2016 COMPLEX SYSTEMS SUMMER SCHOOL

AT THE SANTA FE INSTITUTE

2016 COMPLEX SYSTEMS SUMMER SCHOOL
GROUP PROJECT ABSTRACTS

Co-evolution of strategic decision making: DOTA 2 as a proxy for cybersecurity environments

A. L. Sellaska, D. Biro, S. Duran, M. Stuart

ABSTRACT

Computer hackers use specific strategies to penetrate systems. These strategies evolve over time, usually in response to the defense mechanisms employed by the system administrators. Being able to identify the strategies and when they change is of paramount importance to ensure the safety of the systems. Because data to help this effort is scarce, this paper explores the possibility of using competitive, strategic video game data as a proxy to identify strategies and their change points.

The data chosen for this project is from the Defense of the Ancients (DOTA 2). This game is a rich data source of real-time adaptive adversaries. DOTA 2 is a multiplayer game where two teams of five individuals each compete against each other to complete objectives and to destroy the other team's base in a time frame of $\sim$ 20 to $\sim$ 90 minutes, while taking on the guise of a "hero" character. Professional games also include a draft, where heroes are chosen (or banned from being chosen) from a pool of $\sim$ 120 characters, each with specific abilities. The players deploy various in-game and between-game tactics and procedures to achieve a specific measurable objective. Professional players vie for tens of millions of dollars in prize pools each year, and over 2 billion games have been played. The results in this paper are using data from a cache of 500 GB of aggregated game data ($\sim$ 2.5 million games played over one year) and raw, event-by-event data of $\sim$ 100 Mb per game. The goal is to use this data to shed light on how one can 1) detect and 2) quantify the rate of change of strategies in co-evolutionary systems.

This paper will cover the complexity of the draft and employ hidden Markov models (HMM) to determine underlying structure both in the draft and in the gameplay itself. For the gameplay, the relative, normalized positions of all ten players were converted into system "states", which served as the observable input to the HMM. The time evolution of these observable states, and the results from the HMM for this part of the analysis are shown in Fig. 1. The dashed lines in the figure denote the breaks between stacked games. The code to estimate the model parameters and the most likely hidden state sequence was provided by Simon DeDeo.*

Also included in the figure is perhaps the most interesting aspect: the modules. These represent the stationary state that the system eventually evolves to and its longest lasting perturbation. As shown in the figure, for this set of data, a given game *will* be in either module 1 or 2 throughout the entirety of the game. Very little oscillation between these modules is observed within games. This is indicative of some underlying structure to be analyzed in future studies.

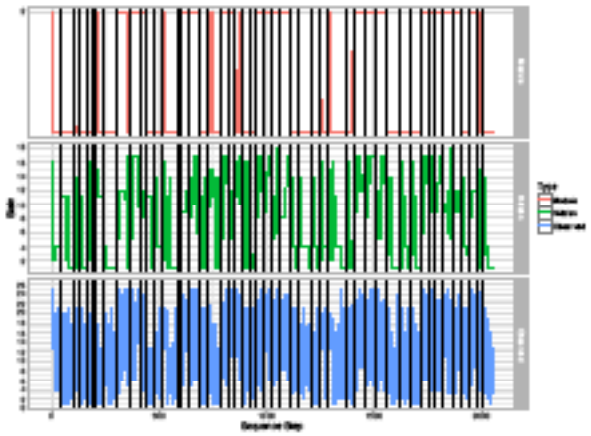


Figure 1. Evolution of hidden and observed states for a sample of 50 games from a single tournament. Note, the hidden state X may not correspond directly to the observed state X. These numerical labels are arbitrary and used only for plotting purposes. Dashed lines indicate the start of new games. The module states show the dynamic flow between the possible stationary state and its longest lasting perturbation.

Delayed differential mutual information in oscillatory networks

Jeffrey Emenheiser, Lindsay Todman, Emanuele Crosato, Sina Tafazoli, Hamza Giaffar, Pinar Oziak, Ryan McGee

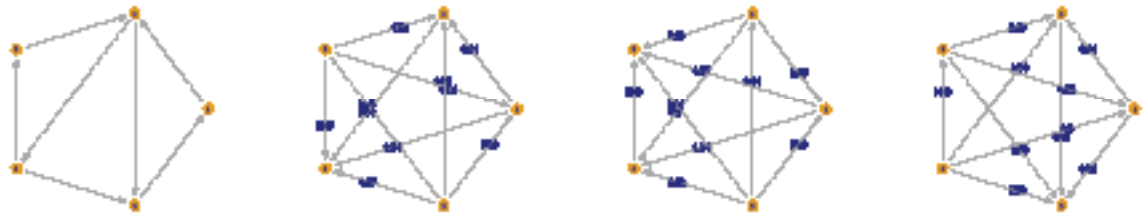
Complex networks of oscillatory components are ubiquitous in the natural and engineered worlds. These networks can display highly nontrivial dynamic behavior, which relies on an efficient and flexible communication structure for the synchronization of their subsystems. Crucially, these networks tend to show collective oscillatory dynamics in which information about the global state is shared between the distributed components.

Quantifying the communication of information among these components has recently been addressed by Kirst et al. (Nat. Comm. 7, 2016). The authors found that the global "information routing pattern" (IRP) could be affected both by modifying a parameter in the dynamics of a single oscillator and by moving the system to a differing attractor of the global dynamics.

To date, there is no established theory for information routing, and diverse information theoretic measures, each capturing different aspects of information transfer, that are typically applied. Kirst et al. adopted delayed versions of differential mutual information (dMI) and differential transfer entropy (dTE) to define information transfer and thus identify the IRPs. These measures are based on continuous (or differential) Shannon entropy.

Discrete Shannon entropy has a clear interpretation in Information Theory; however, there are dilemmas in interpreting the continuous version. Interpretations have been suggested, but the meaning of "differential entropy" over continuous random variables is not satisfactorily explained.

In this work we study one measure used by Kirst et al., delayed differential mutual information, on mathematical models of small networks to better understand what the resulting IRPs can reveal about a network. Specifically, we compute the dMI between each directed pair of nodes in various networks, in which noise is "injected" at the nodes and is propagated throughout the network. The computation is done by numerically solving the integral expression for dMI as presented by Kirst, et al., derived in the limit of weak noise around a known limit cycle attractor.



(a) (b) (c) (d)

Figure 1. (a) The five node network under study. (b-d) IRPs corresponding to three different noise configurations in which two nodes are injected with twice as much noise as the other three. What is striking about these IRPs is that none of the ten edges point the same way in all three patterns.

We find that the delayed differential mutual information is largely influenced by the variance of noise at each node and that it does not intuitively correspond to active communication of the injected signal. Furthermore, we see that controlling the noise injection levels is sufficient to change the direction of any edge in the IRP of a particular five node network (Figure 1).

