International Workshop

"Signed Relations and Structural Balance in Complex Systems: From Data to Models"

When: 15 - 17 May 2024 (Wednesday-Friday)

Where: *15 May:* ETH Zurich, Lecture Hall E101, LEE Building, Leonhardstr 21
16 May: ETH Zurich, Alumni Pavillon MM C78.1, Polyterrasse
16 May: ETH Zurich, Lecture Hall E101, LEE Building, Leonhardstr 21

Organization: Prof. Janusz Holyst, Faculty of Physics, Warsaw University of Technology
Prof. Frank Schweitzer, Chair of Systems Design, ETH Zürich

Funding: Polish National Science Foundation
Swiss National Science Foundation (SNSF Grant No: 105213L_192746)
Group of Physics in Economy and Social Sciences (Prof. Holyst)
Chair of Systems Design (Prof. Schweitzer)

Synopsis

According to the theory of structural balance, interacting systems balance the (positive or negative) relations between different system elements such that local conflicts are minimized. Hence, structural imbalances induce a dynamics to resolve such conflicts. This dynamics plays a vital role in evolutionary processes because a multitude of possible solutions exists. At the same time, if these solutions cannot be reached, this can hamper the functionality of systems.

This general problem also occurs in social systems, where instead of a more balanced state, for instance, the polarization of opinions emerges. Are we able to address this problem from a formal perspective? Do we have data available to study it in real systems? Can we develop models that help us to understand when structural balance fails, and how it can be mitigated?

Our workshop shall provide a platform to discuss these questions from a multi-disciplinary perspective, involving researchers from the complexity and the social sciences. Contributions revolve around three interlinked topics:

1. Signed Relations and Structural Balance in Complex Systems
2. Evolution of Signed Relation and Emergence of Structural Balance
3. Mitigating the Implications of Structural Imbalance

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Program and Abstracts

Wednesday, 15 May 2024

09:30-09:45	**Frank Schweitzer** (ETH Zürich) *Welcome and Introductory Remarks*
09:45-10:15	**Introduction of Participants**
10:15-10:45	**Coffee Break**
10:45-12:30	**Session 1:** Chair/Discussant: Pawel Sobkowicz (University of Warsaw)
10:45-11:30	**Michael Macy** (Cornell University) **Keynote:** *The Shallowness of Deep Division* Computational models reveal a tipping point in political polarization beyond which there is a potentially irreversible phase transition characterized by asymmetric hysteresis trajectories and triadic balance.The cascade dynamics display two disturbing properties: opinions become aligned across seemingly disparate political and cultural dimensions, and existential threats to shared interests (like a lethal pandemic, catastrophic global warming, or aggression by a foreign adversary) have a divisive rather than unifying effect. This unraveling of the social fabric suggests partisan divisions that are deeply rooted in opposing interests and ideologies. However, an RCT experiment suggests it may be the other way around. What appear to be irreconcilable differences in an increasingly polarized society may have arisen through a tipping dynamic that might just as easily have tipped the other way but for the luck of the draw among early movers. Paradoxically, the depth of the social fissure points to the shallowness of disagreements between idiosyncratic tribal combatants whose vitriolic hostility is substantively unwarranted.

11:45-12:15 **Giacomo Vaccario** (ETH Zurich)

Structural balance in complex network: Observation, Emergence and Implications

ince its first conceptualization in psychology, the theory of Structural balance was extended to economics, ecology and social science. Trespassing disciplinary boundaries, one of its first simple network formulations posits that triangles in signed networks should have an even number of negative links. This very simple statement has two significant consequences. First, it strongly affects our expectations about the macroscopic structure and functioning of an analyzed system. Second, it allows us to define specific dynamics at the microscopic level, i.e., different rules for describing the evolution of signed relations between system elements.
From its first formulation, multiple measures, many algorithmically advanced, have been proposed to quantify structural balance. However, these measures may be at odds with each other and give different perspectives on the status of an analyzed system. Sometimes, these differences are intended to capture different nuances of the micro-rule originating the structural balance. Other times, they are unintended and depend on different (unconscious) understandings of the system itself.
Connected to this first observability problem, there are two other central problems. First, the emergence of structural balance as a macroscopic property can be obtained by other theories with different (but compatible) microscopic rules. This fact raises the question: Is structural balance theory and its dynamics needed to model systems? Second, there are contradicting results about how the SB dynamics and macroscopic properties arising from it affect a system's performance. For instance, structural balance in traders' affective relations positively impacts their performance. Conversely, structural balance in the relations of Wikipedia contributors negatively impacts the quality of the edited articles. This type of opposite findings keeps the discussion about the link between structural balance and performance open, raising the question: Is structural balance good or bad in real-world systems?
By touching on these topics and questions, I will delve into the discussion regarding the observation, emergence and implications of structural balance to understand its role in complex systems.

