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University of California - Davis Sponsored Programs 1850 Research Park Drive, Suite 300 Davis, CA 95618 -6153	
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13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Raissa D'Souza
UU	UU	UU	UU		19b. TELEPHONE NUMBER 530-754-8405

RPPR Final Report
as of 13-Mar-2020

Agency Code:

Proposal Number: 70694EGDRP

Agreement Number: W911NF-17-1-0077

INVESTIGATOR(S):

Name: Raissa M. D'Souza
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Principal: Y

Organization: **University of California - Davis**
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Country: USA

DUNS Number: 047120084

EIN: 946036494

Report Date: 04-Feb-2019

Date Received: 21-Feb-2020

Final Report for Period Beginning 05-Jan-2017 and Ending 04-Jan-2019

Title: Principles of self-organization for resilience and control

Begin Performance Period: 05-Jan-2017

End Performance Period: 04-Jan-2019

Report Term: 0-Other

Submitted By: Raissa D'Souza

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3

STEM Participants: 4

Major Goals: Complex collectives display a myriad of emergent behaviors like tipping points, cascading failures, adaptation and resilience. It is increasingly important to understand these behaviors as modern systems are built on a collection of self-organizing systems at different scales, integrating socio-technical, cyber-physical, and eco-social considerations. The overarching goal of this project is to understand underlying principles and mechanisms of self-organization and then use this knowledge for prediction, early detection, and control of complex collectives. We study three guiding principles of self-organization: (i) emergent hierarchies, (ii) consequences of mutualistic interactions (involving bipartite cooperative and competitive interactions), and (iii) self-organized cascading failures.

Accomplishments: See attached PDF.

Training Opportunities: - This grant serves as first opportunity for Co-PI Marton Posfai to secure an extramural research award, providing a significant milestone towards securing a future faculty job.

- Co-PI Marton Posfai successfully completes his Postdoctoral training at UC Davis and secures a tenure track faculty position as Assistant Professor of Network and Data Science, at Central European University.

- Postdoctoral Scholar Keith Burghardt successfully completes his training at UC Davis and secures a position as a permanent Research Scientist at the Information Sciences Institute, University of Southern California, in Marina del Rey.

- Postdoctoral Scholar Martin Rohden completes his training at UC Davis and secures a position as a research scientist at the University of Leiden.

- Postdoctoral Scholar Weiran Cai, continues his training at UC Davis but has secured a position as Full Professor at Soochow University in China to commence 2020.

- PhD candidate Jordan Snyder completes dissertation and secures position as a postdoctoral scholar in Applied Mathematics at the University of Washington.

- PhD candidate Jordan Snyder attends the Santa Fe Institute Complex Systems Summer School (CSSS 2018), Santa Fe, NM, June 10-July 6, 2018.

- PhD candidate Jordan Snyder summer internship in Center for Nonlinear Studies, Los Alamos National Lab, June-Sept 2017, and July-Sept 2018.

- PI D'Souza involves undergraduate student Grayson Gordon in this research and he gains valuable skills in research, data analysis and programming.

- PI D'Souza and co-PI Pósfai supervise PhD candidate Yuansheng Lin through Jan 2018, who is visiting from Beihang University Beijing, China with support from China Scholarships Council. He worked on models of self-organized criticality and dragon kings.

- PhD candidate Yuansheng Lin (visiting from Beihang University Beijing, China), successfully defends PhD thesis in Systems Engineering in Jan 2018.

- PI D'Souza and co-PI Pósfai supervised graduate student Niklas Braun (Mechanical engineering, UC Davis), who worked on data analysis of macaque societies, providing experimental data to corroborate theoretical findings the FUNCC project.

- MS candidate Niklas Braun completes degree and secures position in industry.

- co-PI Posfai receives valuable postdoctoral training, including many invited talks, with research visit to FunCC collaborator Paul Bogdan at USC. Additionally, Marton presented his work at the seminar series at Viterbi School of Engineering.

Results Dissemination: Invited talks:

1) Raissa D'Souza, Seminar, Center for Complex Systems, University of Sydney, April 2, 2017.

2) Raissa D'Souza, Invited speaker, 2017 SIAM Conference on Dynamical Systems, mini-symposium Explosive Transitions in the Structure and in the Dynamics of Complex Networks, May 22, 2017.

3) Raissa D'Souza, Lecturer, NetSci 2017 International School, NetSci 2017, June 20, 2017.

4) Raissa D'Souza, Invited speaker, Symposium of Controlling Complex Networks, NetSci 2017, June 19, 2017.

5) Raissa D’Souza, Keynote speaker, Conference on Complex Systems 2017, Cancun Mexico, Sept 19, 2017.