Our conclusion is that directionality in IRPs is sensitive to noise response, which must be taken into account when considering real systems. Because the IRPs may be so wildly different under different noise configurations, we suggest that they be applied to real systems only with particular caution regarding heterogeneous noise levels in that real system. Uniform noise should be considered only if that is a reasonable assumption in the applicable context and should be stated very clearly as an assumption of the system.

Evaluation Of Preliminary Models Of Swidden Agriculture In The Toledo District Of Belize

Lindsay Todman, Fabio Correa

Abstract

Swidden farming in the Toledo district of Belize is a relatively young subsistence agricultural technique in which each farmer enlists help from his friends to clear a patch of land, grow crops, and harvest. The resulting near-reciprocal social network of exchange of agricultural labor constitutes an essential component of the coupled human natural system that operates in this region. This paper describes a preliminary effort to develop an agent-based model of this system, which started as a demonstration model in NetLogo and evolved into 3 candidate models that were evaluated for basic viability criteria to exhibit fundamental features of the Toledo district, such as its characteristic cultivation cycle in which a patch is usually farmed for 2 years at most, then left to fallow for 7 years at least. In our evaluation, we were able to conclude that the 3 proposed models cannot meet the proposed criteria, thus leaving us with the alternative of introducing the cycle as an explicit constraint. We plan to use what we have learned and the tools we have built in the development of future models that produce viable scenarios in order to move on to the study of social properties and emergent phenomena of such models.

The Evolution of Pitch Information in Contemporary Popular Music

Chenling Antelope[1], Jesús Arroyo[2], Lin-Qing Chen[3], Mark McCann[4], Marcus Nordström[5], and Donovan Platt[6]

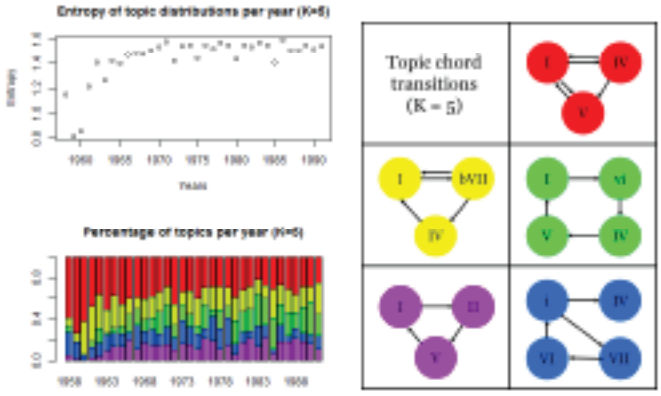
[1]University of California, Berkeley
[2]University of Michigan, Department of Statistics
[3]Perimeter Institute and University of Waterloo
[4]MRC / CSO Social and Public Health Sciences Unit, University of Glasgow
[5]Royal Institute of Technology, Sweden
[6]University of the Witwatersrand, School of Computer Science and Applied Mathematics

ABSTRACT

In this investigation, we study how the sophistication of popular music has changed in recent years. We perform a quantitative analysis of changing trends in pitch and chord usage in popular music. Using different statistical tools and models, the analysis reveals certain insights of music evolution in a quantitative and objective manner that complements the conventional theoretical study in the music community.

For our analysis, we focus on two datasets: the *Million Song Dataset*, which presents pitch information of songs as a series of chroma features sampled at discrete time points, and the *McGill Billboard Project* dataset, which contains the chord progressions of a sample of 800 songs from the Billboard Hot 100 chart from 1958 to 1991.

Regarding the pitch information, firstly, our result rejects one of the main conclusions of Serra et al (2012, Scientific Reports 2), which claims that the distribution of the usage frequency of *codewords* follows a power law. After a more careful analysis, we show that the distribution is much closer to lognormal through the usage of the BIC criteria. Hence the self-information of each codeword follows a normal distribution. Considering that the very notion of codewords is more mechanical than musically meaningful, we analyze the evolution of chord transitions in the McGill Billboard Project dataset through topic modeling (Latent Dirichlet Allocation). For certain types of popular songs, the chord transitions can be viewed as a layout of the underlying mood and the skeleton of a song. The topic model is able to identify some of the most popular chord progressions, and we can observe the evolution of their usage in different years, showing an increase in the variety of progressions during the 60's, which has stayed static since then without significant changes. Finally, through the usage of information theoretic techniques, we investigate the temporal changes in the Shannon entropy of both the pitch chroma features extracted from the Million Song Dataset, and the chord transition topics extracted from the McGill Billboard Project. These calculations show evidence of a gradual increase in the sophistication in the usage of pitch information during the 1960s and 1970s, eventually peaking and remaining stable in the 1980s. Another crucial feature of how music has changed over time is the emergence of a greater range of genres. We assessed how the self-information of songs varied over time both within and between genres using Multilevel regression models which show there is significant variation in information between genres as well as between songs.



Human Path Finding in a Semantic Word Game

Frank Marrs[1], Mika J. Straka[2], and Nicole M. Beckage[3]

[1]Colorado State University, Department of Statistics, Fort Collins, CO, USA
[2]IMT School of Advanced Studies Lucca, Piazza San Ponziano 9, 5510 Lucca, Italy
[3]University of Kansas, Department of Electrical Engineering and Computer Science, Lawrence, KS, 66044 USA

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Human decision-making processes are inevitably influenced by mental images, which are triggered by cues such as objects, concepts, and words. The cognitive associations between words can be thought of as a mental lexicon and may be well captured in a semantic network with words as nodes and associations between words represented as graph edges. How efficiently can humans traverse a word association network given a target word if, at each moment, they can only choose among a set of possible next words? Using the data from an online semantic game Mindpaths[1], we show that human players do not rely on a simple guessing strategy but navigate quite efficiently to a specific target word. Moreover, choices of the next move are only partially motivated by eigencentrality and in-degree of the selected words. Fig. 1 summarizes the results for different models by comparing the game lengths, i.e. the number of moves before the target goal is reached, for humans and various algorithms. Our results suggest that models driven by semantic similarities and relations between words are necessary for further understanding how individuals make specific choices resulting in successful navigation to target words.

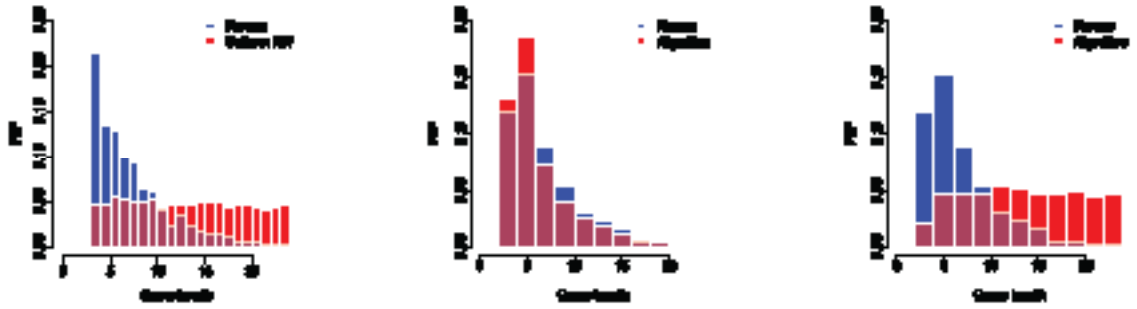


Figure 1: Performances of different algorithms in comparison to the human players. The middle and right panel refer to games which can be solved in four moves. Left: Humans clearly outperform an unbiased random walker requiring fewer moves on average. Middle: A trained random walker with partial memory on successful trials emulates human performance well. Right: Transition probabilities are obtained via a Bayes' estimation based on neighbor words' eigencentralities and in-degrees. It is evident that this information is not sufficient to capture the human decision-making process.