12:30-14:00 **Lunch Break**

14:00-15:45 **Session 2:** Chair/Discussant: Janusz Holyst (Warsaw Univ. of Technology)

14:00-14:45 **Stefan Thurner** (Complexity Science Hub Vienna)

Keynote: *How diadic homophilic relations cause structural balance*

We present a simple model of a society where individuals are represented as a vector of opinions. Individuals are connected to each other in a temporal network where signed links represent a positive or negative relation between them. In a co-evolutionary dynamic setup individuals can change their opinions or change link signs. The model is phrased as a spinglas model. We study the phase diagram of the corresponding Hamiltonian and find that the "triad-statistics" that is expected from structural balance is obtained for specific parameter values. We compare the theoretical results to data obtained from actual social networks. The exciting result is that homophilic (diadic) relations are fulle sufficient to explain the emergence of realistic social balance – a triangle based statistics.

15:00-15:30 **Georges Andres** (Chair of Systems Design, ETH Zürich)

Reconstructing signed relations from interaction data

Positive and negative relations play an essential role in human behaviour and shape our communities. Polarization in the internal structure of these communities strongly affects their functioning. Imagine a community where two groups of individuals have positive relations within but negative relations across the groups. While such a polarized setting is stable according to structural balance theory, it may hinder constructive dialogue, foster division, and impede collective problem-solving.
To understand if a community is polarized in its relational structure, it is imperative to possess data on the signs of the relations. Unfortunately, such data is rare and commonly gathered through surveys. Conversely, interaction data is more abundant, for instance, in the form of proximity or communication data. We show how the underlying signed relations in communities can be extracted from interaction data.
Employing a statistical network approach, we infer signed relations using interaction data for five social systems and reconstruct their signed networks. Subsequently, we leverage the reconstructed signed networks to study group cohesion and structural balance. Finally, we establish a connection between these concepts and the emergence of polarization in social systems.

15:45-16:15 **Coffee Break**

16:15-17:45 **Session 3:** Chair/Discussant: Piotr Gorski (Warsaw Univ. of Technology)

16:15-16:45 **Anna Gallo** (IMT School for Advanced Studies, Lucca)

Assessing frustration in real-world signed networks: Towards a statistical theory of balance

The abundance of data about social and economic relationships has opened an era in which social theories can be tested against empirical evidence, allowing human behaviour to be analysed like other natural phenomena. Here we focus on balance theory [1], which postulates coherence between positive and negative interactions in real, social networks. To make balance theory testable, one needs 1) a proper representation of social networks, 2) a definition of “frustration” (or imbalance) and 3) a set of null models to quantify the statistical significance of the latter. The first two ingredients have been already explored comprehensively: social interactions can be represented via signed graphs and “frustrated” configurations are defined as those having cycles with an odd number of negative links. The third ingredient, however, is way less developed, since the existing null models typically do not account for the different, intrinsic tendencies of individual actors to establish positive and negative interactions. To reduce this gap, here we extend the ERG framework to binary, undirected, signed networks with both global and local constraints. Moreover, we define two variants for each benchmark: one where the topology is kept fixed and one where it is left to vary along with the edge signs.
Our analysis shows that homogeneous null models with global constraints tend to favour the weak version of balance theory, according to which only the triangle with one, negative link should be under-represented in real networks; on the other hand, heterogeneous null models with local constraints tend to favour the strong version, according to which the triangle with all negative links should be under-represented as well. As a comparison, biological networks display almost inverted patterns, confirming that structural balance inherently distinguishes social networks from other types of signed networks.
The generalisation of the concept of balance at the mesoscopic scale leads to the so-called k-balance theory, which interprets a generic graph as structurally balanced if its vertex set can be partitioned into k subsets (or modules) with positive, intra-modular links and negative, inter-modular links. If adopted as a strict “yes/no” criterion, however, k-balance theory would too quickly interpret the vast majority of real-world networks as “frustrated”; therefore, we again make use of our null models to assess the significance of the empirical deviation from ideal k-balanced configurations and propose a statistically grounded test of hypothesis. Along the way, we show that the signed analogue of the resolution limit for community structure can be naturally re-interpreted as a threshold-based criterion for discerning whether a given, signed configuration is balanced. Finally, we advance a proposal for the statistical characterisation of the so-called relaxed balance theory and compare the relaxed and traditional variants in terms of their performance.

