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# RPPR Final Report
as of 29-Sep-2020

Agency Code:

Proposal Number: 63826CSMUR **Agreement Number: W911NF-13-1-0340**
**INVESTIGATOR(S):**

**Name:** Raissa M. D'Souza
**Email:** raissa@cse.ucdavis.edu
**Phone Number:** 5307548405
**Principal:** Y

Organization: **University of California - Davis**
Address: Sponsored Programs, Davis, CA 956186153
Country: USA
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**Final Report** for Period Beginning 01-Sep-2013 and Ending 30-Nov-2018
**Title:** Predicting and Controlling Systems of Interdependent Networks_Exploiting Interdependence for Control
**Begin Performance Period:** 01-Sep-2013 **End Performance Period:** 31-May-2020
**Report Term:** 0-Other
Submitted By: Raissa D'Souza Email: raissa@cse.ucdavis.edu
Phone: (530) 754-8405
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 19 **STEM Participants:** 7

**Major Goals:** I. Collective phenomena in complex networks

The overarching goal of our project is to understand the origins of collective phenomena in complex networks and how to control such phenomena. We are particularly interesting in leveraging the interdependence of networks for control purposes. Our goals range from developing basic theoretical underpinnings -- including new mathematical tools and new understanding of nonlinear dynamics, statistical physics and phase transitions -- to implementing control in real-world test beds, including networks of nanoelectromechanical (NEMs) oscillators, interdependent critical infrastructure networks, and the multi-faceted networks of macaque monkey societies. Ultimately we wish to understand and control how disparate collections of autonomous agents interacting through numerous networks with myriad time-scales and length-scales give rise to collective phenomena, such as cooperation, competition and conflict, and how the state of the agents, the networks, and the noisy and dynamic environment shape the collective behaviors through feedbacks

II. Information dynamics on networks

Collective phenomena arise due to information exchange between the constituent elements of a system. Our goal is to develop the foundations of modeling complex systems as networks and to develop new mathematical and information-theoretic tools for analyzing their behavior. These tools will be used on all our test beds, most directly to analyze experiments and simulations on networks of NEMS oscillators.

III. Network controllability

Our group continues a three-pronged approach for this period: 1) extensively collaborate with our colleagues in infrastructure networks to explore data-guided control, producing work that is proving to be of great interest to the research community; 2) extensively collaborate with our colleagues in NEMs nonlinear dynamics to examine how system theoretic tools can be applied to control the patterns of synchronization; 3) And finally, we have been contributing to fundamental aspects of network control, exemplified by the role of network symmetries and extensions for the control of dynamic networks.

IV. Infrastructure networks

Infrastructure networks offer detailed instantiations of interdependent networks. Electricity, telecom, transportation, oil and natural gas networks all rely upon one another for proper functioning yet their interdependencies are

typically only manifest during times of extreme failures. Our goal is to uncover coupling and recovery processes from empirical databases; to identify real trends from ad-hoc multisystem evolvement and response; and to inform rigorous theoretical principles of network structure, function and multi-modal controlled restoration or intervention. Ultimately we wish to develop theoretically principled, feasible control strategies for critical infrastructure, coupled systems, and social response. We emphasize strategies that are implementable in practice and that include the three stages of control (prevention, intervention, and recovery), to facilitate risk assessments and sensitivity analyses for informed decision support. Our focus this reporting period is on decentralized restoration and control that leverages interdependencies.

V. Networks of nanoelectromechanical (NEMs) nonlinear oscillators

Using mathematical models to analyze the onset of large-scale synchronization in networks of oscillators forms a cornerstone for understanding collective phenomena in complex networks. The bulk of existing work here has focused on the simple “Kuramoto”-style phase oscillators where oscillators synchronize due to dissipative coupling which requires that neighboring oscillators minimize their phase differences, essentially forcing the onset of large-scale synchronization. Instead our focus is on much broader and realistic coupling functions that allow us to analyze the self-organization phenomena guiding collective behaviors and moreover, to implement this in a real-world system. Real engineered systems inevitably have defects and heterogeneity that cannot be accounted for by simplified mathematical models and push our ability to connect theory and experiment. Our goal is to build a flexible platform of high-quality NEMs oscillators with reconfigurable coupling functions and network topology where we can connect theory and experiment in all aspects of the project, including “kicking control” between stable attractors to node knockout experiments, all the while validating the robustness of our theories to real engineered systems.

VI. Macaque monkey societies

Primate societies parallel human societies in many aspects and we have the unique access to extensive, highly time-resolved data of interactions in macaque monkey societies. The interactions are multi-faceted and layered, including grooming networks, status signaling networks, aggression networks, affiliative networks and genealogical networks. In general, monkey societies are stable to perturbations but occasionally we observe complete societal collapse. The goal is to develop theoretical tools that uncover the interplay between the different network layers including multi-layered early warning signs of societal collapse, and real control interventions that can stabilize the system.

**Accomplishments:** See pdf file attached at end for Accomplishments.

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**Training Opportunities:** The postdoctoral scholars, graduate students, and undergraduate students involved in the MURI team have gained invaluable training in multi-disciplinary research. Overall, our research activities had direct involvement from 35 Graduate students, 7 undergraduate students, 2 REUs, 15 Postdoctoral Scholars, and 6 Staff Scientists, all of whom received significant training opportunities while working in the labs of the MURI team PIs. We graduated 11 PhD students and 1 MS student. Several students were involved with the national labs via summer internships or employment. All trainees have gone onto very successful positions including named postdoctoral fellowships and also 3 who are now faculty members (at U Oklahoma, U Melbourne, and Central European University).
More specific training details include:

- PhD student Jordan Snyder successfully defends PhD in Applied Mathematics June 2019, and secures postdoctoral scholar position at the University of Washington.

- PhD student Mathias Hudoba de Badyn successfully defends PhD in Control Theory and Aerospace Engineering in June 2019, and secures postdoctoral scholar position at ETH Zurich.

- PhD student, Kelly Finn successfully defends PhD and is awarded the Neukom Institute for Computational Science Postdoctoral Fellowship for 2019-2021. (Awarded Spring 2019)

- Postdoctoral scholar, Marton Posfai, secures a tenure-track faculty position in the Department of Network and Data Sciences at Central European University, Vienna Austria, starting Jan 2020.

- Postdoctoral scholar, Martin Rohden, completes his training and secures a research staff position at University of Leiden, Germany.

- PhD student Andrew Smith defends PhD in Computer Science in March 2018 and becomes a Member of the Technical Staff at Sandia National Laboratory.

- Undergraduate student, Jordan Wheeler, completes B.S. in Civil and Environmental Engineering at Rice University (May 2019).

- PhD student Andres Gonzalez successfully defends PhD in Civil Engineering (May 2018) and is now Assistant Professor of Industrial and Systems Engineering at University of Oklahoma.

- Postdoc Airlie Chapman completes her postdoctoral training and is now Assistant Professor of Mechanical Engineering at the University of Melbourne.

- PhD student Eric Schoof successfully defends PhD in MAE and accepted a research faculty position at the University Melbourne.

- PhD student Sarah E. Marzen successfully completes PhD in Physics, August 2016, and is now the Physics of Living Systems postdoctoral fellow at MIT.

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

- PhD student Alexander Boyd successfully defends PhD in Physics in December 2017, and is now a postdoctoral scholar in Singapore.

- Ph.D. students from Duenas-Osorio's team enroll in semester-long Technical Writing training sponsored by the School of Engineering at Rice University.

- Ph.D. students from Duenas-Osorio's team completed a Great Courses video series on "The Science of Information", with the aim to inspire new collaborations between UC Davis and Rice on network information theory and applications.

- Evan Lopez, completes B.S. in Civil and Environmental Engineering at Rice University (May 2018).

- PhD candidate Yuansheng Lin (visiting from Beihang University Beijing, China with support from China

Scholarships Council), successfully defends PhD thesis in Systems Engineering in Jan 2018.

- Duenas-Osorio and Ph.D. students completed a 12-lecure video course on Understanding Complexity by Scott E. Page.

- Ph.D. students from Duenas-Osorio's team enroll in semester-long Technical Writing training sponsored by the School of Engineering at Rice University.

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

- PhD candidate Anastasiya Salova passes final Qualifying Exam and advances to PhD candidacy, March 21, 2018.

- PhD candidate Jeff Emenheiser passes final Qualifying Exam and advances to PhD candidacy, Jan 25, 2018.

- 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.

- NSF REU student Hyun Su Kim hosted at UC Davis (Summer 2017)

- NSF REU student Bahti Zakirov hosted at UC Davis (Summer 2017)

- 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's research team includes PhD candidate Yuansheng Lin (visiting from Beihang University Beijing, China with support from China Scholarships Council), who works on models of self-organized criticality and dragon kings.

- PhD student Paul Riechers successfully completes PhD in Mathematics: December 2016.