[1]See mindpaths.socientias.eu for more detail, to play the game and to contribute to ongoing research.

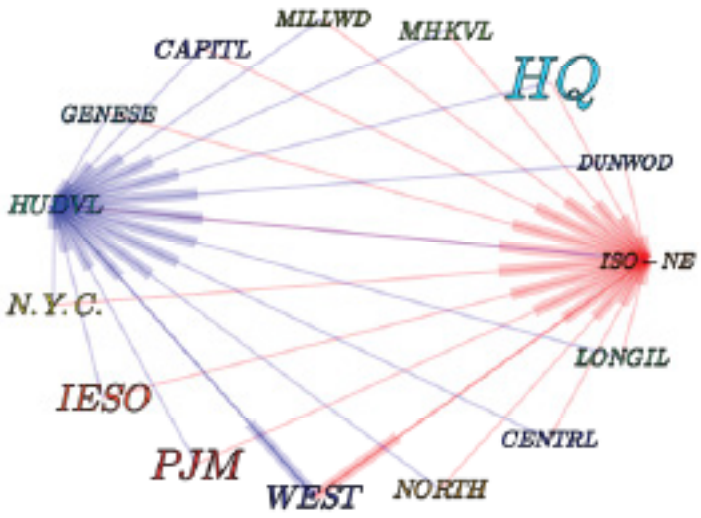
Inferring Network Structure: the New York Power Grid

James R. Thompson[1], Charlotte James[2], Ryan McGee[3], Harrison B. Smith[4], Aina O. Vila[5], and Mika Straka[6]

[1]MITRE Corporation, Washington D.C., USA
[2]University of Bristol, Bristol, UK
[3]University of Washington, Seattle, WA , USA
[4]Arizona State University, Phoenix, AZ , USA
[5]Pompeu Fabra University, Barcelona, Spain
[6]IMT School of Advanced Studies, Lucca, Italy

ABSTRACT

Opening wholesale power markets to speculative trading is a deliberate attempt to incorporate the benefits of competition and price discovery to a historical monopoly. Whether those benefits are being realized is an ongoing discussion, but it begs the question: do the new policies unintentionally make the grid more vulnerable to cascading failure? More importantly can we measure that vulnerability and take steps to minimize it, making our critical infrastructure more resilient and secure? Much of the power market research to date focuses on the optimization algorithms required to dispatch power and solve for location based pricing. Agent-based models have been constructed to investigate the economic impact of market deregulation, and the financial industry has employed data analytics and machine learning algorithms to measure financial risk associated with congestion contracts and other financial instruments. The perspective of most of these studies are the economic benefits and improvement of normal day-to-day business practices. Few studies, if any, have taken a grid security perspective at the Independent Service Operator level, which necessarily changes the study objectives and focus. This research takes a bottom-up approach to market operations in an effort to understand the risks of cascading failures at the national level. We analyze the processes employed by market participants to deliver power, and investigate if the underlying grid network structure and vulnerabilities can be inferred from the analysis.



Interdisciplinary Analysis for Human Group Dynamics

Jesus Mario Serna[1,*], Mark McCann[2], Andrew Christian[3], Danilo Liuzzi[4], Gaetano Dato[5], Justin Williams[6], Lorraine Sugar[7], Sina Tafazoli[8]

[1]Université Paris 7, USPC, Recherches en Psychanalyse, Paris, France
[2]University of Glasgow, UK
[3]NASA Langley Research Center, USA
[4]University of Milan, Milan, Italy
[5]University of Trieste, Italy
[6]University of North Texas, USA
[7]University of Toronto, Department of Civil Engineering, Toronto, Canada
[8]Princeton University, USA
* jesus.mario.sw@gmail.com

ABSTRACT

There are still considerable breaches between purely qualitative and quantitative approaches in many working models for group dynamics in psychology and social sciences. We argue that an interdisciplinary approach may help bridge these gaps towards more integrative models. We ran a discussion group based on the Operative Group Model (OGM), using a complex systems approach to reinterpret its dynamics, and applied network theory as well as thematic discourse analysis (DA). Finally, we consider the potential advantages of performing an acoustic analysis on the audio recordings from the group sessions. To our knowledge, this integrative approach has never been applied in the context of an OGM.

In this study we provide two main levels of analysis: the participant's personal and group experience, and the experimentation and analysis methods' aspect. For the former, we gather data from group theory in psychology, psychoanalysis, the OGM, and the participants' feedback. We then use DA and a bipartite graph identifying weighted "thematic nodes" as a research framework. Finally we explore possible ways to incorporate an acoustic analysis, notably implementing a Hidden Markov Model (HMM). The goal is to identify appropriate interdisciplinary models to analyze human group dynamics with both quantitative and qualitative methods. We present some preliminary results from overlapping data that might pinpoint movements towards group cohesion. We then discuss further considerations on the analysis framework and future applications. Finally we consider the advantages of implementing the OGM to foster meaningful interdisciplinary dialogue in research groups, notably to overcome communication difficulties between researchers and enhance collaboration.

Keywords

Human Group Dynamics, Interdisciplinarity, Discourse Analysis, Thematic Analysis, Acoustics, Operative Group, Psychoanalysis, Empirical Research.