17:00-17:30 **Emma Fraxanet** (Pompeu Fabra University, Barcelona)

Unpacking Polarization: Antagonism and Alignment in Signed Networks of Online Interaction

Political conflict is an essential element of democratic systems, but can also threaten their existence if it becomes too intense. This happens particularly when most polit- ical issues become aligned along the same major fault line, splitting society into two antagonistic camps. In the 20th century, major fault lines were formed by structural conflicts, like owners vs workers, center vs periphery, etc. But these classical cleavages have since lost their explanatory power. Instead of theorizing new cleavages, we present the FAULTANA (FAULT-line Alignment Network Analysis) pipeline, a computational method to uncover major fault lines in data of signed online interactions.
Our method makes it possible to quantify the degree of antagonism prevalent in different online debates, as well as how aligned each debate is to the major fault line. This makes it possible to identify the wedge issues driving polarization, characterized by both intense antagonism and alignment. We apply our approach to large-scale data sets of Birdwatch, a US-based Twitter fact-checking commu- nity and the discussion forums of DerStandard, an Austrian online newspaper. We find that both online communities are divided into two large groups and that their separation follows political identities and topics. In addition, for DerStandard, we pinpoint issues that reinforce societal fault lines and thus drive polarization.
We also identify issues that trigger online conflict without strictly aligning with those dividing lines (e.g. COVID-19). Our methods allow us to construct a time-resolved picture of affective polarization that shows the separate contributions of cohesiveness and divisiveness to the dynamics of alignment during contentious elections and events.

18:30-21:00 **Conference Dinner**

Restaurant Linde, Universitätstrasse 91, 8006 Zürich

Thursday, 16 May 2024

09:30-10:30 **Session 4:** Chair/Discussant: Sophia Schlosser (ETH Zürich)

09:30-10:15 **Boleslaw Szymanski** (Rensselaer Polytechnic Institute, Troy, NY)

Keynote: *Political Polarization At the Age of Social Media*

We all agree that social media has changed the way political information spreads across the internet, but there is paucity of research on how exactly this new way of spreading works. In this talk, we will start by discussing the new patterns of data flow and new roles for users in spreading information and this new model coexists with remnants of the classic two-level propagation. Then, using the polarization model inspired by the Ising model, we discuss how the presence of social media increases polarization. Political scientists have documented increasing partisan division, finding extremist positions to be more pronounced among political elites than among voters, raising the question of how polarization might be attenuated.
In this talk, we introduce a general model of opinion change to see if the self-reinforcing dynamics of influence and homophily may enable tipping points that make reversibility problematic. We also introduced exogenous shocks corresponding to events that create a shared interest against a common threat (e.g., a global pandemic). Phase diagrams of political polarization reveal difficult-to-predict transitions that can be irreversible due to asymmetric hysteresis trajectories. We focus on social media, which has been transforming political communication dynamics for over a decade. Using a billion tweets, we analyzed the change in Twitter's news media landscape between the 2016 and 2020 U.S. Presidential elections. We then identify influencers, users with the top ability to spread news in the Twitter network. The more influential 2016 users were, the higher was their rate of remaining active and keeping their level of influence in 2020. We also analyze changes in influencers' real-world affiliations, political biases, and in Twitter users' choices as to which influencers to retweet and which ideology to subsequently support. We also compare 2020 Twitter dynamic and compare it to Parler dynamic in the same period. We observe that the initial polarization tends to be stable.

10:30-11:00 **Coffee Break**

11:00-12:30 **Session 5:** Chair/Discussant: Laurence Brandenberger (ETH Zürich)

11:00-11:30 **Pawel Sobkowicz** (University of Warsaw)

On the Individual Roots of Polarization: Combining Experiments and Modeling

Most of the sociophysical and Agent Based models of opinion dynamics attempting to describe polarization focus on social interactions. The internal mechanisms of the individual opinion changes are usually significantly simplified. One of the reasons for such simplification is that the actual mechanisms are not very well understood in social psychology. They depend heavily on the contexts, the individual mental and emotional state, communication media and multiple, often conflicting forces.The presentation is based on [1], in which we have set out to study two possible mechanisms influencing political polarization at an individual level. The first is the in-group praise, motivated by the desire to be accepted and recognized group members. The second is the out-group derogation, focusing not on the virtues of one's own group, but on the deficiencies and errors of the opposition. These two mechanisms were studied experimentally and compared to the effects of evidence-based argumentation. The experiments were accompanied by a simple ABM model, in a rather unique process where both approaches augmented and developed each other. We shall discuss the potential use of the results in future ABM models that combine both the individual and social dynamics.