6) Raissa D’Souza, Keynote speaker, NetSci X 2018, Hangzhou China, Jan 5-8, 2018.

7) Raissa D’Souza, Invited talk at American Physical Society March meeting, March 8, 2018.

8) Raissa D’Souza, Keynote talk at NetONets 2018, satellite workshop of NetSci 2018, Paris France, June 12, 2018.

9) Raissa D’Souza, Keynote at SIAM Network Science 2018 conference, Portland Oregon, July 12, 2018.

10) Raissa D’Souza, Keynote speaker, NetSci X 2019, Jan 3-5, Santiago, Chile.

11) M. Posfai, Central European University, Budapest, Hungary, May 4, 2017.

12) M. Posfai, Dynamics on and of Complex Networks, Satellite of NetSci 2017, June 19, 2017.

13) M. Posfai, Invited talk at Wuhan University, Wuhan, China, October 23, 2017.

14) M. Posfai, Invited talk at Hunan University of Commerce, Changsha, China, October 28, 2017.

15) M. Posfai. Invited talk at Southwest University, Chongqing, China, October 30, 2017.

16) M. Rohden, “The Self-Organization of Dragon Kings”, Potsdam Institute for Climate Impact Research, Aug 28, 2018.

Contributed talks:

17) Raissa D’Souza, DARPA Complex Collectives meeting, Nov 14, 2018

18) Raissa D’Souza, Army Research Lab NS-CTA talk at U. Delaware, April 25, 2018.

19) M. Posfai, Dynamics Days Europe 2017, Hungary, June 6, 2017.

20) M. Posfai, NetSci 2017, Indianapolis, June 23, 2017.

21) M. Posfai. Talent and experience shape competitive hierarchies. UC Davis Postdoctoral Research Symposium, Davis, CA, April 23, 2018.

22) M. Posfai. DARPA Fundamentals of Complex Collectives Meeting, June 20, 2018.

23) K. Burghardt, "Cooperation Network Responses to Shocks", Conference: Conference on Complex Systems, Cancun, Mexico, Sept. 17–22, 2017.

24) K. Burghardt, "Self-Organization of Dragon Kings", Postdoctoral Research Symposium, UC Davis, October 5, 2017.

25) K. Burghardt, "Cooperative Network Responses to Shocks", Annual International Conference on Computational Social Science (IC2S2), Northwestern University (Chicago, IL), July 12–15, 2018

26) K. Burghardt, "Self-Organization of Dragon Kings", SIAM Workshop on Network Science, Portland, OR, July 12–13, 2018.

Poster presentations:

27) Cai, Snyder, Hastings, and D'Souza, SIAM Network Science Workshop, Portland, July 12-13, 2018.

28) Snyder, Cai, and D'Souza, SIAM Student Conference, UC Merced, Apr. 27, 2018.

29) K. Burghardt, Twelfth International AAAI Conference on Web and Social Media (ICWSM 2018), Stanford University, June 25–28, 2018.

Conference organization:

1) NetSciX 2018, Hangzhou China, Jan 5-8, 2018.

2) NetSci 2018, Paris France, June 11-15, 2018.

Additional outreach:

- During the duration of this grant, D'Souza was President of the Network Science Society and oversaw all the NetSci conferences and developed the outreach plan for the society, including k-12 education. During this reporting period she oversaw NetSciX 2018 in Hangzhou China (with 600 registered participants and over 4000 viewers of the "wechat" live stream), and NetSci 2018 in Paris France (with over 800 registered participants). She also solicited bids and led the committee to approve NetSci X 2019 (in Santiago Chile) and NetSci 2019 (in Burlington Vermont) and oversees all the current planning. She is currently leading the Society's efforts to lobby NSF to build a research program on Network Science.

- D'Souza joined the Scientific Board of Quanta Magazine (published by the Simons Foundation) to help disseminate results on collective phenomena, mathematics and physics to the general public.

Honors and Awards: - Raissa D’Souza awarded the 2017 UC Davis College of Engineering, Outstanding mid-career faculty research award, Oct 2017.

- D'Souza and collaborators awarded the Test of Time Award at The ACM Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering 2018 (FSE/ICSE 2018) for paper with most lasting impact from FSE/ICSE 2008.

- Postdoctoral scholar Keith Burghardt receives SIAM Travel Award to attend the Network Science 2018 meeting.

- Postdoctoral scholar Keith Burghardt received Honorable Mention for the UC Davis Award for Excellence in Postdoctoral Research, May 2018.

- Postdoctoral scholar Keith Burghardt receives Travel Scholarship to attend the 4th Annual International Conference on Computational Social Science (IC2S2).