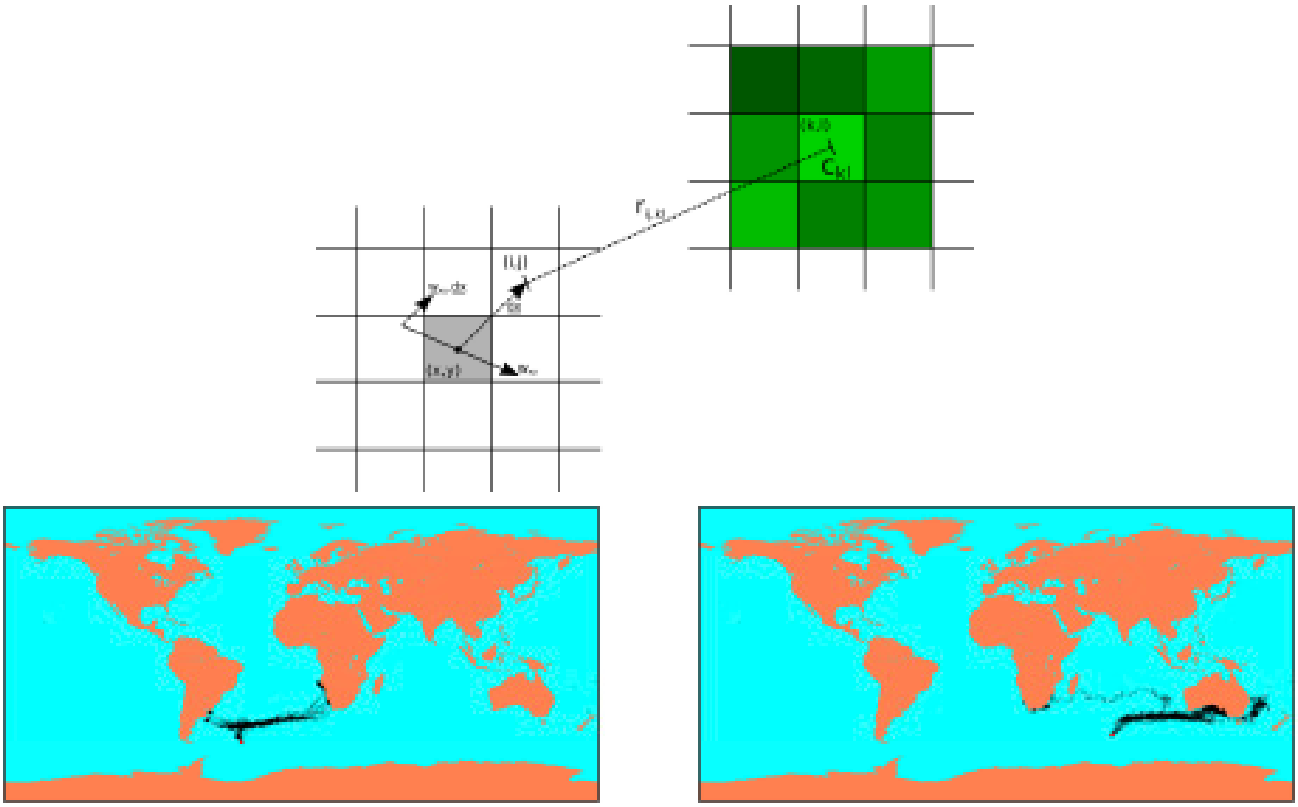
A Mechanistic Explanation Of Non-Breeding Movement Patterns In Seabird Populations

Christopher Revell[1] and Marius Somveille[2]

[1]University of Cambridge, Cavendish Laboratory, Department of Physics
[2]University of Oxford, Edward Grey Institute for Field Ornithology, Department of Zoology

ABSTRACT

In this paper, we introduce a mechanistic model of migratory movement patterns in birds, inspired by ideas and methods from physics. Previous studies have shed light on the factors influencing bird migration but have mainly relied on statistical correlative analysis of tracking data. Our novel method offers a "bottom up" explanation of population-level migratory movement patterns. It differs from previous mechanistic models of animal migration and enables predictions of pathways and destinations from a given starting location. We define an "environmental potential" landscape from environmental data and simulate bird movement within this landscape based on simple decision rules drawn from statistical mechanics. We explore the capacity of the model by qualitatively comparing simulation results to the non-breeding migration patterns of a seabird species, the Black-browed Albatross (*Thalassarche melanophris*). This minimal, two-parameter model was able to capture remarkably well the previously documented migration patterns of the Black-browed Albatross, with the best combination of parameter values conserved across multiple geographically separate populations. Our physics-inspired mechanistic model could be applied to other bird and highly-mobile species, improving our understanding of the relative importance of various factors driving migration and making predictions that could be useful for conservation.



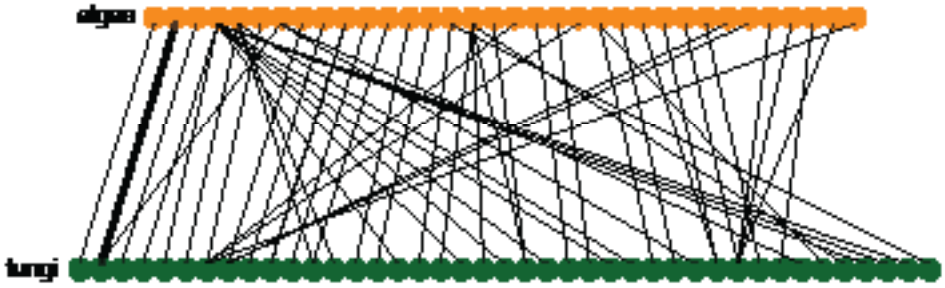
Modeling Coevolutionary Dynamics in the *Lobaria pulmonaria* Lichen Symbiosis

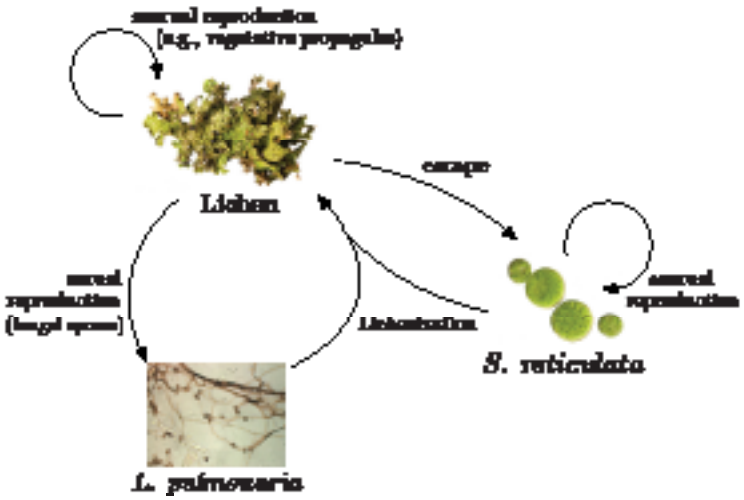
Simon Carrignon[1,2], Aina Ollé-Vila[2,3], Julia N. Adams[4], and Salva Duran-Nebreda[2,3]

[1]Barcelona Supercomputing Center, Carrer de Jordi Girona, 29-31, 08034 Barcelona, Spain.
[2]Institució Catalana per a la Recerca i Estudis Avançats-Complex Systems Lab, Universitat Pompeu Fabra, 08003 Barcelona, Spain.
[3]Institut de Biologia Evolutiva (CSIC-Universitat Pompeu Fabra), Passeig Marítim de la Barceloneta 37, 08003 Barcelona, Spain.
[4]University of California, Riverside (UCR), Riverside, CA 92521

ABSTRACT

Lichenization is an evolutionarily and ecologically successful strategy for Ascomycete fungi, resulting in approximately 18,000 lichen species known to date. Although the nature of the lichen symbiosis is still widely debated, many sources agree that the lichen symbiosis represents an ecologically obligate mutualistic interaction whereby the net fitness of all partners is maximized. In order to elucidate the potential factors driving the evolution of the lichen symbiosis and the broader ecological and evolutionary interactions in the *Lobaria pulmonaria* model organism, an agent-based model based on the widely used ECHO framework was constructed. The tag system of ECHO was used to model molecular recognition (receptors and physical embedding) between algae and fungi, two of the partners necessary to reconstitute the *L. pulmonaria* lichen symbiosis. We compared the simulations' results with *L. pulmonaria* microsatellite data and our model reproduced some features of this data. Molecular data have shown that the mode of reproduction significantly affects within-population genetic structure of *L. pulmonaria*, most likely contributing to the modular structure of this population. Our results also show that the interaction type does not significantly change network metrics (modularity and nestedness), showing that fungal-algal interactions ranging from parasitic to mutualistic can support a successful or stable biological entity.