11:45-12:15 **Angela Fontan** (KTH Royal Institute of Technology, Stockholm)

Collective decision-making on networked systems: From social networks to political decision-making

Collective decision-making refers to a process in which the agents of a community exchange opinions to reach a common decision. It is often assumed that a collective decision is reached through collaboration among individuals. However, in many contexts, concerning for instance collective human behavior, it is more realistic to assume that the agents can collaborate or compete with each other. In this case, different types of collective behavior can be observed. This talk will focus on collective decision-making and will present a concrete example of political decision-making. I will present a nonlinear model for collective decision-making in a community of agents where both cooperative and antagonistic interactions coexist, represented as a signed interaction graph. The aim is to shed light on the role of frustration of the signed network (quantifying the amount of social tension in the network) in the decision-making process. A concrete example of the findings to the process of government formation in parliamentary democracies will be discussed.

12:30-14:00 **Lunch Break**

14:00-15:30 **Session 6:** Chair/Discussant: Alexandre Bovet (University of Zürich)

14:00-14:30 **Berno Buechel** (Department of Economics, University of Fribourg)

Stable Signed Networks

While standard social networks suppress negative ties, signed networks capture them by coding relations as $+1$ if positive, -1 if negative, and 0 if neutral. The economics literature on social networks has always had a particular focus on strategic network formation, but signed networks have been largely ignored. Hence, there is the fundamental question: How do signed networks form among strategic agents? We address this question by studying how agents strategically form and dissolve positive and negative ties. In our framework agents change their ties, while anticipating the costs and benefits the network means. We extend the notion of pairwise stability to signed networks requiring that deviations to add a positive link or to delete a negative link must be bilateral, while deviations to delete a positive link or to establish a negative link can be unilateral. By analytical derivations and by computational methods, we characterize which networks are stable, and hence likely to emerge, and how they differ from the efficient, i.e., welfare-maximizing, networks. This enables us to show how incentives shape the evolution of signed networks.

14:45-15:15 **Piotr Gorski** (Warsaw University of Technology)

Under-representation of nonhierarchical triads in structural balance model

We introduce an agent-based model integrating structural balance and status, which are prominent theories of signed link formation process. For complete networks, our analytics matches simulations showing continuous or discontinuous phase transition between unbalanced and structurally balanced paradise states. We identify nonhierarchical triads for which principles of status theory are broken.
Extending our analysis to large online and small face-to-face networks, we observe that nonhierarchical triads tend to be under-represented. We reproduce these deviations in our simulations by adjusting, among others, the parameter related to the competition between balance and status. Relating obtained levels of competition with the face-to-face dataset's characteristics revealed that networks with a higher prevalence of strong relations favor balance, while those with a greater prosociality of agents exhibit higher under-representations, indicating the larger influence of status theory.

15:30-16:00 **Coffee Break**

16:00-17:30 **Session 7:** Chair/Discussant: Georges Andres (ETH Zürich)

16:00-16:30 **Matus Medo** (University of Bern)

The fragility of opinion formation in a complex world

How does the complexity of the world around us affect the reliability of our opinions? Motivated by this question, we discuss a simple model in which an observer gradually forms opinions about a world composed of subjects interconnected by a signed network of mutual trust and distrust.
We show that when the underlying signed network is not balanced, the opinion formation process is highly fragile. An individual who initially trusts a few credible information sources, for example, likely ends up trusting many deceptive information sources. The introduced mathematical framework allows us to ask further questions such as how to improve the reliability of the formed opinions, why is there a phase transition in opinion formation, and how is this related to group formation.