- Postdoctoral scholar Marton Posfai receives the UC Davis Award for Excellence in Postdoctoral Research, May 2019.

Protocol Activity Status:

Technology Transfer: - D'Souza leads the ongoing efforts of the Network Science Society to encourage the NSF to build a research program on network science and complex collectives.

- D'Souza continues ongoing collaboration with Dr. Anathram Swami at the Army Research Lab, ARC, Adelphi Maryland.

- PhD candidate Jordan Snyder summer internship in Center for Nonlinear Studies, Los Alamos National Lab, June-Sept 2017, and July-Sept 2018.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Raissa M D'Souza
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Marton Posfai
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Niklas Braun
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Yuansheng Lin
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Jordan Snyder
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Grayson Gordon
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Keith Burghardt
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Martin Rohden
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Weiran Cai
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.98.022127
Volume: 98 Issue: 2 First Page #: 022127
Date Submitted: 8/28/18 12:00AM Date Published: 8/27/18 2:00PM
Publication Location:
Article Title: The self-organization of dragon king failures
Authors: Yuansheng Lin, Keith Burghardt, Martin Rohden, Pierre-Andre Noel, Raissa M. D'Souza
Keywords: self-organized criticality; cascading failures; dragon kings
Abstract: Outliers involving mechanisms absent in smaller events, known as Dragon Kings, are seen in many complex systems. In this Letter, we develop two closely-related stylized models where nodes in a network self-organize to be either "weak" or "strong" in the face of failure. Although the first variant (based on simple contagion spreading and inoculation) exhibits relatively traditional self-organized criticality, the second one (based on both simple and complex contagion spreading) creates self-organized Dragon Kings that are highly sensitive to initial failures: a failure in a small portion of the network can consistently lead to global cascading failures. We pinpoint the mechanistic origin of these Dragon Kings, which allows us to predict their onset with high accuracy, by mapping the probability of an initial cascade to a generalized birthday problem. We then demonstrate a simple control strategy that can decrease the frequency of Dragon Kings by orders of magnitude.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.96.012317
Volume: 96 Issue: 1 First Page #: 012317
Date Submitted: 8/31/17 12:00AM Date Published: 7/1/17 2:00PM
Publication Location:
Article Title: Explosive percolation on directed networks due to monotonic flow of activity
Authors: Alex Waagen, Raissa M. D'Souza, Tsai-Ching Lu
Keywords: Collective behavior; Social networks; Directed networks; Phase transition
Abstract: An important class of real-world networks has directed edges, and in addition, some rank ordering on the nodes, for instance the popularity of users in online social networks. Yet, nearly all research related to explosive percolation has been restricted to undirected networks. Furthermore, information on such rank-ordered networks typically flows from higher-ranked to lower-ranked individuals, such as follower relations, replies, and retweets on Twitter. Here we introduce a simple percolation process on an ordered, directed network where edges are added monotonically with respect to the rank ordering. We show with a numerical approach that the emergence of a dominant strongly connected component appears to be discontinuous. Large-scale connectivity occurs at very high density compared with most percolation processes, and this holds not just for the strongly connected component structure but for the weakly connected component structure as well.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.98.020302
Volume: 98 Issue: 2 First Page #:
Date Submitted: 8/28/18 12:00AM Date Published: 8/1/18 7:00AM
Publication Location:
Article Title: Talent and experience shape competitive social hierarchies
Authors: Márton Pósfai, Raissa M. D'Souza
Keywords: Emergent hierarchies; social physics
Abstract: Experimental evidence shows that both intrinsic abilities of individuals and social reinforcement processes impact emergent social hierarchies; existing mathematical models, however, focus on the latter. Here, we develop a rigorous model that incorporates both features. For pairwise interactions, we show that there is a trade-off between relationship stability and having the most talented individuals in the highest ranks. Extending this to open societies, where individuals enter and leave the population, we show that important societal effects arise from the interaction between talent and social processes: (i) despite positive global correlation between talent and rank, paradoxically, local correlation is negative, and (ii) the removal of an individual can induce a series of rank reversals.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Science
Publication Identifier Type: DOI Publication Identifier: 10.1126/science.aaq0474
Volume: 358 Issue: 6365 First Page #: 860
Date Submitted: 8/28/18 12:00AM Date Published: 11/1/17 7:00AM
Publication Location:
Article Title: Curtailing cascading failures
Authors: Raissa M. D'Souza
Keywords: Cascading failures, power grids
Abstract: Cascading behaviors are ubiquitous, from power-grid failures to “flash crashes” in financial markets to the spread of political movements such as the “Arab Spring”. The causes of these cascades are varied with many unknowns, which make them extremely difficult to predict or contain. Particularly challenging are cascading failures that arise from the reorganization of flows on a network, such as in electric power grids, supply chains, and transportation networks. Here, the network edges (or “links”) have some fixed capacity, and we see that some small disturbances easily dampen out, but other seemingly similar ones lead to massive failures. On page 886 of this issue, Yang et al. establish that a small “vulnerable set” of components in the power grid is implicated in large-scale outages. Although the exact elements in this set vary with operating conditions, they reveal intriguing correlations with network structure.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.99.032308
Volume: 99 Issue: 3 First Page #: 032308
Date Submitted: 2/18/20 12:00AM Date Published: 3/1/19 8:00AM
Publication Location:
Article Title: Cascading failures in scale-free interdependent networks
Authors: Malgorzata Turalska, Keith Burghardt, Martin Rohden, Ananthram Swami, Raissa M. D'Souza
Keywords: Self organized cascades, network architecture for resilience
Abstract: Large cascades are a common occurrence in many natural and engineered complex systems. In this paper we explore the propagation of cascades across networks using realistic network topologies, such as heterogeneous degree distributions, as well as intra- and interlayer degree correlations. We find that three properties, scale-free degree distribution, internal network assortativity, and cross-network hub-to-hub connections, are all necessary components to significantly reduce the size of large cascades in the Bak-Tang-Wiesenfeld sandpile model. We demonstrate that correlations present in the structure of the multilayer network influence the dynamical cascading process and can prevent failures from spreading across connected layers. These findings highlight the importance of internal and cross-network topology in optimizing robustness of interconnected systems.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: DOI Publication Identifier: 10.1088/1367-2630/ab14b3