Modeling Stopover Sites of Migratory Birds' Routes for Conservation of Population and Prevention of Disease

Ilya Bayram[1,*], Ruichen Sun[2], and William Lee[3]

[1]PhD student, Computer Science at University of Cincinnati, Cincinnati-Ohio, 45219, USA
[2]PhD student, University of California, San Diego, 92093, USA
[3]MITRE, Bedford, 01824, USA
*bayramia@mail.uc.edu

ABSTRACT

Modeling migratory paths of birds is an emerging area of complexity science in which attracts interdisciplinary collaborations from ornithologists, computer scientists, epidemiologist, and policy makers. However, due to the unpredictability of climate and habitat changes, our understanding of bird migratory paths is still limited. Not accounting for environmental changes when modeling bird migration will mislead our conservation efforts. Hence, in this paper, we are using validated training data to predict future stopover sites of migratory bird species. We used white-fronted geese migratory paths as training data and modeled stopover sites with Markov Chains to predict future changes on the stopover sites.This prediction will allow researchers to realize how to better conserve the habitat locations at and around stopover sites in the light of current climate changes. Since birds often stop and interact with the nearby environment, our work will also allow researchers to predict potential dangers emerged from long-range migrations, such as new avian viruses along these routes.

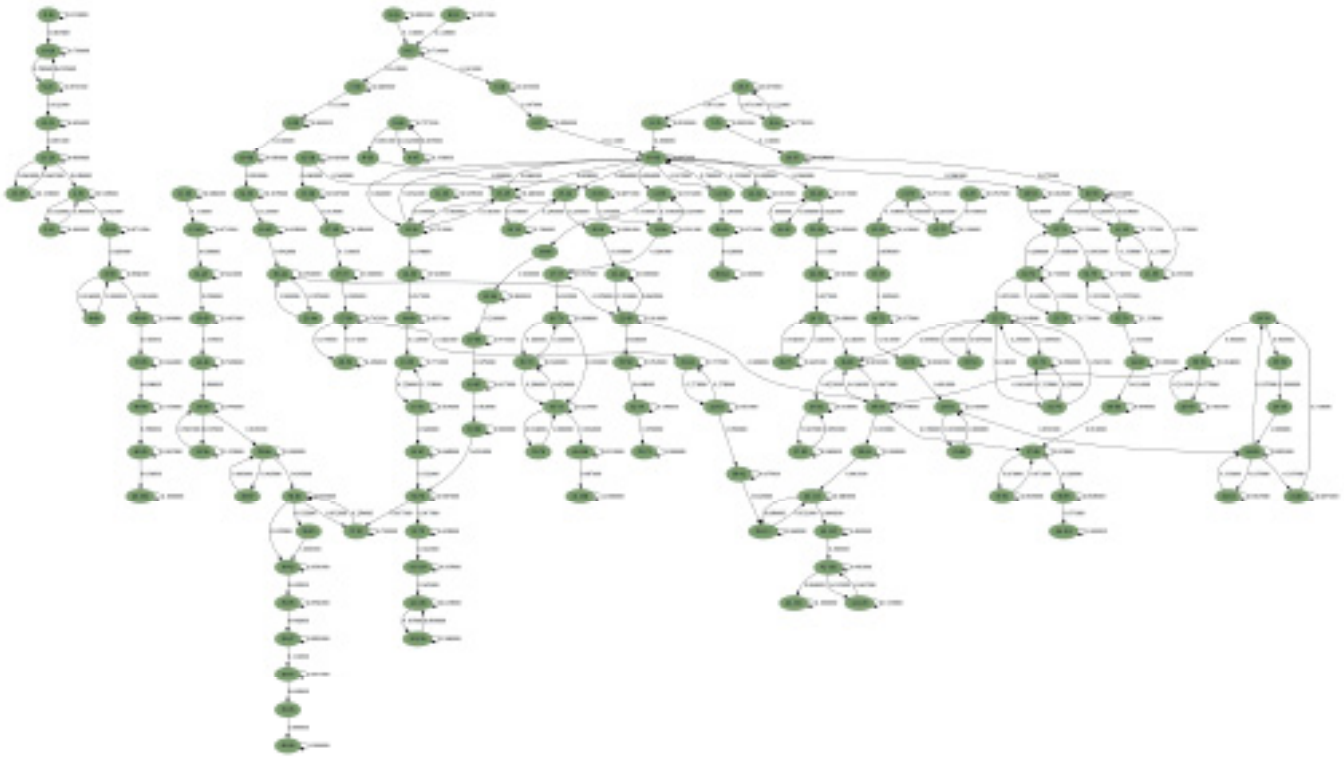
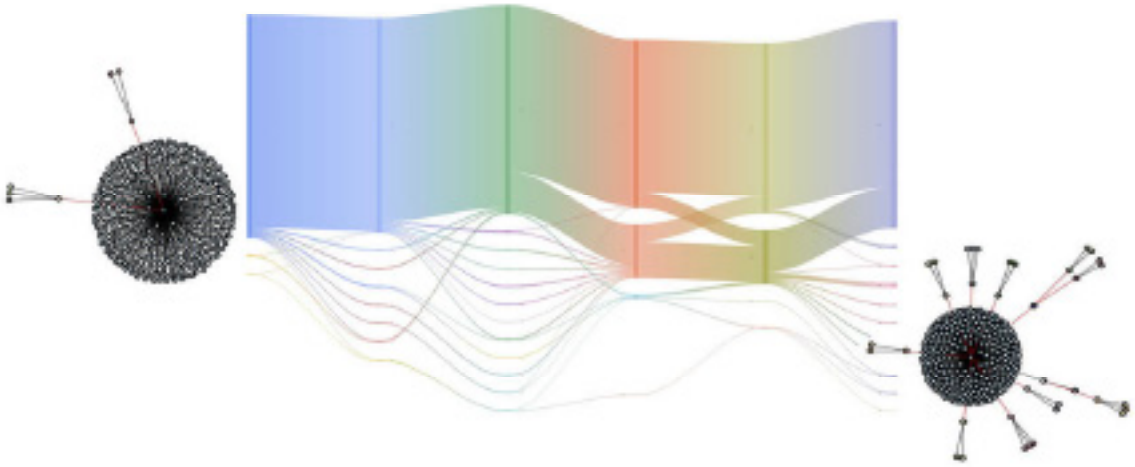


Figure 1. Markov chains network between stopover sites on Spring migration routes.