16:45-17:15 **Krishnadas Mohandas** (Warsaw University of Technology)

Critical properties of Heider balance on multiplex networks

Heider's structural balance theory has proven invaluable in comprehending the dynamics of social groups characterized by both friendly and hostile relationships. Since people's relations are rarely single-faceted, we investigate Heider balance dynamics on a multiplex network, consisting of several copies of the same agent displaying correlated relations at different layers building the multiplex. Intralayer interactions in our model adhere to Heider dynamics, while interlayer correlations stem from Ising interactions, with the heat bath dynamics of link signs.
The investigations uncover a multifaceted system with a diverse equilibrium landscape contingent on the coexistence of distinct phases across layers. We observe that starting from a paradise state with positive links in all layers, an increase in temperature triggers a discontinuous transition to a disordered state akin to single-layer scenarios. The critical temperature surpasses that of the single-layer case, a fact verified through extended mean-field analysis and agent-based simulations.
Furthermore, the scenario shifts when one layer exhibits a two-clique configuration instead of a paradise state. This change introduces additional transitions: synchronization of inter-layer relations and a transition to the disorder, appearing at a different, lower temperature compared to matching paradise states. This exploration shows the intricate interplay of Heider balance and multiplex interactions.

17:30 **Daily Closing**

Friday, 17 May 2024

09:30-10:30 **Session 8:** Chair/Discussant: Frank Schweitzer (ETH Zürich)

09:30-10:15 **Samin Aref** (University of Toronto)

Keynote: *Structural analysis of signed networks by optimally clustering them using integer programming models*

A signed network is one with positive and negative edges. We analyze signed networks from the perspective of balance theory. A signed network is strongly balanced (weakly balanced) if its nodes can be partitioned into $k \leq 2$ clusters (k clusters) such that positive edges are within the clusters and negative edges are between the clusters. We use mathematical programming models to optimally cluster the nodes of a network by minimizing the total number of intra-cluster negative and inter-cluster positive edges.
These optimization models cluster a network into clusters of nodes that are internally cohesive and mutually divisive. The optimal partitions of a network allow us to quantify the extent to which it is weakly or strongly balanced. In other words, we measure the distance of a network to weak and strong balance in terms of the minimum number of edges whose sign change leads to weak and strong balance respectively.
The concepts of strong and weak balance in signed networks can be extended to applications beyond the classic friend-enemy interpretation of balance theory in the social context. Through extensive computational analysis, we explore common structural patterns across a range of networks representing philosophers and Wikipedia editors to Bitcoin traders and US Congress legislators. This talk provides an overview of using integer programming to develop exact graph optimization models and algorithms for signed networks. A wide range of use cases will be discussed for signed networks from sociology, biology, chemistry and physics to finance, international relations, and political science.

10:30-11:00 **Coffee Break**

11:00-12:30 **Session 9:** Chair/Discussant: Giacomo Vaccario (ETH Zürich)

11:00-11:30 **Giulia De Pasquale** (Automatic Control Laboratory, ETH Zürich)

Binary Models for Opinion Dynamics and Interpersonal Relationships via Influence and Homophily Mechanisms

In this talk we propose two discrete time binary models for opinion dynamics. The first one is based on the homophily mechanism. We show that the binary homophily model can drive an initially structurally unbalanced network towards a socially balanced one. In order to characterise non-structurally balanced equilibrium points, we introduce a (V, Σ)-factorization that finds an interesting interpretation in terms of structurally balanced subclasses.
The second one is a revisitation of a recently proposed discrete time model for the interplay between homophily-based appraisal dynamics and influence-based opinion dynamics. We show that a simplified (and, in some situations, more feasible) version of the model, that accounts only for the signs of the agents' appraisals provides an equally accurate and effective model of the opinion dynamics in small networks. The equilibria reached by our model correspond, almost surely, to situations in which the agents' network is complete and structurally balanced. On the other hand, we ensure that such equilibria can always be reached in a finite number of steps, and, differently from the original model, we rule out other types of equilibria that correspond to disconnected social networks.

11:45-12:15 **Andreia Sofia Teixeira** (University of Lisbon)

Analyzing Signed Networks: Insights from Multiscale Structural Balance Theory and Dynamics in High School Social Relations

This presentation delves into the rich landscape of signed networks, approaching the intricate positive and negative relationships that shape social dynamics, including phenomena like polarization and evolving social ties. Offering a dual perspective on theory and dynamics, the first part of the talk will focus on the theoretical complexities of polarization, introducing the "Multiscale Semiwalk Balance" approach. This methodology addresses computational challenges, providing scalable insights into balance degrees within real-world social systems. Shifting the lens, the second part of the talk will discuss navigating through the dynamics of high school social relations, investigating the interplay of Structural Balance (SB) and stochastic mechanisms. A continuous time model, integrating cognitive constraints, is presented to faithfully replicate observed network dynamics. This talk bridges theoretical nuances and practical applications, shedding light on key aspects of signed networks and their implications for social relations.

12:30-12:45 **Janusz Holyst** (Warsaw University of Technology)

Closing and Farewell