Volume: 21 Issue: 5 First Page #: 055001
Date Submitted: 2/18/20 12:00AM Date Published: 5/1/19 7:00AM
Publication Location:
Article Title: Consensus ranking for multi-objective interventions in multiplex networks
Authors: Márton Pósfai, Niklas Braun, Brianne A Beisner, Brenda McCowan, Raissa M D’Souza
Keywords: multi-objective network interventions, multiplex networks
Abstract: High-centrality nodes have disproportionate influence on the behavior of a network; therefore controlling such nodes can efficiently steer the system to a desired state. Existing multiplex centrality measures typically rank nodes assuming the layers are qualitatively similar. Many real systems, however, are comprised of networks heterogeneous in nature, for example, social networks may have both agnostic and affiliative layers. Here, we use rank aggregation methods to identify intervention targets in multiplex networks when the structure, the dynamics, and our intervention goals are qualitatively different for each layer. For any multi-objective intervention, optimal targets only exist in the Pareto- sense; we, therefore, use a weighted generalization of consensus ranking to investigate the trade-off between the competing objectives. We use a collection of model and real networks to systematically investigate how this trade-off is affected by multiplex network structure.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-019-48036-0
Volume: 9 Issue: 1 First Page #:
Date Submitted: 2/18/20 12:00AM Date Published: 8/1/19 7:00AM
Publication Location:
Article Title: Competitive percolation strategies for network recovery
Authors: Andrew M. Smith, Márton Pósfai, Martin Rohden, Andrés D. González, Leonardo Dueñas-Osorio, Raiss
Keywords: Optimal network recovery, explosive percolation, critical infrastructure
Abstract: Restoring operation of critical infrastructure systems after catastrophic events is an important issue, inspiring work in multiple elds, including network science, civil engineering, and operations research. We consider the problem of nding the optimal order of repairing elements in power grids and similar infrastructure. Most existing methods either only consider system network structure, potentially ignoring important features, or incorporate component level details leading to complex optimization problems with limited scalability. We aim to narrow the gap between the two approaches. Analyzing realistic recovery strategies, we identify over- and undersupply penalties of commodities as primary contributions to reconstruction cost, and we demonstrate traditional network science methods, which maximize the largest connected component, are cost ine cient. We propose a novel competitive percolation recovery model accounting for node demand and supply, and network structure.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: Nature Communications
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 2/18/20 12:00AM Date Published:
Publication Location:
Article Title: Evolution of Mutualistic Networks from Adaptive Niche Interactions
Authors: Weiran Cai, Jordan Snyder, Alan Hastings, Raissa M. D’Souza
Keywords: mutualistic networks, network stability, cascading failures
Abstract: Mutualistic networks are vital ecological and social systems shaped by evolution. They involve bipartite cooperation such as the exchange of goods or services across different types of actors. The relationships seen in empirical mutualistic networks across genres and geographical factors exhibit simultaneously nested and modular patterns. Yet, the underlying evolutionary mechanisms leading to these structural patterns remain unclear. We propose here a unified mechanism for the evolution of mutualistic networks based on niche interactions, where both nestedness and modularity emerge simultaneously. The patterns demonstrate complementary facets of an optimal niche structure. Due to the dynamical systems formulation of our model we can analyze its stability properties. We reveal foremost the bidirectional role of mutualism on the stability of the evolved network. The adaptive nature of niche relations underlies a broad class of interactions that engage in bipartite cooperation.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted
Journal: Physical Review Research
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 2/18/20 12:00AM Date Published:
Publication Location:
Article Title: Degree-targeted cascades in modular, degree-heterogeneous networks
Authors: Jordan Snyder, Weiran Cai, Raissa M. D'Souza
Keywords: Activation cascades, modular networks, network resilience
Abstract: Many large scale phenomena, such as rapid changes in public opinion and the outbreak of disease epidemics, can be fruitfully modeled as cascades of activation on networks. This provides under- standing of how various connectivity patterns among agents can influence the eventual extent of a cascade. We consider cascading dynamics on modular, degree-heterogeneous networks, as such features are observed in many real-world networks, and consider specifically the impact of the seeding strategy. We derive an analytic set of equations for the system using a reduced description that lets us accurately capture different seeding strategies using only one dynamical variable per module. We establish that highest-degree seeding can cause a global cascade in a regime where random seeding would cause only tiny events. Yet, degree-targeted seeding does not facilitate the spread of a cascade to other modules.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
Journal: IEEE Transactions on Network Science and Engineering
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 2/18/20 12:00AM Date Published:
Publication Location:
Article Title: Control Complexity: Diversity of structural controllability of complex networks with given degree sequence
Authors: Abdorasoul Ghasemi, Marton Posfai, Raissa M. D'Souza
Keywords: network control, structural controllability, complex networks
Abstract: The necessary number of external signals or driver nodes needed to control a complex network has emerged as an important measure of controllability. Here, we investigate how the degree sequence of directed networks constrains the number of driver nodes. We develop a pair of algorithms along with an upper bound for the maximum and a lower bound for the minimum number of driver nodes, and we show that the algorithms always find realizations such that we reach these bounds for all real and model networks. Exploiting these algorithms, we introduce the notion of control complexity to quantify how hard it is to control a network given its degree sequence, capturing the richness of its structure beyond its degree distribution. We find that the minimum number of drivers is determined by number of sources or sinks in the network, while the maximum number of drivers is strongly affected by the presence of hubs.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 4-Under Review
Conference Name: CSCW 2020
Date Received: 20-Feb-2020 Conference Date: 17-Oct-2020 Date Published:
Conference Location: Minneapolis, MN,
Paper Title: Mitigating Algorithmic Instabilities in Crowdsourced Ranking
Authors: KEITH BURGHARDT, TAD HOGG, RAISSA M. D'SOUZA, KRISTINA LERMAN, MA?RTON PO?SFAI
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: UC Davis
Date Received: 18-Feb-2020 Completion Date: 1/2/19 7:21PM
Title: Rank Aggregation Methods For Consensus Ranking in Multilayer Networks
Authors: Niklas Braun
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: UC Davis
Date Received: 18-Feb-2020 Completion Date: 6/14/19 8:09PM
Title: Collective Behavior in Dynamics on Networks
Authors: Jordan Snyder
Acknowledged Federal Support: **N**

