their neighbors.

Network science is an interdisciplinary field integrating tools and concepts from disciplines like sociology, mathematics, physics, computer science and statistics. In the last decades the statistical physics approach has emerged as a legitimate paradigm to investigate large-scale networked systems [7,8], both theoretically and empirically, for its peculiar ability to represent the connection between emergent, collective behavior in complex systems aggregating many entities and the local, microscopic interactions that take place between the individual constituents. It provides both a general conceptual framework to bridge microscopic and macroscopic phenomena and methodologies to tackle nonlinear dynamics, to represent equilibrium *vs* non-equilibrium systems and to describe critical phenomena and phase transitions. Among such methodologies, the formalism of the master equation governing the evolution of the probability distribution in the phase space, the theory of percolation, and methods to get approximate solutions like the mean-field approach, have been extensively exploited. Large-scale numerical simulations of the dynamics of many-particle systems using Monte Carlo techniques also have a long tradition in physics and have proved useful when exact or approximate analytical solutions cannot be achieved.

Network science has been successfully applied to the study of dynamical processes on network systems in many different contexts. Network models are particularly relevant to the modeling of the diffusion of infectious diseases in epidemiology [9–14]. This was one of the first research fields to highlight the special role of "hubs", or strongly connected vertices, in the unfolding of dynamical processes on networks. It is a very active field of research and the recent COVID-19 pandemics has once again stressed its relevance.

The spreading of information or rumors in both social networks and technological infrastructures like the World Wide Web [15–17] can be modeled through epidemic-like dynamics, with many important applications to data dissemination and advertising in digital businesses.

Collective or group behaviors, like consensus formation, have been modeled [18–24] as the result of influence interactions at the level of individual agents and the theory of percolation has been used extensively both to study network response and robustness to random failures of nodes or targeted attacks, and as a general framework to investigate associated critical phenomena [25].

Traditionally, network modeling has been used also in the study of ecosystems. Food webs encode prey–predator relationships between species or trophic levels and the corresponding flow of energy in the system. Population dynamic models describe mutualism, competition and cooperation in multi-species systems. They correspond to dynamical network systems where the numbers of individuals of each species is often described by Lotka–Volterra equations depending on the matrix of interactions between species. Static analyses and studies of stability with respect to perturbations have been followed by more recent approaches [26–28] where the dynamics of species is allowed to coevolve with the network structure.

Decisions making by individuals is also influenced by the social network they live in. Usually, the payoff an individual receives from taking action depends on the behaviors and actions of their neighbors. This makes the framework of game theory a natural choice to model such strategic interactions [29–32], with potential applications, for instance, to exchange or trade on networks. Classic games such as the prisoner's dilemma have been studied in the form of repeated interactions of agents with their neighbors on both regular lattices and complex networks [19,33,34]. Important phenomena relating to the presence and evolution of both defective or cooperative phenomena can be studied in such framework. Game theory and dynamical models have been used to model the interaction between physicians and patients [35,36], their behavioral choices and their dynamics in large populations of agents. In particular, in [36] an evolutionary game approach is used to analyze how physicians prevent negligence charges by practicing defensive medicine or resorting to insurances. Recently, a framework combining network dynamics and a game-theoretic approach with incomplete information has been proposed to model strategic interactions between patients and physicians that practice defensive medicine [37].

Network science has proved to be effective as a framework to understand the structure and dynamical behavior of financial networks [38–49] where agents (e.g. credit institutes, investment companies, individual investors) interact through a pattern of financial relationships such as credit exposures, ownership of company shares or participation in investment funds. Interbank networks where banking institutions exchange loans are simple paradigmatic examples. More abstract ones are those originating from investment similarities through asset commonality in mutual funds' portfolios. Basic tools from statistical physics like ensemble representation or entropy maximization have used to model the shape of such systems, their robustness to vertex default and behavior under the propagation of financial shocks. These researches have also led to the adoption of network concepts, like that of vertex centrality or network controllability, to define unexpected dimensions of systemic importance and to the definition of novel *ad-hoc* measures of systemic importance that carefully asses the "centrality" of an institution in the network. Recently, the financial industry and regulators have been realizing the importance of investment activities that take into account climate-related aspects and environmental sustainability. This area of investigation deals with even more complex patterns of interdependence, from the physical assets to financial institutions and final investors through exchanged securities and obligations.