Opportunistic attachment assembles plant–pollinator networks

Lauren C. Ponisio, Marilia P. Gaiarsa & Claire Kremen

Species and interactions are being lost at alarming rates and it is imperative to understand how communities assemble if we have to prevent their collapse and restore lost interactions. Using an 8-year dataset comprising nearly 20 000 pollinator visitation records, we explore the assembly of plant–pollinator communities at native plant restoration sites in an agricultural landscape. We find that species occupy highly dynamic network positions through time, causing the assembly process to be punctuated by major network reorganisations. The most persistent pollinator species are also the most variable in their network positions, contrary to what preferential attachment – the most widely studied theory of ecological network assembly – predicts. Instead, we suggest assembly occurs via an opportunistic attachment process. Our results contribute to our under- standing of how communities assembly and how species interactions change through time while helping to inform efforts to reassemble robust communities.



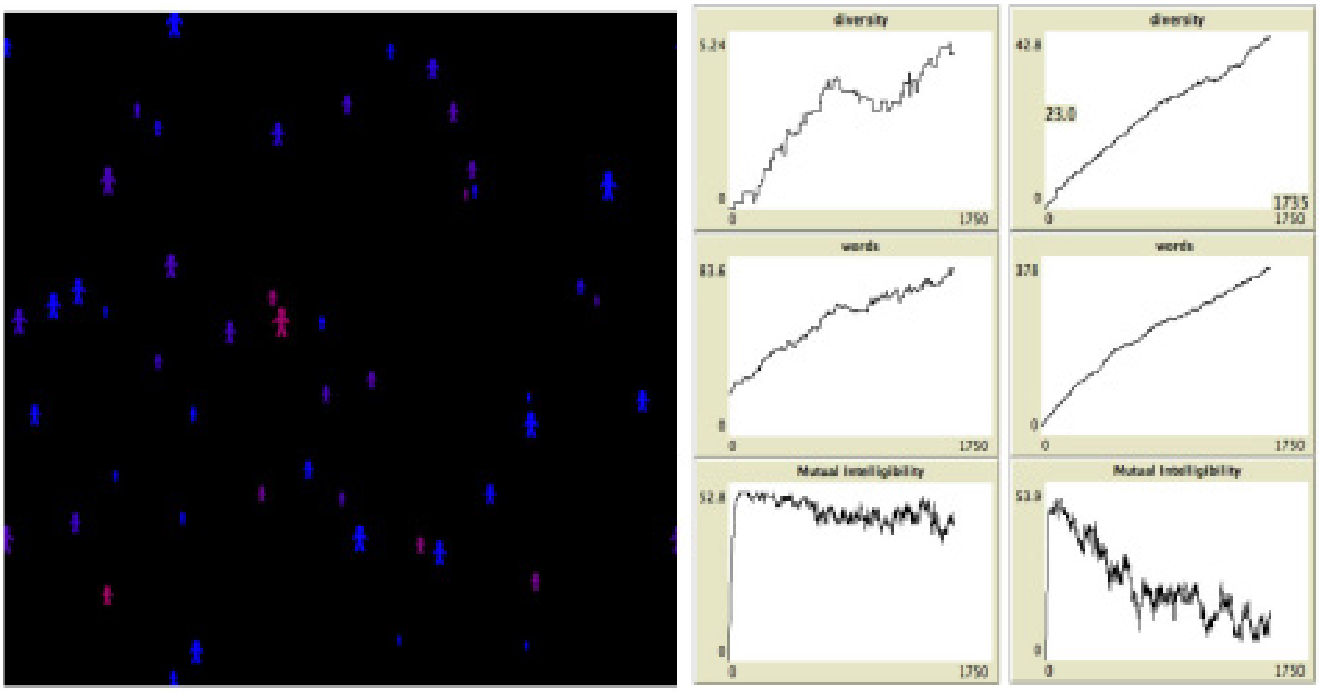
A Parsimonious Agent-Based Spatial Reconstruction of Variations in Language Usage

Juste Raimbault[1], Matteo Monini[2], Sina Tafazoli[3], Hamza Giaffar[4], Danilo Liuzzi[5], Jelena Grujic[6]

[1]Université Paris VII, Paris, France, and Ecole Nationale des Ponts et Chaussées, Champs-sur-Marne, France
[2]Ecole Normale Supérieure de Lyon, France, and University of Turion, Italy
[3]Princeton Neuroscience Institute, Princeton University, Princeton, 08540, USA
[4]Watson School of Biological Sciences, Cold Spring Harbor Laboratory, NY, 11724, USA
[5]Ca' Foscari University of Venice, Department of Management, Venice, Italy
[6]AI Lab, Vrije Universiteit Brussel, Brussels, 1050, Belgium

ABSTRACT

We have explored the evolution of stylized artificial languages using a spatial model in which agents are free to move and interact when in close proximity. Interactions consist of communication attempts, which can either succeed or fail depending on the distance between the vocabularies used by each partner. The aggregate rate of successful communications is defined as global mutual intelligibility. A unit of communication is a set of words composed by syllables. Language evolves either through inter-agent influence (an agent may adopt his partner's inflections) or random mutations. We look for unexpected, emerging properties of the system. Our findings indicate that simple rules are sufficient to generate statistically significant language communities, that the introduction of memory changes the emergent language in non-intuitive ways and that geography has a significant impact on language structure.



THE PHYSICAL WORLD WIDE WEB – Patterns in Globalization through the Free Port of Trieste, 1850-1910

Gaetano Dato[a], Tucker Ely[b], Simon Carrignon[c], Philip Pika[d], Brian Ferguson[e] Anjali Tarun[f], Rudi Mirdra[g], Ben Zhu[h].

[a]University of Trieste, Italy. [b]Arizona State University, USA. [c]Barcelona Supercomputing Center - Universitat Pompeu Fabra, Spain. [d]University of Bristol, UK. [e]US Navy, USA. [f]University of the Philippines, Philippines. [g]Truvid Financial, USA. [h]Delft University of Technology, Netherlands.

ABSTRACT

The global world order is increasingly experiencing a rise in "populism", a national trend that argues for more closed borders and an inward focus. The broader trend is often rooted in a backlash against the great era of globalization that has been expanding since the close of Cold War.

While these sentiments are often unsettling in geopolitics, and in global economics, they are not unique to the 21st century. Such public outcries formed in the era that closed the 19th century and led to the first World War. While we are unable to tell the trajectory of today's populism, in the 19th century, it came on the heals of an unprecedented era of globalization.

Led by Great Britain, the 19th century was marked by massive global trend, open borders, and a vastly increasing shipping industry. Those trends, among many others, led to a vastly complex system of shifting and growing global populations, evolving national borders, conflicts between nations, and a greater demand for goods. Even today, while historians and economists are able to point to the many hallmarks of the 19th century era of globalization, few are able to articulate how these systems were connected, how they interacted and ultimately, what the 'physical world wide web' was driven by.