Accomplishments

I. Overview:

Complex collectives display a range of emergent behaviors like tipping points, cascading failures, adaptation and resilience. Our goal in this project was to develop guiding principles underpinning self-organization in complex collectives and use this knowledge for prediction, early detection, and control of complex collectives. The three pillars of our focus are (i) emergence and stability of hierarchies, (ii) consequences of mutualistic interactions, and (iii) self-organized cascading failures.

Key theoretical breakthroughs:

(i) With respect to emergent hierarchies we developed a first-principles theoretical model which reveals how the tension between innate talent and social learning can lead to cascading instabilities of rank rearrangements in social systems [1]. We also developed multi-layer ranking techniques to accomplish multiple-objective node removal interventions, which were tested both on theoretical and real-world networks [2]. Finally we developed an experiment run on Amazon's Mechanical Turk to test empirically the interplay of innate talent and social learning to uncover and overcome biases in crowd-sourced rankings [3].

(ii) A prototypical class of complex systems is based upon the principled of mutualistic interactions. Here entities of two different types have beneficial cross-type interactions but competitive interactions with other entities of the same type. Such types of systems are observed across domains from ecology to socio-technical partnerships. We develop a first-principles model that allows us to model how the optimization of mutualistic partnerships leads to the emergence of the key features observed in empirical data on their interaction networks, namely modularity and nestedness [4]. The analytic framework allows us to perform stability calculations in attempt to uncover maximally destabilizing interventions. From an empirical perspective, using a large database of networks of terrorist groups and nation states that support these groups, we show that terrorist networks and their state supporters show the signatures of nestedness and how we might potentially disrupt subversive self-organized social groups [5].