- Summer NSF REU students trained at UC Davis:
— Josh Reubeck (Summer 2016)
— Hyun Su Kim (Summer 2017)
— Bahti Zakirov (Summer 2017)

- PhD student Jordan Snyder attended the CRITICS Summer School and Workshop on Critical Transitions in Complex Systems held in Kulhuse, Denmark.

- Ph.D. students with Co-PI Duenas-Osorio enrolled in a semester-long Technical Writing course sponsored by the School of Engineering at Rice University.

- Senior Ph.D. students with Co-PI Duenas-Osorio participated in research proposal writing for the Defense Threat and Reduction Agency (DTRA) and the National Science Foundation (NSF).

- Ph.D. students with Co-PI Duenas-Osorio received peer and faculty feedback to technical presentations in advance of conferences and workshops attended during the reporting period.

- Co-PI Duenas-Osorio sponsors a number of undergraduate research assistants (3 during the reporting period), to assist his team with data analyses, computer code development, literature reviews, etc.

- Postdoc Azadeh Ansari came to the Caltech group from a GaN MEMS background at University of Michigan. She was trained at Caltech in AlN processing and experimental techniques for measuring nonlinear dynamics in NEMS/MEMS.

- PhD in Physics, UC Davis: Vikram Vijayaraghavan, Nov 2015.

- PhD in Computer Science, UC Davis: Samuel D. Johnson, Jan 2016.

- PhD in Mathematics, UC Davis: Nix Barnett, June 2016.

- PhD in Fire Engineering, Central South University of China: Jian Li June of 2016

- Summer REU students:
— Josh Reubeck (Summer 2016)
— David Gier (Summer 2015)

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**Results Dissemination:** * CONFERENCES ORGANIZED INCLUDE:

- NetSci 2014, Clark-Kerr Campus, UC Berkeley (D'Souza was main organizer).

- NetSci 2016, 2017, 2018 (as President of the Network Science Society, D'Souza oversaw conferences).

- Symposium on control of synchronization, SIAM Snowbird conference, May 17-21, 2015.

- Symposium on Thermodynamics and non-linear dynamics in the information age, Telluride Science Center, 13-17 Jul, 2015.

- Symposium on Information Engines at the Frontiers of Nanoscale Thermodynamics, Telluride Science Center, 25 July-1 Aug 2019.

* OUTREACH TO ARMY & ARO:

- Year 4 MURI Team Annual Review, held at Army Reseach Lab, Adelphi MD, Aug 2018. ARL researchers and ARO & DTRA PMs joined.

- Year 2 MURI Team Annual Review at the Santa Fe Institute, introducing ARO and DARPA PMs to SFI researchers and facilitating potential grant opportunities.

* GENERAL OUTREACH:

- 2017-present, D'Souza is on the Scientific Board of Quanta Magazine (published by the Simons Foundation) to help disseminate results from network science to the general public.

* HIGHLIGHTS OF PLENARY/KEYNOTE/INVITED LECTURES (inverse chronological):

1) R. D'Souza, NetSci X 2019, Jan 3-5, Santiago, Chile.

2) R. D'Souza, Complenet'19, 18-21 March 2019, Tarragona, Spain.

3) R. D'Souza, Colloquium Speaker, Department of Operations Research and Financial Engineering, Princeton University, April 16, 2019.

4) R. D'Souza, Santa Fe Institute Symposium on the End of Everything, May 4, 2019.

5) R. D'Souza, Euler Award lecture, NetSci 2019, May 31, Burlington, VT.

6) R. D'Souza, Plenary lecture, European Control Conference 2019, 25-28 June 2019, Naples, Italy.

7) Duenas-Osorio, L, Keynote speaker. 13th international conference on applications of statistics and probability in civil engineering (ICASP13), Seoul, South Korea, May 29th, 2019.

8) Duenas-Osorio, L., Invited Panelist. “How Will Quantum Computing Impact Energy - and When?” Cambridge Energy Research Associates, Houston, TX, March 13th, 2019.

9) Duenas-Osorio, L., School of Industrial and Systems Engineering, U Oklahoma, Norman, OK, Dec 10th 2018.

10) Duenas-Osorio, L, Center for Informatics and Computational Science, U Notre Dame, November 14th, 2018.

11) M. Matheny, Invited talk, Frontiers of Nanomechanical Systems (2019), Sixteenth International Workshop on Nanomechanical Sensors. 12) ICFO (The Institute of Photonic Sciences), June 14, 2019. 13) ETH-Zurich (Swiss Federal Institute of Technology in Zurich), June17, 2019.

15) M. Rohden, Cambridge University, UK, June 28, 2019.

16) M. Rohden, Max Plank Inst for Dynamics and Self-Organization, Göttingen, Germany, July 2, 2019.

17) M. Rohden, Technical University Wien, July 3, 2019. IST Wien, Germany, July 4, 2019.

18) M. Pósfai. Central European University – Budapest, Hungary, March 2019.

19) M. Pósfai. Perspectives on Complex Systems Workshop 2018 – Berlin, Germany, Dec 2018.

20) R. D'Souza, Keynote speaker, Conference on Complex Systems 2017, Cancun Mexico, Sept 19, 2017.

21) R. D'Souza, Keynote speaker, NetSci X 2018, Hangzhou China, Jan 5-8, 2018.

22) R. D'Souza, American Physical Society March meeting, March 8, 2018.

23) R. D'Souza, Keynote talk at NetONets 2018, satellite workshop of NetSci 2018, Paris France, June 12, 2018.

24) R. D'Souza, Keynote talk at SIAM Network Science 2018 conference, Portland Oregon, July 12, 2018.

25) B. McCowan, Keynote talk NetSci 2018, Paris France, June 15, 2018.

26) M. Roukes, Keynote talk at 11th International Symposium on Materials Nanoarchitectonics (MANA), Tsukuba Japan, March 2018.

27) M. Roukes, NEC Fundamental Research Laboratory, April 2018.

28) L. Duenas-Osorio, International Conference on Complex Systems, Boston, Massachusetts, July 23rd, 2018.

29) L. Duenas-Osorio, "Quantum Engineering." Army Research Laboratory (ARL South) - Rice University Day, Houston, Texas, USA, April 26th, 2018.

30) L. Duenas-Osorio, Department of Civil and Environmental Engineering, Rice University, Houston, Texas, USA, September 29th, 2017.

31) J. Crutchfield, Physics Department Colloquium, Stanford University, 17 April 2018.

32) J. Crutchfield, Physics Department Colloquium California Institute of Technology, 9 November 2017.

33) M. Rohden, Potsdam Institute for Climate Impact Research, Aug 28, 2018.

34) M. Pósfai, Wuhan University, Wuhan, China, Oct 23, 2017.

35) M. Pósfai, Changsha, China, Oct 28, 2017.

36) M. Pósfai, Chongqing, China, Oct 30, 2017.

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

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

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

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

41) M. Pósfai, Central European University, Budapest, Hungary, May 4, 2017.

42) M. Pósfai, Dynamics on and of Complex Networks, Satellite of NetSci 2017, June 19, 2017.

43) M. Roukes, Distinguished EE Lecture at EPFL, Lausanne, 6 Sep 2016.

44) M. Roukes, Physics Colloquium at Aalto University, Helsinki, 7 Oct 2016.

45) M. Roukes, ULT 2017, Heidelberg, 19 Aug 2017.

46) M. Roukes, Keynote Lecture at Napa Microsystems Workshop, CA, 22 Aug 2017.

47) Duenas-Osorio, L., Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA, December 2nd, 2016.

48) Duenas-Osorio, L., Kinder Institute for Urban Research at Rice University, Houston, Texas, USA, September 19th, 2016.

49) Duenas-Osorio, L., Schlumberger Reliability and Maintainability Workshop, Katy, Texas, USA, August 30th, 2016.

50) M. Matheny, SIAM Applications of Dynamical Systems, May 19, 2015.

51) J. Emenheiser, SIAM Applications of Dynamical Systems, May 19, 2015.

52) R. D'Souza, The John von Neumann Public Lecture, Wisconsin Institutes for Discovery, University of Wisconsin, Nov. 5, 2014.

53) R. D'Souza, Invited Distinguished Lectures, University of Alaska, Anchorage, Complex Systems lecture series, April 2-3, 2015.

54) R. D'Souza, Keynote Speaker, UC Davis, Statistical Sciences Symposium, April 10-11, 2015.

55) R. D'Souza, UC Davis, Institute for Social Sciences 2015 Conference, May 8, 2015.

56) R. D'Souza, Keynote Speaker, NetSci 2015, Zaragoza Spain, June 1-5, 2015.

57) M. Mesbahi, University of Minnesota, May 2015.

58) M. Mesbahi, University of Southern California, April 2015.

59) M. Roukes, Kick-off Symposium, Max Planck Institute for Brain Research, Frankfurt, Germany, 24 Sep 2014.

60) M. Roukes, Distinguished Lecturer in Electrical Engineering, EPFL, Lausanne, Switzerland, 2 Oct 2014.