In this paper, a large trove of publicly accessible data from the Port of Trieste is used as the first in a series of studies to build data on the flow of goods between ports, and how that flow reflects geopolitical changes around the world. This data is significant in that it was captured by two reliable sources: the historical leger of the Chamber of Commerce of Trieste and, Generali, a major insurance company of the 19th century.

The work aims to identify how global export and import trends display the underlying behavior that led toward "populism" in the late 19th century and ultimately, two World Wars. An information theoretic measure, Kullback-Leibler divergence, is leveraged to overlay the data of Generali's insurance legers, investments, and risk analytics to further identify the complex interplay of global trade in geopolitics.

In a first of several iterations on this research, a focus was put on using quantitative tools to extract patterns from data, in order to understand the dynamics of trade. A complementary approach is then to understand the processes at the origin of those patterns. No concrete findings are yet apparent. However, correlations in insurance data, specifically, financial risk in bond investments as a forecast for global uncertainty is one of many fascinating trends.

Next iterations will overlay more variables, especially those from human and environmental disasters that would further correlate to shipping patters on specific goods, insurance investment strategy, and ultimately how a global economy moved from radically open to an intractable geopolitical system that sparked WWI.

Quantification of Learning Effects on Fruit Fly Walking Behavior in a Bob-Dylan Box

Ruichen Sun1,4,*, Cheng Jin2,4, Kelly Finn3,4, and Ralph Greenspan1

1Kavli Institute for Brain and Mind, Division of Biological Sciences, University of California, San Diego, La Jolla, CA 92093-0126, USA

2Institute of Artificial Intelligence, College of Computer Science and Technology, Zhejiang University, Hangzhou, China, 310027

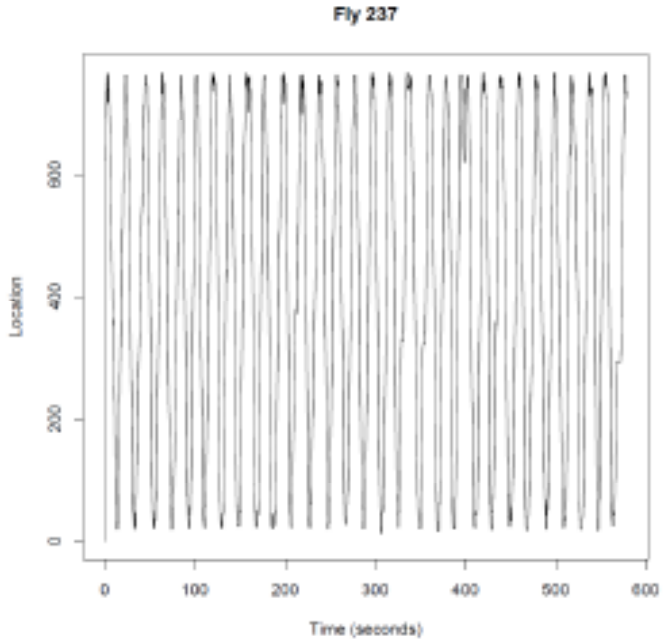
3Animal Behavior Graduate Group, University of California Davis, Davis, CA 95616, USA

4Santa Fe Institute, Santa Fe, NM 87501, USA

*Correspondence and requests for materials should be addressed to R.S. (r5sun@ucsd.edu)

ABSTRACT

Walking behavior is central to all mobile animals. However, it is still an open question as to Whether this behavior can be affected or even regulated by learning in animal models. In this paper, we addressed this question by using a fruit fly walking behavior Bob Dylan Box data se. Fruit flies have robust walking behavior in the Bob Dylan box (see figure below), and this walking behavior can be perturbed by heat stress. Using four flies as examples, we segmented the behavioral traces according the two distinct behavioral states: walking and pause, and found that after heat stress training, the initial robust walking behavior of a fly, the long and continuous walking segments separated by brief pause, changed into irregular bursty walking pattern: short walk spaced between long and short pauses. Our methods and analysis can be used for the rest of the Bob Dylan data set.



An example time series recording of a fly's robust walking behavior.

Shift in the Networks of Residential Mobility with the Economic Recession of 2008: Madrid (Spain)

Usama Bilal[1,2] (ubilal@jhmi.edu), Andrew Miller[3], Jesus Arroyo[4], Scott Armstrong[5], Catriona M. M. Stacey[6,7], Anjali Tiwari[8], Ellen D. Hodgley[9], Michael T. Schaub[10]

1: Johns Hopkins Bloomberg School of Public Health. Department of Epidemiology. Baltimore, MD, 21205, USA; 2: Universidad de Alcala. Social and Cardiovascular Epidemiology Research Group. Alcala de Henares, Madrid, 28871, Spain; 3: Department of Applied Mathematics, School of Mathematics, University of Leeds, Leeds, LS2 9JT, UK; 4: Department of Statistics, University of Michigan, Ann Arbor, 48104, USA; 5: Environmental Dynamics Lab, Geography and Environment Unit, University of Southampton, Southampton, SO17 1BJ, UK; 6: Department of Physics, University of Auckland, Auckland, 1010, New Zealand; 7: Te Pūnaha Matatini, Auckland, New Zealand; 8: University of the Philippines Diliman, Quezon City, 1101, Philippines; 9: The MITRE Corporation, Mclean, VA., USA; 10: Institute for Data, Systems, and Society, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

ABSTRACT

Mobility and movement of people is a driver for growth, development, and culture within a city. In a world where urbanization is becoming more and more important, unravelling the interplay between these topics is crucial. A proxy for such mobility are residential flows, or movement between residences. Using a novel dataset, we studied the residential mobility of the city of Madrid, Spain, over a 11-year period from 2004 to 2015, and assessed the effect of the 2008 financial crisis on residential mobility flows.

We characterized mobility flows within and in and out of the city of Madrid, stratified by age, education and country of origin. We characterized the mobility network using centrality measures and looked for communities of residential mobility. We explored the characteristics of these communities and the mobility preferences within and between them.

Residential mobility flows followed a strong temporal pattern mirroring the economic performance of the housing market: large mobility flows appear in the mid 2000s, in the midst of the economic boom, and were reduced afterwards. Nonetheless, some of the areas displayed strong mobility flows through the entire period. These areas were almost entirely developed through the 2000s and some of them even continued developing after the recession. We observed a spatial pattern in the communities of residential mobility flows. We found six groups of neighborhoods that represented areas in different stages of development and socioeconomic status. The evolution of these six communities in terms of sociodemographic and sociobehavioral characteristics diverged over time and allowed for a very detailed description of each (e.g.: one of the communities displayed clear signs of gentrification). Mobility preferences within and between communities changed widely after the economic recession, as some areas became more segregated while others mixed more.

In summary, we managed to describe a residential mobility network of an entire city finding promising patterns for future research. Of special interest are the changes that happened after the 2008 recession, where future research will be headed to.