(iii) Self-organized cascades (SOC) of failure abound in the interconnected, global systems key to modern society. In particular balancing the tensions of optimizing multiple objectives can drive systems to the "critical point" where the sizes of observed failure cascades follow a power-law distribution. One disturbing consequence is that this predicts the eventual occurrence of a failure of unbounded size. We first develop a theoretical model that captures degradation and hardening in engineered networks, and show this leads to SOC failures and eventually to a second mechanism of Dragon King (DK) failures where the entire system is destroyed [6]. We show that the latter failures result from a novel self-amplifying mechanism that kicks in once a critical fraction of the initial network is destroyed and use knowledge of that mechanism to predict the onset of a DK and to develop small control interventions to prevent them. Finally, we focus on the classic "sandpile" model of SOC and show that optimal architectures to suppress cascades exist in interconnected networks [7]. Finally we have developed ideas for establishing a comprehensive theory of cascades as briefly discussed in [8].

Publications and training: The funds from this grant contributed to the publication of 10 peer-reviewed journal publications, 3 which are currently under review and one conference publication currently under review, and in addition, one PhD and one MS thesis. Some of the publications have been cited substantially, including a publication in *Science* (impact factor 41), and in *Advances in Physics* (impact factor 26). Significant training opportunities were also supported, in particular for postdoctoral scholars, primarily Marton Posfai, but also 3 others, who have all secured outstanding tenure-track or permanent positions. Moreover, Posfai went on to win the UC Davis Award for Excellence in Postdoctoral Research in 2019. A second postdoc supported in small part by this grant, Keith Burghardt, received Honorable Mention for this award in 2018.

Dissemination: The research results were widely disseminated with team members overall giving 16 invited talks (many of these keynote talks), 10 contributed talks, and three poster presentations at conferences. In addition, the PI oversaw the organization of two major international conferences in network science, NetSciX 2018 and NetSci 2018, where some of the results obtained were featured.

Honors: In addition to the postdoctoral awards mentioned above, during this grant period the PI was awarded the 2017 UC Davis College of Engineering, outstanding mid-career faculty research award, and the Test of Time Award at the FSE/ICSE 2018 conference for paper with most lasting impact from FSE/ICSE 2008. Postdoctoral scholars received travel awards and invitations to give talks at several international venues.

Details of the key breakthroughs and additional associated research results are now presented.

II. Emergent hierarchies

Self-organized, emergent hierarchical organization is a common feature of many complex systems, particularly human and animal societies. It has a profound effect on resource allocation, collective decisions, and social stability. Experimental evidence shows that both intrinsic abilities -- such as strength or talent -- and social reinforcement processes both play a crucial role in the emergence and maintenance of hierarchy. Yet, analytic studies have focused on the role of social reinforcement.

II.A. Theoretical first principles, Ref [1]:

We developed a model to incorporate these two important sources of complexity: heterogeneous talent distribution and social interactions. We modeled open societies, where individuals enter and leave the population, and we showed that important societal effects arise from the interaction between talent and social processes: (i) Despite a positive global correlation between talent and rank, paradoxically, local correlation is negative. (ii) Experimental studies involving primates show that the removal of an individual may cause a series of rank reversals and social upheaval. We show that in our model the removal of an individual can only induce further changes in the hierarchy if the effect of social reinforcement and talent differences are on the same scale. We analytically solved the model using exact combinatorics, continuous time-approximations, and scaling arguments. We found a lower bound for the local anti-correlation of rank and talent and an upper bound for the probability that the removal of an individual induces additional rank reversals in the hierarchy. Remarkably, these bounds are universal in the sense that they do not depend on the shape of the talent distribution, furthermore, the bounds are reached with increasing population size. The manuscript detailing our results was recently published as a Rapid Communication in Physical Review E [1]. (Note, as stated on the journal website, "Physical Review E Rapid Communications are devoted to the accelerated publication of especially important new results.")