61) Roukes, Distinguished Lecture Seminar, Molecular Foundry, LBNL, Berkeley, CA , 14 Oct 2014.

62) M. Roukes, Kavli Futures Workshop / Kick-off Symposium Columbia University Neurotechnology Center, New York, NY, 3 Nov 2014.

63) M. Roukes, Niels Bohr Lecture – University of Copenhagen, Copenhagen, Denmark, 12 Nov 2014.

64) M. Roukes, Invited Colloquium – Danish Technical University, Lyngby, Denmark, 13 Nov 2014.

65) M. Roukes, Director’s Colloquium Distinguished Speaker – Los Alamos National Laboratory, Los Alamos, NM, 27 Jan 2015.

66) M. Roukes, Munushian Distinguished Lecturer, Department of Engineering, University of Southern California, Los Angeles, CA, 2 Feb 2015.

67) Michael Roukes, Keynote Speaker, SPIE NBSIS Conference (Nano-Bio Sensing, Imaging & Spectroscopy), Jeju Island, Korea, 27 Feb 2015.

68) M. Roukes, Cooper Colloquium in Physics, Cornell University, Ithaca, NY, 27 Apr 2015.

69) M. Roukes, Invited Speaker, Presidential Symposium, Internation Brain Research Organization, Rio de Janiero, Brazil, 8 July 2015.

70) Flack, J.C., Plenary Lecture, Netsci, June 2014.

71) J. P. Crutchfield, the John von Neumann Complexity and Computation Public Lecture, Wisconsin Institutes for Discovery, 6 November 2013.

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**Honors and Awards:** - PI D'Souza appointed to the Board of Reviewing Editors, Science Magazine, 2020.

- PI D'Souza is the inaugural winner of the Euler Prize of the Network Science Society, May 2019.

- PI D'Souza elected Fellow of the Network Science Society, Class of 2019.

- PI D'Souza elected Fellow of the American Physical Society, 2016.

- co-PI Mesbahi elected Fellow of IEEE, Class of 2015.

- co-PI Mesbahi named the Endowed University Professor for Control Systems and Networks at the University of Washington, 2017.

- co-PI L. Duenas-Osorio receives the 2017 IASSAR Early Achievement Research Award, given every four years by the International Association for Structural Safety and Reliability (IASSAR). The award goes to researchers who are “at early stages of their careers and generally below 40 years of age,” and recognizes “contributions to and impact on the field of structural safety and reliability.” August 2017.

- Postdoc Marton Posfai wins the 2019 UC Davis Award for Excellence in Postdoctoral Research.

- PI D'Souza awarded the 2017 Outstanding Mid-career Research Award for the College of Engineering at UC Davis.

- PI D'Souza wins the ESEC/FSE 2018 Test of Time award.

- PI D'Souza selected as Lead Editor of Physical Review Research, 2019.

- PhD student, Kelly Finn, is awarded the Neukom Institute for Computational Science Postdoctoral Fellowship for 2019-2021.

- PhD student, Airlie Chapman, receives Springer Outstanding Thesis Award, 2015.

- PI D'Souza, Elected President of the Network Science Society, June 2015-May 2018.

- co-PI Duenas-Osorio, 2015 Best Journal Paper award from Earthquake Spectra.

- PhD student, Jian Li, receives Best Paper Award, International Civil Engineering Risk and Reliability Association, 2015.

- co-PI Crutchfield, receives Best paper of 2003 in Chaos, awarded May 2015.

- co-PI Mesbahi selected as the graduate-level Professor of the Year, University or Washington, in 2016.

- co-PI Mesbahi selected as the Graduate Instructor of the Year, Department of Aeronautics & Astronautics, University of Washington, 2015.

- co-PI Mesbahi is the distinguished speaker at the 2019 Chinese Control Conference.

- co-PI Mesbahi selected Vice Chair for Conference on Decision and Control, 2018.

- PhD student, Jordan Snyder, selected as a visiting scholar at IPAM's long program on machine learning for physics and the physics of learning, Fall 2019.

- PhD student, Anastasiya Salova, selected as a visiting scholar at IPAM's long program on machine learning for physics and the physics of learning, Fall 2019.

- co-PI Mesbahi is the International Program Committee Chair for IFAC Workshop on Distributed Estimation and Control of Networked Systems (NecSys2018).

- Ph.D. Candidate R. Paredes received an IASSAR Student Scholarship (08/2017): Presented to by the International Association for Structural Safety and Reliability (IASSAR) at the twelfth international conference on structural
safety and reliability (ICOSSAR), Vienna, Austria.

- PhD candidate Jordan Snyder receives SIAM Travel Award to attend the SIAM Network Science 2018 meeting.

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

- Postdoctoral scholar Weiran Cai receives SIAM Travel Award to attend the Network Science 2018 meeting.

- Postdoctoral scholar Keith Burghardt received the 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).

- PhD candidate Daniella Masante is funded with UCMEXUS Graduate Fellowship, which supports her graduate career in Physics at UC Davis.

- PhD candidate David Gier receives NSF Graduate Fellowship, 2016-2020.

**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.

- D'Souza gives overview lecture on Network Science at the CCDC ARL Network Science Expo, Army Research Lab, Adelphi Research Center, Aug 14, 2019.

- Year 4 annual review held at the Network Science Center, Army Research Lab, ARC, Adelphi MD, and involved many ARL researchers as well as ARO and DTRA Program Managers.

- Year 2 MURI Team Annual Review at the Santa Fe Institute, introducing ARO and DARPA PMs to SFI researchers and facilitating potential grant opportunities. (D'Souza received DARPA award W911NF-17-1-0077 as a follow on to this meeting.)

- Our team's quantum circuit for network reliability assessment, originally tested on IBMQ's quantum computer, was tested on an experimental Ion Trap set up at the Department of Physics of the University of Maryland, showcasing less errors and potential instance scalability.

- UC Davis awards 2 faculty positions to Network Science, one in social sciences and one in computer science, showing long term institutional commitment to network science and the work of this MURI. The PI served as the faculty recruitment chair for these positions.

- PhD student Jordan Snyder is a summer research intern at Los Alamos National lab June-Sept 2017, and July-Sept 2018.

- Dr. Andrew Smith completed PhD in 2018 and went on to be a full time Member of the Technical Staff at Sandia National Laboratories.

- PhD student Alex Waagen is a summer research intern at the Network Science Center at the Army Research Lab, ARC, Adelphi MD.

- Participation in the ARL South Day at Rice University, where L. Duenas-Osorio's team discussed quantum algorithms for network reliability assessment.

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

- All algorithms and associated data sets used in journal publications are fully available via specific linkages to supplemental material in the relevant publications.

- Open Source Python Package 'dit' for discrete information theory extensively expanded to include, for instance, multivariate information measures for dynamical and stochastic networks. Available on github. Postdoc Ryan James led break-out session at workshops for participants to learn dit.

Data sets generated:

D1) González, A., and Duenas-Osorio, L. (2017). "Benchmark time-dependent interdependent network design problem (td-INDP) dataset for optimal restoration." Benchmark 1: http://duenasosorio.rice.edu/Content.aspx?id=2147483674

D2) Paredes, R., and Duenas-Osorio, L. (2017). "Benchmark reliability assessment of complex networked systems." Benchmark 2: http://duenas-osorio.rice.edu/Content.aspx?id=2147483674

**PARTICIPANTS:**

**Participant Type:** Co PD/PI
**Participant:** Leonardo Duenas-Osorio
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Co PD/PI
**Participant:** Mehran Mesbahi
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Co PD/PI
**Participant:** Michael Roukes
**Person Months Worked:** 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Co PD/PI
**Participant:** Jessica Flack
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Co PD/PI
**Participant:** David Krakauer
**Person Months Worked:** 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Co PD/PI
**Participant:** Brenda McCowan
**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:** James Patrick Crutchfield
**Person Months Worked:** 7.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** PD/PI
**Participant:** Raissa Michelle D'Souza
**Person Months Worked:** 13.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Airlie Chapman
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Pierre-Andre Noel
**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:** Marton Posfai
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Alex Waagen
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Charles Brummitt

**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:** Chris Ellison
**Person Months Worked:** 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Brian Daniels
**Person Months Worked:** 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Eddie Lee
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Ryan James
**Person Months Worked:** 6.00 **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:** 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)

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as of 29-Sep-2020

**Participant:** Azadeh Ansari
**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:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)
**Participant:** Jessica Vandeleest
**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:** Afshin Mesbahi
**Person Months Worked:** 15.00 **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:** 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Matthew Matheny
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Warren Fon
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Brianne Beisner
**Person Months Worked:** 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Xiaoqun Wu
**Person Months Worked:** 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Edward Myers
**Person Months Worked:** 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Staff Scientist (doctoral level)
**Participant:** Darcy Hannibal
**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:** Jeff Dudek
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