In many cases, complexity of local interactions, large dimensions of the system, time variability and multi-layer structure make analytical investigations a difficult task. Especially in social networks, ties form and disappear, or change their strength depending on agent preferences or environmental factors. Explicitly representing individual interactions at the micro-level and performing large-scale computer experiments is a convenient way of deducing aggregate behaviors, testing assumptions about the dynamical laws of the systems, as well as investigating local properties and effects on individual agents. Evolution in time and space dimension can be represented explicitly by agent-based models, making them an effective way of studying the determinants of many types of interactions and the effects of and consequences on network topology. Such an approach has been exploited extensively in many context [50–57].

Knowledge of many real-world networks suffer from missing or partial information, which motivates active research on network reconstruction. Effective approaches to this problem are based on the entropy-maximization principle and a number of algorithms, both deterministic and probabilistic, have been proposed to reconstruct networks in equilibrium or, conversely, to evaluate deviations from equilibrium, see for instance [58–61].

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Attività previste (Max 8.000 caratteri)

The network topology is usually dynamical, and it changes partly independently of and partly as a result of the dynamical processes that take place on the network. In particular, the relative speed at which link change respect to the time scale of vertex state variations can have strong effects on emergent behaviors, leading for instance to consensus *vs* fragmentation, cooperative *vs* defective behavior, depending on the parameters. The interplay between dynamical processes and modifications of network topology is fundamental for understanding many phenomena.

We will first select a limited number of networks that are of primary interest for their environmental, socio-economic, welfare or governmental issues. These could fall in the following categories: financial networks and infrastructures; ecological and compartmental networks; social and contact networks; networks of organizations; healthcare networks. For each selected system we will try to retrieve a complete and up-to-date network representation. Depending on cases, this may be already available from previous studies or it will also require the acquisition and analysis of further datasets. In the latter case, empirical analyses to identify and quantify complex topologies, clustered or modular structures will be performed and provide the background for further analytical developments and dynamical analysis. Attention will be paid to asses the relevance of a single-layer *vs.* a multi-layer network representation of the systems at hand and to isolate the most significant aspects of their temporal evolution.

We will focus on specific dynamical processes that are characteristic of the selected networks, e.g. epidemic spreading in contact networks, or information diffusion and opinion formation in social networks, or the propagation of various kinds shocks in financial networks and infrastructures. Starting from the identification of the relevant variables defining the dynamical state of the vertices, and from the expression of the individual local interactions between the vertices, a mathematical representation of the evolution will be provided in terms of differential equations. This will typically be in the form of a master equation that describes directly the temporal evolution of the network's probability distribution in the phase space. It depends on the transition rates/probabilities for the transition from a dynamical state to another. The latter have to reflect the dynamical laws of the microscopic interactions as closely as possible. In this regard, a challenging aspect will be to cast in this framework the effects of multi-layer interactions. Following an approach that is typical of statistical physics, macroscopic quantities characterizing equilibrium systems can be obtained as averages from a suitable partition function.

The master equation can be solved exactly only in very simple cases and we plan to resort to suitable approximation methods to deduce basic properties of the dynamical processes from approximate analytical solutions. In particular, mean-field theory will be leveraged when justified by a sufficient degree of homogeneity. Alternatively, projections of the probability distribution can be considered when focusing on specific statistical properties of the network, like its degree distribution, that allow for a simpler solution. The generality of this dynamical approach is suitable to identify general mechanisms of growth and evolution as the roots of observed topological properties.

Laplacian dynamical systems are also expected to be useful for systems where the behavior of an individual results from averaging with respect to neighbors, like swarming or flocking phenomena in biology. Applications of models of phase-coupled oscillators, like the Kuramoto model will be also investigated in connection to coordination phenomena.