II.B. Mechanical Turk online experiment, Ref [3]:

The above model makes a series of predictions involving the relation of talent and rank in emergent hierarchies. Some of these predictions, such as the local anti-correlation between rank and talent, are challenging to verify experimentally, since they require exact identification and measurement of talent. To overcome this difficulty, we have set up an online experiment using Mechanical Turk with our collaborators at USC. In the experiment, we study rankings of answers based on their popularity. We pose questions that have exact numerical answers, and we ask online participants to pick the best answer out of a list of candidates. Positive reinforcement of ranks is provided by displaying the popularity of answers, and the "talent" of the answers is their distance from the correct value. Manipulating the displayed popularity and choosing the candidate answers provides full control over all parameters, allowing us to quantitatively study the dynamics of hierarchy formation. We show how the insights gained allow us to mitigate algorithmic instabilities in crowd-sourced rankings [3].

II.C. Multilayer network interventions, Ref [2]:

Many real systems can be represented as multi-layer networks, in particular we often are concerned with the same set of individuals who can have many different type of interactions, both affiliative and agonistic, and we use a distinct network layer to represents each distinct type of relationship. We use rank aggregation methods to identify intervention targets in multiplex networks when the structure, the dynamics, and our intervention goals are qualitatively different for each layer. Our approach is to rank the nodes separately in each layer considering their different function and desired outcome, and then we use Borda count or Kemeny aggregation to identify a consensus ranking—top nodes in the consensus ranking are expected to effectively balance the competing goals simultaneously among all layers. To demonstrate the effectiveness of consensus ranking, we apply our method to a degree-based node removal procedure such that we aim to destroy the largest component in some layers, while maintaining large-scale connectivity in others. For any multi-objective intervention, optimal targets only exist in the Pareto- sense; we, therefore, use a weighted generalization of consensus ranking to investigate the trade-off between the competing objectives. We use a collection of model and real networks to systematically investigate how this trade-off is affected by multiplex network structure. In particular we find social networks have a structure optimized to allow node-removal interventions that simultaneously preserve connectivity in affiliative layers and destroy connectivity in agonistic layers [2].

III. Emergent mutualistic structures and network resilience

Mutualistic interactions are vital drivers of the organization and collective phenomena in complex systems. In mutualistic networks, two different types of agents interact, such as plants and pollinators, and the interactions between agents of the same type are competitive, while interactions with agents of the different type are cooperative. Such mutualistic systems are seen pervasively in ecological and socio-economic systems. They are known to have characteristic architectures of nested and modular interaction networks. Yet significantly less understood are their dynamical properties, including stability and resilience. Uncovering the principles of the emergence of mutualistic networks will allow us to identify small interventions to maximally disrupt or enhance the network's function.

III.A. First-principles models for the emergence of mutualism, Ref [4]:

Empirical studies have found that the reciprocal relations among the participating partner species often have the salient features of simultaneously having nested and modular architecture. However the mechanisms that give rise to these features simultaneously are not known. Most proposed mechanisms consider only the cause of nestedness while the origin of modularity is much less explored. We propose a dynamic model based on the adaptation of niche relations that gives rise to both structural features. We apply Hutchinson's conception of niche space to topologically linked species and quantify the interaction intensities by niche overlaps. Modularity and nestedness emerge concurrently as a manifestation of the niche affinity and demographic heterogeneity of species.

Key dynamical properties are revealed by our unified model. Strikingly, we find that whether an evolved mutualistic network is more or less stable than its random counterpart is primarily determined by the level of competition, rather than by the intensity of mutualistic interactions. At a larger time scale, a profound history-dependency of the network structure is shown through hysteretic response to environmental changes, meaning that suboptimal structures can be frozen into systems due to environmental change even if the environmental conditions are restored. Our framework extends Hutchinson's conception from the continuous niche space to the niche network, which capture a broader class of ecological relations and also socio-economic networks that engage in bipartite cooperation [4].

III.B. Disrupting subversive self-organized social groups, Ref [5]:

Along with our theoretical studies, we have pursed data on mutualism in DoD relevant real systems. We have uncovered the key signatures of mutualism (nestedness and modularity) in networks formed by the partnerships between terrorist groups and the nation states that support them. This network consists of intentional support and de-facto support that are analogous to ecological mutualism and parasitism. We used a powerful time-evolving modularity detection algorithm to establish the clear existence of modular structure in these networks. We are now in position to understand how these modules of terrorist organizations are born and die out, and how they merge and split over a broad range of historical contexts. More than that, by characterizing the roles of nodes or relations, we will develop strategies for small interventions with large impact on disrupting network connectivity or stability. We are using the understanding gained from the theoretical model to predict which nodes and relations will be crucial for achieving this [5].

IV. Self-organized criticality

Finding an operating condition that balances the tradeoffs between competitive objectives often leads a system to self-organize into a precarious equilibrium called a critical point, where the likelihood of large failure sizes follows a power law distribution. Classic models from statistical physics, such as the sandpile model, provide a theoretical underpinning, yet describe only the most general features. A comprehensive theory of self-organizing cascades, that captures more realistic and fine-grained features, is needed.