# RPPR Final Report
as of 29-Sep-2020

**Participant Type:** Undergraduate Student
**Participant:** Carlos Montes
**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:** Pooneh Mohammadiara
**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:** Vikram Vijayaraghavan
**Person Months Worked:** 7.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Charles Brummitt
**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:** Andres Gonzalez
**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:** Jian Li
**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:** Roger Paredes
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Akwasi Mensah
**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:** Jeffrey Emenheiser
**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:** Andrew Smith
**Person Months Worked:** 13.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Alec Boyd
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Russell Hawkins
**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:** Dmitry Shemetov
**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:** Jason Barnett
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Mathias Hudoba de Badyn
**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:** Alex Waagen
**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:** Eric Schoof
**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:** Jordan Snyder
**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:** Haochen Wu
**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:** Kelly Finn
**Person Months Worked:** 10.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Paul Reichers
**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:** Nix Barnett
**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:** Greg Wimsatt
**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:** Niklas Braun
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:

International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Research Experience for Undergraduates (REU) Participant
**Participant:** Josh Reubeck
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Research Experience for Undergraduates (REU) Participant
**Participant:** David Gier
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Xincheng Lei
**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:** Anastasiya Salova
**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:** Bowen Fu
**Person Months Worked:** 10.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Ryan Macon
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Lauren Woodelll
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Nicole Lin
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Anh-Thu Le
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Josephine Hubbard
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Hesam Talebiyan
**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:** Dian-Jing Chen
**Person Months Worked:** 2.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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

**Participant Type:** Graduate Student (research assistant)
**Participant:** Siavash Alemzadeh
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Undergraduate Student
**Participant:** Zoe Anderson
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Undergraduate Student
**Participant:** Bob Zhang
**Person Months Worked:** 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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

**Participant Type:** Undergraduate Student
**Participant:** Grayson Gordon

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**Person Months Worked:** 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Undergraduate Student
**Participant:** Jordan Wheeler
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Undergraduate Student
**Participant:** Akshay Kalyan
**Person Months Worked:** 3.00 **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 Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.112.155701
Volume: 112 Issue: 15 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Microtransition Cascades to Percolation
**Authors:**
**Keywords:** Early warning signs, percolation
**Abstract:** We report the discovery of a discrete hierarchy of microtransitions occurring in models of continuous and discontinuous percolation. The precursory microtransitions allow us to target almost deterministically the location of the transition point to global connectivity. This extends to the class of intrinsically stochastic processes the possibility to use warning signals anticipating phase transitions in complex systems.
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

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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.89.012807
Volume: 89 Issue: 1 First Page #: 12807
Date Submitted: Date Published:
Publication Location:
**Article Title:** Bottom-up model of self-organized criticality on networks
**Authors:**
**Keywords:** networks, cascading failure, self-organized criticality
**Abstract:** The Bak-Tang-Wiesenfeld (BTW) sandpile process is an archetypal, stylized model of complex systems with a critical point as an attractor of their dynamics. This phenomenon, called self-organized criticality, appears to occur ubiquitously in both nature and technology. Initially introduced on the two-dimensional lattice, the BTW process has been studied on network structures with great analytical successes in the estimation of macroscopic quantities, such as the exponents of asymptotically power-law distributions. In this article, we take a microscopic perspective and study the inner workings of the process through both numerical and rigorous analysis. Our simulations reveal fundamental flaws in the assumptions of past phenomenological models, the same models that allowed accurate macroscopic predictions; we mathematically justify why universality may explain these past successes. Next, starting from scratch, we obtain microscopic understanding that enables mechanistic models; such mode
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** IEEE Transactions on Automatic Control
Publication Identifier Type: DOI Publication Identifier: 10.1109/TAC.2014.2328757
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Controllability and Observability of Network-of-Networks via Cartesian Products
**Authors:**
**Keywords:** Composite networks, coordination algorithms, graph Cartesian product, network controllability, network observability.
**Abstract:** The paper presents a system theoretic analysis framework for a network-of-networks, formed from smaller factor networks via graph Cartesian products. We provide a compositional framework for extending the controllability and observability of the factor networks to that of the composite network-of-networks. We then delve into the effectiveness of designing control and estimation algorithms for the composite network via its symmetry and gramian structure. An example demonstrating the usefulness of our results in the context of social networks with a Cartesian product structure is then presented.
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

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as of 29-Sep-2020

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.89.042135
Volume: 89 Issue: 4 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Many roads to synchrony: Natural time scales and their algorithms
**Authors:**
**Keywords:** synchronization, Markov order, cryptic order, stochastic process, hidden Markov model, length scales
**Abstract:** We consider two important time scales--the Markov and cryptic orders--that monitor how an observer synchronizes to a finitary stochastic process. We show how to compute these orders exactly and that they are most efficiently calculated from the ?-machine, a process's minimal unifilar model. Surprisingly, though the Markov order is a basic concept from stochastic process theory, it is not a probabilistic property of a process. Rather, it is a topological property and, moreover, it is not computable from any finite-state model other than the ?-machine. Via an exhaustive survey, we close by demonstrating that infinite Markov and infinite cryptic orders are a dominant feature in the space of finite-memory processes. We draw out the roles played in statistical mechanical spin systems by these two complementary length scales.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physical Review E
Publication Identifier Type: Publication Identifier:
Volume: 89 Issue: 4 First Page #: 42119
Date Submitted: Date Published:
Publication Location:
**Article Title:** Bayesian structural inference for hidden processes
**Authors:**
**Keywords:** Bayesian inference, Markov chains, information theory, stochastic process, hidden Markov model
**Abstract:** We introduce a Bayesian approach to discovering patterns in structurally complex processes. The proposed method of Bayesian Structural Inference (BSI) relies on a set of candidate unifilar hidden Markov model (uHMM) topologies for inference of process structure from a data series. We employ a recently developed exact enumeration of topological ?-machines. (A sequel then removes the topological restriction.) This subset of the uHMM topologies has the added benefit that inferred models are guaranteed to be ?-machines, irrespective of estimated transition probabilities. Properties of ?-machines and uHMMs allow for the derivation of analytic expressions for estimating transition probabilities, inferring start states, and comparing the posterior probability of candidate model topologies, despite process internal structure being only indirectly present in data. We demonstrate BSI's effectiveness in estimating a process's randomness, as reflected by the Shannon entropy rate, and its structure
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

# RPPR Final Report
as of 29-Sep-2020

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Entropy
Publication Identifier Type: DOI Publication Identifier: 10.3390/e16041985
Volume: 16 Issue: 4 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Intersection Information Based on Common Randomness
**Authors:**
**Keywords:** entropy, information theory, synergy, decomposition, redundant information, partial information, intersection information
**Abstract:** The introduction of the partial information decomposition generated a flurry of proposals for defining an intersection information that quantifies how much of “the same information” two or more random variables specify about a target random variable. As of yet, none is wholly satisfactory. A palatable measure of intersection information would provide a principled way to quantify slippery concepts, such as synergy. Here, we introduce an intersection information measure based on the Gacs-Korner common random variable that is the first to satisfy the coveted target monotonicity property. Our measure is imperfect, too, and we suggest directions for improvement.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Nature Communications
Publication Identifier Type: DOI Publication Identifier: 10.1038/ncomms6415
Volume: 5.0E+000 Issue: 0 First Page #: 1
Date Submitted: Date Published:
Publication Location:
**Article Title:** Target control of complex networks
**Authors:**
**Keywords:** Complex networks, partial control
**Abstract:** Controlling large natural and technological networks is an outstanding challenge. It is typically neither feasible nor necessary to control the entire network, prompting us to explore target control: the efficient control of a preselected subset of nodes. We show that the structural controllability approach used for full control overestimates the minimum number of driver nodes needed for target control. Here we develop an alternate ‘k-walk’ theory for directed tree networks, and we rigorously prove that one node can control a set of target nodes if the path length to each target node is unique. For more general cases, we develop a greedy algorithm to approximate the minimum set of driver nodes sufficient for target control. We find that degree heterogeneous networks are target controllable with higher efficiency than homogeneous networks and that the structure of many real-world networks are suitable for efficient target control.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