When modeling strategic interactions, we will couple game theoretic analysis and network theory. Indeed, many dynamical networks are characterized by repeated contacts and the network structure can have deep implications for the dynamical evolution of patterns that emerge in repeated games. Important economic applications may concern bargaining, exchange and business relationships that realized through a network of interactions.

As many real-world systems exhibit high heterogeneity and complex relationships of different kinds, we will implement the actual microscopic dynamic rules that govern the evolution and simulate the dynamical system within an agent-based approach through Monte Carlo techniques.
Experiments based on computer models are indeed convenient. They will allow the comparison of alternative assumptions about the agents, their interactions and the context or environment.

When appropriate for the case at study we will try to quantify system robustness. Operatively, such an assessment depends on the specific dynamical process and on the definition of suitable objective functions, the value of which is monitored at different stages of degradation or disruption of the network. In the case of communication networks, for instance, the networks is usually observed as an increasing number of vertices are removed or fail. In inter-bank networks, the number of banks defaulting may be registered or, in portfolio holdings networks, the total values of portfolios are considered during the propagation of exogenous shocks to asset prices. In particular, we will try to quantify the effects on contagion and diffusion processes of a multiplex structure characterized by ties of different nature.

The focus will be on using the aforementioned analytical and computational tools to model systems of interacting entities having states that dynamically change due to the interactions with their neighbors. In particular, efforts will be made to connect network structure and behavior, going from microscopic interactions to macroscopic, measurable quantities and to describe how collective behaviors, like cooperation or consensus formation, and emergent phenomena stem from a very large number of local interactions.

Where it makes sense, we will try to apply similar modeling frameworks to describe different systems. For example, modeling financial distress propagation can leverage similarities to contact processes, diffusion theory and epidemics; concepts from ecosystem modeling may also apply to networks of competing "products" or "services", where rising in the sales of a product corresponds to preying on a competing products. At the same time, we will carefully consider the specificities of the individual dynamics that can easily break apparent analogies.

Ricercatori impegnati nel progetto

ANTOCI ANGELO
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The participant will contribute to the mathematical modeling of the dynamical processes of interest; to the solution of the evolution equations; to the analysis of the solutions in terms of stability, asymptotic behavior, existence of equilibria or periodicity, chaotic behavior and dependency of all these properties from the parameters; to the game-theoretic formulation of network dynamics when applicable.

He will contribute substantially to the interpretation of the socio-economic implications of the models and to formulate useful policy indications.

(Breve descrizione dell'attività del partecipante - Max 500 caratteri)

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The participant will contribute to modeling network structures and dynamical processes on networks, particularly within the conceptual framework of statistical physics; to characterize system evolution through exact or approximate solutions and through sensitivity analysis; to the analysis of the network representations of the phenomena under consideration in a network science perspective; to perform agent-based simulations of network dynamics; to the formulation of network reconstruction algorithms; to quantitatively assess systemic robustness and resilience.

(Breve descrizione dell'attività del partecipante - Max 500 caratteri)

RUSSU PAOLO
Professore Associato
Dipartimento di Scienze Economiche e Aziendali
SECS-S/06

The participant will contribute to the mathematical modeling of the dynamical processes of interest and to the implementation of computer simulations in an agent-based modeling framework; to the solution of the evolution equations; to the study of the qualitative behavior of the solutions and of their dependency on parameters through comparative statics analysis; to the game-theoretic formulation of network dynamics when applicable.
He will contribute to the interpretation of the socio-economic implications of the models and to formulate useful policy indications.