IV.A. Self-organizing Dragon King failures, Ref [6]:

Complex systems are resilient to failure of their components, meaning that typically an error only causes local disruption. In rare cases, however, a local failure can be amplified and can cascade through the entire system. Indeed, in many real systems cascade sizes follow a heavy tailed distribution. However, not all catastrophic events are captured by these heavy tailed distributions: failures that are statistical outliers on the scale of the system size have been observed in financial systems, nuclear accidents, and city sizes. These outliers, called dragon kings, are driven by different underlying mechanism than regular cascading failures. And while the possible underlying mechanisms supporting the power law distribution are relatively well understood (e.g., self-organized criticality), the origins of dragon kings are still an open question.

We developed a first-principles model that exhibits both heavy tailed distribution of failures and dragon kings. The model considers a network where nodes can be either strong or weak against failure. Through the processes of failure cascades and node reinforcement and degradation, the network self-organizes in a way that produces dragon kings. We identified the mechanistic origin of these dragon kings, allowing us to predict their onset with high accuracy and also develop simple, but highly effective control interventions to prevent dragon kings from forming. We also theoretically derived conditions necessary for dragon kings and how key properties depend on system size. Our manuscript appeared in Physical Review E [6].

IV.B. Optimal architectures to suppress cascades, Ref [7]:

We also investigated large cascades spreading across interconnected complex systems and ways to suppress them. Using the classical BTW sandpile model, we explored how realistic network topologies affect cascades. We found that three properties, scale-free degree distribution, assortativity, and hub-to-hub connections, are all necessary components to significantly reduce the size of large cascades. We demonstrated that correlations present in the structure of a multilayer network influence the dynamical cascading process, preventing failures to spread across connected layers, highlighting the importance of internal and cross-network topology in optimizing stability and robustness of interconnected systems. These findings suggest that there are optimal network structures to suppress cascades, and that engineered systems, may reduce the likelihood of cascading errors by organizing into modular clusters, with small connectivity across clusters via linking cluster leaders. Our manuscript appeared in Physical Review E [7].

IV.C. Formulating a comprehensive theory for cascades, Ref [8]:

Most first-principles models of cascading failures on networks assume that the network is tree-like, without any loops. In reality many networks, like power grids, benefit from the redundancy provided by loops. These loops that provide alternate paths through a network make it particularly difficult to predict which small initial failures will cascade to becoming massive in size. We laid out our hypothesis on k-core structures and conservation laws being the key to a general theory in a perspectives piece that appeared in *Science* in November 2011.

V. Some additional research accomplishments

V.I. Explosive phenomena on complex networks, Ref [9]:

The emergence of large-scale connectivity and synchronization crucially underlie the structure, proper functioning, and failure of many complex socio-technical networks. Thus, there has been great interest in understanding phase transitions to large-scale connectivity and global synchronization, including how to enhance or delay their onset. For many decades, percolation and synchronization were studied predominately as a second-order phase transition where at the critical threshold, the order parameter increases in a rapid but continuous way. In 2009, work of the current PI showed there could be an explosive, i.e. extremely rapid, transition for a network growth process where links compete for addition. This observation of "explosive percolation" started an enormous surge of analyzing explosive phenomena and their consequences for the structure and function in complex networks. This lead also to the discovery of "explosive synchronization" in networks, and there is now a huge volume of scientific literature on this topic. These models all delay the emergence of large-scale collective behaviors leading to extremely abrupt transitions (especially for large but finite networks), with drastic consequences for the topology and dynamics of the underlying network. Important mechanisms that achieve the required delay for explosive transitions include history dependence and strong correlations during the dynamical processes.

The PI teamed up with the lead authors of the explosive synchronization work to write a review paper on this topic. We synthesize the literature and findings over the past 9 years. We report the main impact of explosive phenomena in networked systems, exposing deep connections between the different types of explosive phenomena identified both in model and experiment. We provide a coherent picture and give a perspective for promising future research to address many exciting and fundamental questions that remained unanswered. This manuscript entitled "Explosive phenomena on complex networks" appeared in *Advances in Physics* [9].

We also developed practical algorithms based on explosive percolation for use for optimal network recovery [10].

V.II. Synchronization, control and opinion dynamics, Refs [11-13]:

In addition to the research highlighted in detail above, other results worth mentioning include the development of Master Stability Functions for analyzing the stability of synchronization patterns in multilayered networks [11], the development of a first-principle model of active social contagion which allows us to rigorously establish the roles of "influential" and "susceptible" individuals in social networks [12], and development of algorithms to analyze the structural control properties of networks beyond simply using their degree-distributions [13].

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