# RPPR Final Report
as of 29-Sep-2020

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Internet Mathematics
Publication Identifier Type: DOI Publication Identifier: 10.1080/15427951.2014.979380
Volume: 1.1E+001 Issue: 3.0E+000 First Page #: 253
Date Submitted: Date Published:
Publication Location:
**Article Title:** Inequality and Network Formation Games
**Authors:**
**Keywords:** Nash equiliorium, inequality, complex networks
**Abstract:** This article addresses the matter of inequality in network formation games. We employ a quantity that we are calling the Nash Inequality Ratio (NIR), defined as the maximal ratio between the highest and lowest costs incurred to individual agents in a Nash equilibrium strategy, to characterize the extent to which inequality is possible in equilibrium. We give tight upper bounds on the NIR for the network formation games of Fabrikant et al. [14] and Ehsani et al. [13]. With respect to the relationship between equality and social efficiency, we show that, contrary to common expectations, efficiency does not necessarily come at the expense of increased inequality.
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Nature Physics
Publication Identifier Type: DOI Publication Identifier: 10.1038/nphys3378
Volume: 1.1E+001 Issue: 7.0E+000 First Page #: 531
Date Submitted: Date Published:
Publication Location:
**Article Title:** Anomalous critical and supercritical phenomena in explosive percolation
**Authors:**
**Keywords:** Percolation, explosive percolation, phase transitions, complex networks
**Abstract:** The emergence of large-scale connectivity on an underlying network or lattice, the so-called percolation transition, has a profound impact on the system’s macroscopic behaviours. There is thus great interest in controlling the location of the percolation transition to either enhance or delay its onset and, more generally, in understanding the consequences of such control interventions. Here we review explosive percolation, the sudden emergence of large-scale connectivity that results from repeated, small interventions designed to delay the percolation transition. These transitions exhibit drastic, unanticipated and exciting consequences that make explosive percolation an emerging paradigm for modelling real-world systems ranging from social networks to nanotubes.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

# RPPR Final Report
as of 29-Sep-2020

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.91.022811
Volume: 9.1E+001 Issue: 2.0E+000 First Page #: 1
Date Submitted: Date Published:
Publication Location:
**Article Title:** Effect of zealotry in high-dimensional opinion dynamics models
**Authors:**
**Keywords:** Opinion dynamics, complex networks, social networks
**Abstract:** Most of the work on opinion dynamics models focuses on the case of two or three opinion types. We consider the case of an arbitrary number of opinions in the mean field case of the naming game model in which it is assumed the population is infinite and all individuals are neighbors. A particular challenge of the naming game model is that the number of variables, which corresponds to the number of possible sets of opinions, grows exponentially with the number of possible opinions. We present a method for generating mean field dynamical equations for the general case of k opinions. We calculate the steady states in two important special cases in arbitrarily high dimension: the case in which there exist zealots of only one type, and the case in which there are an equal number of zealots for each opinion. We show that in these special cases a phase transition occurs at critical values pc of the parameter p describing the fraction of zealots. In the former case, the critical value determine
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Proceedings of the IEEE
Publication Identifier Type: DOI Publication Identifier: 10.1109/JPROC.2014.2368790
Volume: 1.02E+002 Issue: 1.2E+001 First Page #: 1873
Date Submitted: Date Published:
Publication Location:
**Article Title:** The Digital Age and the Future of Social Network Science and Engineering
**Authors:**
**Keywords:** Social networks, digital footprints, control, complex networks
**Abstract:** This is an exciting moment in human history as the digital world and the physical world become increasingly intertwined in a seamless manner. This special issue focuses on how digital technology is changing the structure and dynamics of social networks and the tools we have for studying and designing them.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