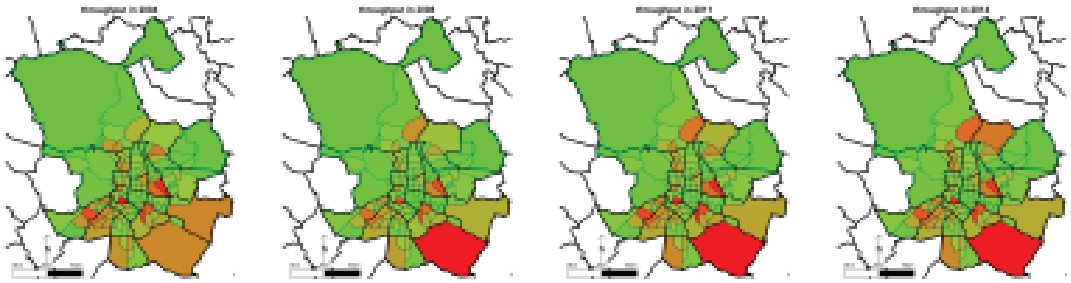


Figure 1: Residential Mobility Throughput (Degree Centrality) in Madrid (Spain) from 2004 to 2014.

A Simple Agent-Based Model of the Development of Trust In Hierarchical Organizations

Donovan Platt[1], Syed Arefinul Haque[2], Nai Seng Wong[3], William Leibzon[4], Xiongrui Xu[5], Rudi Minxha[6], and Lu Liu[7]

[1]University of the Witwatersrand, School of Computer Science and Applied Mathematics
[2]Northeastern University, Network Science Institute
[3]Monetary Authority of Singapore
[4]University of California Irvine, Institute for Mathematical Behavioral Sciences
[5]University of Electronic Science and Technology of China, ComplexX Lab, Web Science Center
[6]Trumid Financial
[7]Pennsylvania State University, College of Information Science and Technology

ABSTRACT

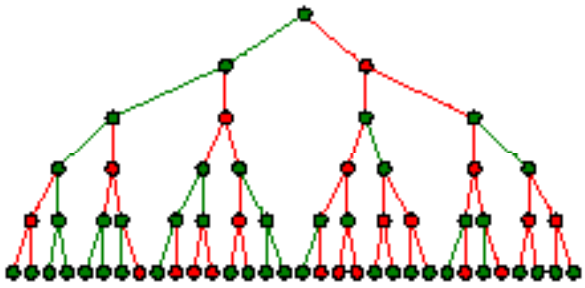
Hierarchical organizations typically rely on a chain of command in which supervisors instruct subordinates to perform certain actions in order to advance the interests and objectives of the organization. The trust between supervisors and subordinates is essential for the functioning of such hierarchical organizations, as it ensures the eventual execution of instructions. Despite this, blind trust and obedience may lead to the execution of instructions with negative consequences, which may have been avoided had a subordinate been more critical of a supervisor's instructions.

We thus aim to model the development of trust between subordinates, their supervisors and the structures of the organization itself, subject to the understanding of the consequences of instructions by subordinates and the eventual outcomes of executed instructions. This is achieved through the construction of an agent-based model involving a hierarchical network structure that is capable of replicating a number of intuitive behaviors and the use of this model to provide an indication of how trust develops over time.

As one would expect, we find that in organizations where the information accessible to members is relatively sparse, which is likely the case in many hierarchical organizations where the upper echelons of leadership have sole access to most organizational secrets, that good leadership inspires an overall higher level of relational trust within the organization than in the case of poor leadership.

Despite this, however, we demonstrate that in our hypothetical, hierarchical organization that good leadership is not a prerequisite for organizational success, provided that members of the organization are allowed to disobey orders if perceived that doing so is in the interests of the organization. We show that in such organizations, agents are capable of learning to identify who and who not to trust based on iterative adjustments of trust based on the overall outcome of specific tasks or missions, eventually resulting in a robust organization in the cases of both good or bad leadership.

In the case of highly-informed agents, we demonstrate that bad leadership may lead to greater stability, with agents tending to make decisions based on available information rather than trust, eventually relegating the leader to a symbolic role. In contrast to this, good leadership may result in the development of trust which is desirable in most cases, but may also result in the propagation of bad orders if a historically good leader unexpectedly gives a bad order, which may lead to disaster for the organization.



Urban Scaling and Economic Analysis of Materials Stocked in Japanese Cities

Lorraine Sugar[1,*], Ellen D. Badgley[2], Devrim Ikizler[3,4], and Lu Liu[5]

[1]University of Toronto, Department of Civil Engineering, Toronto, ON, Canada
[2]The MITRE Corporation, McLean, VA, USA
[3]Magee and Magee, Austin, TX, USA
[4]University of Texas at Austin, Department of Economics, Austin, TX, USA
[5]Penn State University, College of Information Science and Technology, State College, PA, USA
*lorraine.sugar@utoronto.ca

ABSTRACT

Cities are complex systems with a variety of interacting agents, resource inputs, and internal processes, all of which combine to create complex economies, cultures, and built environments. One way to explore the complexity in cities is through urban scaling analysis. Urban scaling relationships are calculated as the slope of a log-log plot between city size (i.e., population) and other indicators, such as crime rates, GDP, length of infrastructure, and household electricity consumption, for all cities in a given country or region. While urban scaling is empirically observed in countries around the world, there is also a theoretical foundation for the phenomenon rooted in the understanding that cities are networks of social interactions (see Bettencourt 2013).

This research addresses a gap in the existing urban scaling literature by focusing on the mass of cities; that is, the weight of concrete, wood, asphalt, and other materials that make up the physical form of the city. These are called *stocked materials*. The analysis used a database developed by Fishman et al. (2014) with the mass of materials stocked in buildings and infrastructure for all of Japan (see Figure 1). In addition to an urban scaling analysis, the research included an economic analysis of the underlying mechanisms influencing the generation of stocked materials.

Results showed a linear scaling relationship between mass stocked in buildings and urban area population, as well as a sublinear scaling relationships between mass stocked in roads, urban area population, and land area. The geographic definition of city was important as well: Metropolitan Employment Area (MEAs) showed the strongest scaling relationship. The non-parametric kernel estimations revealed four potentially influencing factors: inhabitable density, total per-capita production, size of the real estate industry, and share of agriculture, forestry, and fisheries in production.

The sublinear scaling of road mass was expected, as this aligns with previous observations of the sublinear scaling of road length and other physical infrastructure quantities. However, the observed linear scaling relationship of building mass was a surprise. Presumably, building mass would include housing (linear), as well as commercial and industrial properties (superlinear). To look into this result further, the researchers tested the scaling relationship between population and total production (as a proxy for GDP). This socioeconomic variable was found to be linear–not superlinear as predicted by theory. This indicates that there may be forces at work in the Japanese city system that result in scaling relationships that diverge from the American and European city systems. In the case of buildings, one such force may be the Japanese tradition to demolish and construct new buildings upon ownership change.

Figure 1. Spatial distribution of a) material stocked in buildings for 2009, b) material stocked in roads in 2010, and c) population. Generated from data from Fishman et al. (2014) and Tatem et al. (2015).