(Breve descrizione dell'attività del partecipante - Max 500 caratteri)

Risultati attesi dalla ricerca, il loro interesse per l'avanzamento della conoscenza e le eventuali potenzialità applicative (Max 8.000 caratteri)

We expect to deliver the following outputs:

- To improve current knowledge of the structure of interesting networks under partial information or temporal variability by exploiting network reconstruction techniques or devising new ones;
- To develop mathematical and computational models that are able to describe the dynamical evolution of networks when the dynamical processes that unfold on the network structure belong to general classes like diffusion, especially in the case of multiplex temporal networks;
- To derive exact or approximate analytical solutions for the network's evolution, at least in simplified cases;
- To tailor specific models for networks of primary interest for their environmental, socio-economic, welfare or governmental issues, like financial networks and infrastructures; ecological and compartmental networks; social and contact networks; networks of organizations; healthcare networks.
- To develop a better understanding and representation of the effects of network topology on the dynamical evolution of the systems, of the way dynamical processes shape network structure and, more generally, of the interplay between dynamics and structure;

- To develop a better understanding of the coupling of game theory and network topology in the case of strategic interactions between the agents;
- To measure the robustness and resilience of selected networks with respect to disruption events or propagation of various types of shocks, and to propose comprehensive indicators of fragility;
- To measure the impact of multi-layer relationships on diffusion and contagion processes;
- To use Monte Carlo techniques to perform extensive simulations of dynamical processes on network in an agent-based approach, particularly for the diffusion of information or infectious diseases, propagation of distress in financial networks, emergence of cooperative or antagonistic behaviors in social networks. This will leverage existing open-source software libraries as well as ad-hoc specialized code written in modern open-source programming languages;
- To use the analytical and computational models developed to make predictions about the emergence of macroscopic behaviors or events and possibly use historical data for backtesting purposes and parameter calibration;
- To establish clear connections between model parameters and policy actions and regulations, especially with respect to ESG dimensions;
- To identify conditions or parameter ranges that may correspond to systemic collapse or failure.

The above results would be of great value in terms of the advancement of basic research, for the understanding of complex networks and dynamical processes both theoretically and for real-world applications. In particular, the interplay of dynamics and network topology and the effects of multi-layer temporal interactions represent a challenge in modeling terms, which is worth to be taken also for their practical implications. For example, contagion processes in financial networks can be mediated by various link types like liquidity, asset commonality or other forms of obligation, and these can have different priorities in case of liquidation or different maturities. This makes essential to understand the overall damage that the system can undergo, which can be something different than the sum of damages in the different layers, and when reinforcement vs mitigation effects are to be expected. As another example, in a healthcare system patients and physicians interact directly through healing relationships. These interactions correspond to a bipartite time-varying network whose shape is determined by agents 'strategies and payoffs as well as patients' preferences in the physician selection process.

We believe that the analysis and characterization of these aspects have relevant practical implications for networks amenable of external regulation and intervention, as a condition for the identification of reliable indicators of systemic riskiness or instability, and ultimately for effective supervision and policy making.

Informazioni relative al contratto di Ricercatore universitario ex art. 24, comma 3, lett. a) L. 240/2010 in regime di impegno tempo pieno da attivare/prorogare

SECS-S/06
(Settore Scientifico Disciplinare)

The researcher will contribute to modeling network structures and dynamical processes on networks; to characterize system evolution through exact or approximate solutions by using analytical or numerical methods and through sensitivity analysis; to the analysis of the network representations of the phenomena under consideration, possibly using or developing network reconstruction algorithms; to implement agent-based simulations of network dynamics; to quantitatively assess systemic robustness and resilience.

(Breve descrizione dell'attività del Ricercatore - Max 500 caratteri)

Durata contratto: triennale

Costo totale RTD a)	**€ 151.191,27**
Costo per l'attività di ricerca	**€ 32.142,07**
Costo totale progetto	**€ 183.333,34**

Si attesta l'impegno a pubblicare un prodotto Open Access valutabile per la VQR in fascia A o B per singolo anno di attività del progetto, nonché a divulgare i risultati della ricerca anche in accordo con l'istituto finanziatore Fondazione di Sardegna.

6 Settembre 2021

Firma del Referente Scientifico

Delpini Danilo
22.09.2021
09:02:43
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Firma del Direttore del Dipartimento

Giovanelli
Lucia
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