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as of 29-Sep-2020

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** The European Physical Journal B
Publication Identifier Type: DOI Publication Identifier: 10.1140/epjb/e2014-50278-x
Volume: 8.7E+001 Issue: 1.2E+001 First Page #: 1
Date Submitted: Date Published:
Publication Location:
**Article Title:** Given enough choice, simple local rules percolate discontinuously
**Authors:**
**Keywords:** Percolation, phase transitions, complex networks
**Abstract:** There is still much to discover about the mechanisms and nature of discontinuous percolation transitions. Much of the past work considers graph evolution algorithms known as Achlioptas processes in which a single edge is added to the graph from a set of k randomly chosen candidate edges at each timestep until a giant component emerges. Several Achlioptas processes seem to yield a discontinuous percolation transition, but it was proven by Riordan and Warnke that the transition must be continuous in the thermodynamic limit. However, they also proved that if the number k(n) of candidate edges increases with the number of nodes, then the percolation transition may be discontinuous. Here we attempt to find the simplest such process which yields a discontinuous transition in the thermodynamic limit. We introduce a process which considers only the degree of candidate edges and not component size. We calculate the critical point tc =(1??(1/k)n and rigorously show that the critical window is of
**Distribution Statement:** 3-Distribution authorized to U.S. Government Agencies and their contractors
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Proceedings of IEEE
Publication Identifier Type: Publication Identifier:
Volume: 1.02E+002 Issue: 1.2E+001 First Page #: 1
Date Submitted: Date Published:
Publication Location:
**Article Title:** Proceedings of the IEEE: Special issue on Impact of Changing Technology on Social Networks
**Authors:**
**Keywords:** Social networks, control, digital footprints
**Abstract:** This special issue of Proceedings of the IEEE is guest editted by D'Souza and Flack and focuses on THE DIGITAL AGE AND THE FUTURE OF SOCIAL NETWORK SCIENCE AND ENGINEERING.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** J. Royal Society Interface
Publication Identifier Type: DOI Publication Identifier: http://dx.doi.org/10.1098/rsif.2015.0712
Volume: 12 Issue: 0 First Page #: 20150712
Date Submitted: 8/31/17 12:00AM Date Published: 12/1/15 4:00PM
Publication Location:
**Article Title:** Coupled catastrophes: sudden shifts cascade and hop among interdependent systems
**Authors:** Charles D. Brummitt, George Barnett, Raissa M. D'Souza
**Keywords:** tipping point; regime shift; fold catastrophe; coupled systems; cascades; the Arab Spring
**Abstract:** An important challenge in several disciplines today is to understand how sudden changes can propagate among coupled systems. Examples include the synchronization of business cycles, population collapse in patchy ecosystems, markets shifting to a new technology platform, collapses in prices and in confidence in financial markets, and protests erupting in multiple countries. A number of mathematical models of these phenomena have multiple equilibria separated by saddle-node bifurcations, so we study this behavior in its normal form as fast–slow ordinary differential equations. In our model, a system consists of multiple subsystems, such as countries in the global economy or patches of an ecosystem. Each subsystem is described by a scalar quantity, such as economic output or population, that undergoes sudden changes via saddle-node bifurcations. The subsystems are coupled via their scalar quantity (e.g., trade couples economic output; diffusion couples populations); that coupling moves th
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** The Journal of Chemical Physics
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.4923066
Volume: 1.43E+002 Issue: 1.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Perspective: Sloppiness and emergent theories in physics, biology, and beyond
**Authors:**
**Keywords:** Emergence, information theory, control
**Abstract:** Large scale models of physical phenomena demand the development of new statistical and computational tools in order to be effective. Many such models are "sloppy," i.e., exhibit behavior controlled by a relatively small number of parameter combinations. We review an information theoretic framework for analyzing sloppy models. This formalism is based on the Fisher information matrix, which is interpreted as a Riemannian metric on a parameterized space of models. Distance in this space is a measure of how distinguishable two models are based on their predictions. Sloppy model manifolds are bounded with a hierarchy of widths and extrinsic curvatures. The manifold boundary approximation can extract the simple, hidden theory from complicated sloppy models. We attribute the success of simple effective models in physics as likewise emerging from complicated processes exhibiting a low effective dimensionality. We discuss the ramifications and consequences of sloppy models for biochemistry an
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 5-Submitted
**Journal:** The Philosophy of Individuality. Eds Lynn Nyhart and Scott Lidgard. University of Chicago Press
Publication Identifier Type: Other Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: 8/16/16 12:00AM Date Published:
Publication Location:
**Article Title:** The information theory of individuality
**Authors:** Krakauer, D. C. ; Bertschinger, N. ; Olbrich, E. ; Ay, N. and J. C. Flack
**Keywords:** Shannon information, mutual information, information decomposition, shared information, synergy, adaptation, evolution, control
**Abstract:** We consider biological individuality in terms of information theoretic and graphical princi- ples. Our purpose is to extract through an algorithmic decomposition system-environment boundaries supporting individuality. We infer or detect evolved individuals rather than as- sume that they exist. Given a set of consistent measurements over time, we discover a coarse- grained or quantized description on a system, inducing partitions (which can be nested). Legitimate individual partitions will propagate information from the past into the future, whereas spurious aggregations will not. Individuals are therefore defined in terms of ongo- ing, bounded information processing units rather than lists of static features or conventional replication-based definitions which tend to fail in the case of cultural change. One virtue of this approach is that it could expand the scope of what we consider adaptive or biological phenomena, particularly in the microscopic and macroscopic regimes of molecular
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Statistical Physics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s10955-015-1327-5
Volume: 1.6E+002 Issue: 6.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Computational Mechanics of Input–Output Processes: Structured Transformations and the $$\epsilon $$ ? -Transducer
**Authors:**
**Keywords:** Sequential machine · Communication channel · Finite-state transducer · Statistical complexity · Causal state · Minimality · Optimal prediction · Subshift endomorphism
**Abstract:** Computational mechanics quantifies structure in a stochastic process via its causal states, leading to the process's minimal, optimal predictor—the ?-machine. We extend computational mechanics to communication channels coupling two processes, obtaining an analogous optimal model—the ?-transducer—of the stochastic mapping between them. Here, we lay the foundation of a structural analysis of communication channels, treating joint processes and processes with input. The result is a principled structural analysis of mechanisms that support information flow between processes. It is the first in a series on the structural information theory of memoryful channels, channel composition, and allied conditional information measures.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physica A: Statistical Mechanics and its Applications
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.physa.2016.01.087
Volume: 453 Issue: 0 First Page #: 84
Date Submitted: 8/23/18 12:00AM Date Published:
Publication Location:
**Article Title:** Characterizing the Topological and Controllability Features of U.S. Power Transmission Networks
**Authors:** Jian Lia, Leonardo Duen?as-Osorio, Changkun Chen, Benjamin Berryhill, Alireza Yazdani
**Keywords:** Power transmission networks, ensemble of networks, structural controllability, driver nodes, redundant nodes, intermittent nodes, relative frequency
**Abstract:** Understanding the controllability of complex networks continues to gain traction across disciplinary fields, including the exploration of infrastructure systems in this study, which focuses on power grids as a class of networks. Through topological principles, this paper investigates the controllability features of an ensemble of 58 U.S. city-level power transmission networks in seven U.S. states. To perform structural controllability analyses, the topological characteristics of the ensemble of networks are first quantified, including degree, shortest path length, clustering coefficient, meshedness and betweenness centrality, as well as the uncertainty associated with these and related properties . Then, the paper focuses on the controllability features of complex networks so as to detect the minimal sets of driver nodes to possibly control the networks given system linearity assumptions. Accordingly, a node is critical, intermittent or redundant if it acts as a driver node in all, som
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Computer-Aided Civil and Infrastructure Engineering
Publication Identifier Type: DOI Publication Identifier: 10.1111/mice.12171
Volume: 31 Issue: 0 First Page #: 334
Date Submitted: 8/23/18 12:00AM Date Published:
Publication Location:
**Article Title:** The Interdependent Network Design Problem for Optimal Infrastructure System Restoration System Restoration
**Authors:** Andres D. Gonzalez, Leonardo Duenas-Osorio, Mauricio Sanchez-Silva, Andres L. Medaglia
**Keywords:** Infrastructure restoration, resilience, Interdependent Networks, Network Design Problem
**Abstract:** This study introduces the Interdependent Network Design Problem (INDP), concerned with defining the minimum-cost reconstruction strategy of a partially destroyed system of infrastructure networks, subject to budget, resources, and operational constraints, while considering interdependencies between them. To solve the INDP, the authors develop an efficient Mixed Integer Programming (MIP) model, which considers different types of interdependency while exploiting efficiencies from joint restoration due to co-location for the first time. The authors also propose heuristic methodologies based on simulation and the iterative use of the INDP model, to enable studying problems with additional complexity, such as accounting for uncertainty from possible disaster scenarios, or determining not only what to reconstruct but the order of reconstruction. Such methodologies enable the analysis of expected costs and performance associated to reconstruction of the system of networks, providing an effect
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** SAFETY, RELIABILITY, RISK AND LIFE-CYCLE PERFORMANCE OFSTRUCTURES AND INFRASTRUCTURES
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Resource allocation for infrastructure networks within the context of disaster management
**Authors:**
**Keywords:** Co-location, geographical interdependence, disaster management, system recovery, Interdependent Networks
**Abstract:** Just in 2011, the economic losses associated to natural disasters worldwide accounted for more than USD 435 billion, which represents a significant 0.62% of the Gross World Product. Natural disasters often occur without enough warning and their impact in the infrastructure networks is widespread and severe. Even more, given that infrastructure networks are ever increasingly interconnected, the problem of preventing, miti- gating, and recovering from disasters across human and physical systems becomes a chronic difficult task. The objective of this paper is to present a new methodology to optimize resource allocation in infrastructure networks after a disaster, thus helping to prepare and recover systems of interconnected networks from a catastrophic event while acknowledging uncertainties and, for the first time, co-location interdependencies. The proposed method- ology simulates disaster scenarios and their impact on a set of networks, and iteratively reconstructs them by evaluating t
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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.91.050106
Volume: 9.1E+001 Issue: 5.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Signatures of infinity: Nonergodicity and resource scaling in prediction, complexity, and learning
**Authors:**
**Keywords:** prediction, nonergodic, structural complexity
**Abstract:** We introduce a simple analysis of the structural complexity of infinite-memory processes built from random samples of stationary, ergodic finite-memory component processes. Such processes are familiar from the well known multiarm Bandit problem. We contrast our analysis with computation-theoretic and statistical inference approaches to understanding their complexity. The result is an alternative view of the relationship between predictability, complexity, and learning that highlights the distinct ways in which informational and correlational divergences arise in complex ergodic and nonergodic processes. We draw out consequences for the resource divergences that delineate the structural hierarchy of ergodic processes and for processes that are themselves hierarchical.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Entropy
Publication Identifier Type: Publication Identifier:
Volume: 1.6E+001 Issue: 4.0E+000 First Page #: 1995
Date Submitted: Date Published:
Publication Location:
**Article Title:** Intersection Information Based on Common Randomness
**Authors:**
**Keywords:** intersection information; partial information decomposition; lattice; Gács–Körner; synergy; redundant information
**Abstract:** The introduction of the partial information decomposition generated a flurry of proposals for defining an intersection information that quantifies how much of “the same information” two or more random variables specify about a target random variable. As of yet, none is wholly satisfactory. A palatable measure of intersection information would provide a principled way to quantify slippery concepts, such as synergy. Here, we introduce in intersection information measure based on the Gács-Körner common random variable that is the first to satisfy the coveted target monotonicity property. Our measure is imperfect, too, and we suggest directions for improvement.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Frontiers in Computational Neuroscience
Publication Identifier Type: Publication Identifier:
Volume: 9.0E+000 Issue: 1.05E+002First Page #: 1
Date Submitted: Date Published:
Publication Location:
**Article Title:** Time resolution dependence ofinformation measures for spiking neurons: scaling and universality
**Authors:**
**Keywords:** statistical complexity, excess entropy, entropy rate, renewal process, alternating renewal process, integrate and fire neuron, leaky integrate and fire neuron, quadratic integrate and fire neuron
**Abstract:** The mutual information between stimulus and spike-train response is commonly used to monitor neural coding efficiency, but neuronal computation broadly conceived requires more refined and targeted information measures of input-output joint processes. A first step toward that larger goal is to develop information measures for individual output processes, including information generation (entropy rate), stored information (statistical complexity), predictable information (excess entropy), and active information accumulation (bound information rate). We calculate these for spike trains generated by a variety of noise-driven integrate-and-fire neurons as a function of time resolution and for alternating renewal processes. We show that their time-resolution dependence reveals coarse-grained structural properties of interspike interval statistics; e.g., ? -entropy rates that diverge less quickly than the firing rate indicate interspike interval correlations. We also find evidence that the ex
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**Journal:** arXiv.org:1412.8520
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
**Article Title:** Understanding and Designing Complex Systems: Response to "A framework for optimal high-level descriptionsin science and engineering - preliminary report"
**Authors:**
**Keywords:** information theory, rate-distortion theory, computational mechanics, information bottleneck, macrostates, microstates, statistical physics, coarse-graining, dimension reduction, minimum description length
**Abstract:** We recount recent history behind building compact models of nonlinear, complex processes and identifying their relevant macroscopic patterns or \macrostates". We give a synopsis of computational mechanics, predictive rate-distortion theory, and the role of information measures in monitoring model complexity and predictive performance. Computational mechanics provides a method to extract the optimal minimal predictive model for a given process. Rate-distortion theory provides methods for systematically approximating such models. We end by commenting on future prospects for developing a general framework that automatically discovers optimal compact models. As a response to the manuscript cited in the title above, this brief commentary corrects potentially misleading claims about its state space compression method and places it in a broader historical setting.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/srep15142
Volume: 5 Issue: First Page #: 15142
Date Submitted: 8/23/18 12:00AM Date Published: 10/13/15 2:00PM
Publication Location:
**Article Title:** Quantifying dynamical spillover in co-evolving multiplex networks
**Authors:** Vikram S. Vijayaraghavan, Pierre-Andre? Noe?l, Zeev Maoz, Raissa M. D'Souza
**Keywords:** Spillover, network co-evolution, coupled networks
**Abstract:** Multiplex networks (a system of multiple networks that have different types of links but share a common set of nodes) arise naturally in a wide spectrum of fields. Theoretical studies show that in such multiplex networks, correlated edge dynamics between the layers can have a profound effect on dynamical processes. However, how to extract the correlations from real-world systems is an outstanding challenge. Here we provide a null model based on Markov chains to quantify correlations in edge dynamics found in longitudinal data of multiplex networks. We use this approach on two different data sets: the network of trade and alliances between nation states, and the email and co-commit networks between developers of open source software. We establish the existence of "dynamical spillover" showing the correlated formation (or deletion) of edges of different types as the system evolves. The details of the dynamics over time provide insight into potential causal pathways.
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**Journal:** Chaos: An Interdisciplinary Journal of Nonlinear Science
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Volume: 26 Issue: 9 First Page #: 094816
Date Submitted: 8/15/16 12:00AM Date Published: 9/1/16 7:00AM
Publication Location: NY,NY
**Article Title:** Patterns of patterns of synchronization: Noise induced attractor switching in rings of coupled nonlinear oscillators
**Authors:** Jeffrey Emenheiser, Airlie Chapman, Márton Pósfai, James P. Crutchfield, Mehran Mesbahi, Raissa M.
**Keywords:** synchronization, attractor switching networks, complex networks
**Abstract:** Following the long-lived qualitative-dynamics tradition of explaining behavior in complex systems via the architecture of their attractors and basins, we investigate the patterns of switching between distinct trajectories in a network of synchronized oscillators. Our system, consisting of nonlinear amplitude-phase oscillators arranged in a ring topology with reactive nearest-neighbor coupling, is simple and connects directly to experimental realizations. We seek to understand how the multiple stable synchronized states connect to each other in state space by applying Gaussian white noise to each of the oscillators' phases. To do this, we first analytically identify a set of locally stable limit cycles at any given coupling strength. For each of these attracting states, we analyze the effect of weak noise via the covariance matrix of deviations around those attractors. We then explore the noise-induced attractor switching behavior via numerical investigations. For a ring of three oscill
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.116.238701
Volume: 116 Issue: 23 First Page #:
Date Submitted: 8/15/16 12:00AM Date Published: 6/1/16 12:00AM
Publication Location:
**Article Title:** Information Flows? A Critique of Transfer Entropies
**Authors:** Ryan G. James, Nix Barnett, James P. Crutchfield
**Keywords:** information flow, complex networks, transfer entropy
**Abstract:** A central task in analyzing complex dynamics is to determine the loci of information storage and the communication topology of information flows within a system. Over the last decade and a half, diagnostics for the latter have come to be dominated by the transfer entropy. Via straightforward examples, we show that it and a derivative quantity, the causation entropy, do not, in fact, quantify the flow of information. At one and the same time they can overestimate flow or underestimate influence. We isolate why this is the case and propose several avenues to alternate measures for information flow. We also address an auxiliary consequence: The proliferation of networks as a now-common theoretical model for large-scale systems, in concert with the use of transferlike entropies, has shoehorned dyadic relationships into our structural interpretation of the organization and behavior of complex systems. This interpretation thus fails to include the effects of polyadic dependencies. The net re
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**Journal:** Physics Letters A
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Volume: 380 Issue: 17 First Page #: 1517
Date Submitted: 8/15/16 12:00AM Date Published: 4/1/16 7:00AM
Publication Location:
**Article Title:** Statistical signatures of structural organization: The case of long memory in renewal processes
**Authors:** Sarah E. Marzen, James P. Crutchfield
**Keywords:** Fractal renewal process, Statistical complexity, Excess entropy, Power-law scaling, 1/f noise Zipf's law
**Abstract:** Identifying and quantifying memory are often critical steps in developing a mechanistic understanding of stochastic processes. These are particularly challenging and necessary when exploring processes that exhibit long-range correlations. The most common signatures employed rely on second-order temporal statistics and lead, for example, to identifying long memory in processes with power-law autocorrelation function and Hurst exponent greater than 1/2. However, most stochastic processes hide their memory in higher-order temporal correlations. Information measures—specifically, divergences in the mutual in- formation between a process' past and future (excess entropy) and minimal predictive memory stored in a process' causal states (statistical complexity)—provide a different way to identify long memory in pro- cesses with higher-order temporal correlations. However, there are no ergodic stationary processes with infinite excess entropy for which information measures have been compared t
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.93.022143
Volume: 93 Issue: 2 First Page #:
Date Submitted: 8/15/16 12:00AM Date Published: 2/1/16 8:00AM
Publication Location:
**Article Title:** Elusive present: Hidden past and future dependency and why we build models
**Authors:** Pooneh M. Ara, Ryan G. James, James P. Crutchfield
**Keywords:** Markov process, elusive information
**Abstract:** Modeling a temporal process as if it is Markovian assumes that the present encodes all of a process's history. When this occurs, the present captures all of the dependency between past and future. We recently showed that if one randomly samples in the space of structured processes, this is almost never the case. So, how does the Markov failure come about? That is, how do individual measurements fail to encode the past? and How many are needed to capture dependencies between the past and future? Here, we investigate how much information can be shared between the past and the future but not reflected in the present. We quantify this elusive information, give explicit calculational methods, and outline the consequences, the most important of which is that when the present hides past-future correlation or dependency we must move beyond sequence-based statistics and build state-based models.
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Volume: 9 Issue: First Page #:
Date Submitted: 8/16/16 12:00AM Date Published: 8/1/15 7:00AM
Publication Location:
**Article Title:** Time resolution dependence of information measures for spiking neurons: scaling and universality
**Authors:** Sarah E. Marzen, Michael R. DeWeese, James P. Crutchfield
**Keywords:** mutual information, information generation, spike train response
**Abstract:** The mutual information between stimulus and spike-train response is commonly used to monitor neural coding efficiency, but neuronal computation broadly conceived requires more refined and targeted information measures of input-output joint processes. A first step toward that larger goal is to develop information measures for individual output processes, including information generation (entropy rate), stored information (statistical complexity), predictable information (excess entropy), and active information accumulation (bound information rate). We calculate these for spike trains generated by a variety of noise-driven integrate-and-fire neurons as a function of time resolution and for alternating renewal processes. We show that their time-resolution dependence reveals coarse-grained structural properties of interspike interval statistics; e.g., ? -entropy rates that diverge less quickly than the firing rate indicated by interspike interval correlations. We also find evidence that th
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**Journal:** Current Opinion in Neurobiology
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.conb.2016.01.012
Volume: 37 Issue: First Page #: 106
Date Submitted: 8/16/16 12:00AM Date Published: 4/1/16 2:00PM
Publication Location:
**Article Title:** Quantifying collectivity
**Authors:** Bryan C Daniels, Christopher J Ellison, David C Krakauer, Jessica C Flack
**Keywords:** collective control, complex systems, information theory
**Abstract:** In biological function emerges from the interactions of components with only partially aligned interests. An example is the brain — a large aggregation of neurons capable of producing unitary, coherent output. A theory for how such aggregations produce coherent output remains elusive. A first question we might ask is how collective is the behavior of the components? Here we introduce two properties of collectivity and illustrate how these properties can be quantified using approaches from information theory and statistical physics. First, amplification quantifies the sensitivity of the large scale to information at the small scale and is related to the notion of criticality in statistical physics. Second, decomposability reveals the extent to which aggregate behavior is reducible to individual contributions or is the result of synergistic interactions among components forming larger subgroups. These measures facilitate identification of causally important components and subgroups that
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**Journal:** Nature Communications
Publication Identifier Type: DOI Publication Identifier: 10.1038/ncomms14301
Volume: 8 Issue: First Page #: 14301
Date Submitted: 8/31/17 12:00AM Date Published: 2/10/17 8:43AM
Publication Location:
**Article Title:** Control of finite critical behaviour in a small-scale social system
**Authors:** Bryan C. Daniels, David C. Krakauer, and Jessica C. Flack
**Keywords:** critical transitions, finite size systems, macaque monkeys
**Abstract:** Over the last decade new technologies for making large numbers of fine-grained measurements have led to the surprising discovery that many biological systems sit near a critical point [1, 2]. These systems are potentially more adaptive in that small changes to component behavior can induce large-scale changes in aggregate structure and function. Examples include networks of neurons [3], ant groups cooperatively carrying a load [4], and animal groups forming flocks and schools [5]. Accounting for criticality remains a challenge as sensitivity to perturbation suggests a lack of robustness. Furthermore, change induced by perturbation may not be adaptive. Compli- cating matters further critical phenomena can result from history-dependent stochastic processes [6]. A question central to distinguishing among these conflicting views of criticality is to what degree criticality can be controlled by the components of the system [2]. We address the control of criticality using data on conflict dy
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.94.032316
Volume: 94 Issue: First Page #: 032316
Date Submitted: 8/31/17 12:00AM Date Published: 9/26/16 7:57AM
Publication Location:
**Article Title:** Controllability of multiplex, multi-timescale networks
**Authors:** M. Posfai, J. Gao, S. P. Cornelius, A.-L. Barabasi, R. M. D'Souza
**Keywords:** structural control, multiple timescales, layered networks
**Abstract:** The paradigm of layered networks is used to describe many real-world systems – from biological networks, to social organizations and transportation systems. While recently there has been much progress in understanding the general properties of multilayer networks, our understanding of how to control such systems remains limited. One fundamental aspect that makes this endeavor challenging is that each layer can operate at a different timescale, thus we cannot directly apply standard ideas from structural control theory of individual networks. Here we address the problem of controlling multilayer and multi-timescale networks focusing on two-layer multiplex networks with one-to-one interlayer coupling. We investigate the practically relevant case when the control signal is applied to the nodes of one layer. We develop a theory based on disjoint path covers to determine the minimum number of inputs (Ni) necessary for full control. We show that if both layers operate on the same timescale t
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Date Submitted: 8/22/17 12:00AM Date Published: 6/1/17 7:00AM
Publication Location:
**Article Title:** Information trimming: Sufficient statistics, mutual information, and predictability from effective channel states
**Authors:** Ryan G. James, John R. Mahoney, James P. Crutchfield
**Keywords:** Collective behavior in networks; Information & communication theory; Neural information; Patterns in complex systems; Self-organization; Stochastic processes; Structural order parameter; Thermodynamics of computation
**Abstract:** One of the most basic characterizations of the relationship between two random variables, X and Y, is the value of their mutual information. Unfortunately, calculating it analytically and estimating it empirically are often stymied by the extremely large dimension of the variables. One might hope to replace such a high-dimensional variable by a smaller one that preserves its relationship with the other. It is well known that either X (or Y) can be replaced by its minimal sufficient statistic about Y (or X) while preserving the mutual information. While intuitively reasonable, it is not obvious or straightforward that both variables can be replaced simultaneously. We demonstrate that this is in fact possible: the information X's minimal sufficient statistic preserves about Y is exactly the information that Y's minimal sufficient statistic preserves about X. We call this procedure information trimming. As an important corollary, we consider the case where one variable is a stochastic ...
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Date Submitted: 8/22/17 12:00AM Date Published: 6/1/17 7:00AM
Publication Location:
**Article Title:** Thermodynamics of random number generation
**Authors:** Cina Aghamohammadi, James P. Crutchfield
**Keywords:** NP-hard problems; Nonequilibrium & irreversible thermodynamics; Nonequilibrium statistical mechanics; Thermodynamics of computation
**Abstract:** We analyze the thermodynamic costs of the three main approaches to generating random numbers via the recently introduced Information Processing Second Law. Given access to a specified source of randomness, a random number generator (RNG) produces samples from a desired target probability distribution. This differs from pseudorandom number generators (PRNGs) that use wholly deterministic algorithms and from true random number generators (TRNGs) in which the randomness source is a physical system. For each class, we analyze the thermodynamics of generators based on algorithms implemented as finite-state machines, as these allow for direct bounds on the required physical resources. This establishes bounds on heat dissipation and work consumption during the operation of three main classes of RNG algorithms—including those of von Neumann, Knuth, and Yao and Roche and Hoshi—and for PRNG methods. We introduce a general TRNG and determine its thermodynamic costs exactly for arbitrary target...
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**Journal:** Journal of Statistical Physics
Publication Identifier Type: DOI Publication Identifier: 10.1007/s10955-017-1822-y
Volume: 168 Issue: 4 First Page #: 873
Date Submitted: 8/22/17 12:00AM Date Published: 6/1/17 7:00AM
Publication Location:
**Article Title:** Fluctuations When Driving Between Nonequilibrium Steady States
**Authors:** Paul M. Riechers, James P. Crutchfield
**Keywords:** Stochastic thermodynamics; Fluctuation theorem; Nonequilibrium; Neuronal ion channel
**Abstract:** Maintained by environmental fluxes, biological systems are thermodynamic processes that operate far from equilibrium without detailed-balanced dynamics. Yet, they often exhibit well defined nonequilibrium steady states (NESSs). More importantly, critical thermodynamic functionality arises directly from transitions among their NESSs, driven by environmental switching. Here, we identify the constraints on excess heat and dissipated work necessary to control a system that is kept far from equilibrium by background, uncontrolled “housekeeping” forces. We do this by extending the Crooks fluctuation theorem to transitions among NESSs, without invoking an unphysical dual dynamics. This and corresponding integral fluctuation theorems determine how much work must be expended when controlling systems maintained far from equilibrium. This generalizes thermodynamic feedback control theory, showing that Maxwellian Demons can leverage mesoscopic-state information to take advantage of the excess ...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-017-04928-7
Volume: 7 Issue: 1 First Page #:
Date Submitted: 8/22/17 12:00AM Date Published: 7/1/17 7:00AM
Publication Location:
**Article Title:** Extreme Quantum Advantage when Simulating Classical Systems with Long-Range Interaction
**Authors:** Cina Aghamohammadi, John R. Mahoney, James P. Crutchfield
**Keywords:** Computer science; Quantum information; Qubits
**Abstract:** Classical stochastic processes can be generated by quantum simulators instead of the more standard classical ones, such as hidden Markov models. One reason for using quantum simulators has recently come to the fore: they generally require less memory than their classical counterparts. Here, we examine this quantum advantage for strongly coupled spin systems—in particular, the Dyson one-dimensional Ising spin chain with variable interaction length. We find that the advantage scales with both interaction range and temperature, growing without bound as interaction range increases. In particular, simulating Dyson’s original spin chain with the most memory-efficient classical algorithm known requires infinite memory, while a quantum simulator requires only finite memory. Thus, quantum systems can very efficiently simulate strongly coupled one-dimensional classical spin systems.
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**Journal:** Chaos: An Interdisciplinary Journal of Nonlinear Science
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Volume: 26 Issue: 9 First Page #: 094816
Date Submitted: 8/22/17 12:00AM Date Published: 9/1/16 7:00AM
Publication Location:
**Article Title:** Patterns of patterns of synchronization: Noise induced attractor switching in rings of coupled nonlinear oscillators
**Authors:** Jeffrey Emenheiser, Airlie Chapman, Márton Pósfai, James P. Crutchfield, Mehran Mesbahi, Raissa M.
**Keywords:** Attractors; Coupled oscillators; Nonlinear dynamics; Eigenvalues; Noise propagation
**Abstract:** Following the long-lived qualitative-dynamics tradition of explaining behavior in complex systems via the architecture of their attractors and basins, we investigate the patterns of switching between distinct trajectories in a network of synchronized oscillators. Our system, consisting of nonlinear amplitude-phase oscillators arranged in a ring topology with reactive nearest-neighbor coupling, is simple and connects directly to experimental realizations. We seek to understand how the multiple stable synchronized states connect to each other in state space by applying Gaussian white noise to each of the oscillators' phases. To do this, we first analytically identify a set of locally stable limit cycles at any given coupling strength. For each of these attracting states, we analyze the effect of weak noise via the covariance matrix of deviations around those attractors. We then explore the noise-induced attractor switching behavior via numerical investigations. For a ring of three ...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physics Letters A
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.physleta.2016.12.036
Volume: 381 Issue: 14 First Page #: 1223
Date Submitted: 8/22/17 12:00AM Date Published: 4/1/17 7:00AM
Publication Location:
**Article Title:** The ambiguity of simplicity in quantum and classical simulation
**Authors:** Cina Aghamohammadi, John R. Mahoney, James P. Crutchfield
**Keywords:** Quantum information; Information theory; Stochastic process; Hidden Markov model; ?-Machine
**Abstract:** A system's perceived simplicity depends on whether it is represented classically or quantally. This is not so surprising, as classical and quantum physics are descriptive frameworks built on different assumptions that capture, emphasize, and express different properties and mechanisms. What is surprising is that, as we demonstrate, simplicity is ambiguous: the relative simplicity between two systems can change sign when moving between classical and quantum descriptions. Here, we associate simplicity with small model-memory. We see that the notions of absolute physical simplicity at best form a partial, not a total, order. This suggests that appeals to principles of physical simplicity, via Ockham's Razor or to the “elegance” of competing theories, may be fundamentally subjective. Recent rapid progress in quantum computation and quantum simulation suggest that the ambiguity of simplicity will strongly impact statistical inference and, in particular, model selection.
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**Journal:** Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.116.238701
Volume: 116 Issue: 23 First Page #:
Date Submitted: 8/22/17 12:00AM Date Published: 6/1/16 7:00AM
Publication Location:
**Article Title:** Information Flows? A Critique of Transfer Entropies
**Authors:** Ryan G. James, Nix Barnett, James P. Crutchfield
**Keywords:** Entropy; Network flow
**Abstract:** A central task in analyzing complex dynamics is to determine the loci of information storage and the communication topology of information flows within a system. Over the last decade and a half, diagnostics for the latter have come to be dominated by the transfer entropy. Via straightforward examples, we show that it and a derivative quantity, the causation entropy, do not, in fact, quantify the flow of information. At one and the same time they can overestimate flow or underestimate influence. We isolate why this is the case and propose several avenues to alternate measures for information flow. We also address an auxiliary consequence: The proliferation of networks as a now-common theoretical model for large-scale systems, in concert with the use of transferlike entropies, has shoehorned dyadic relationships into our structural interpretation of the organization and behavior of complex systems. This interpretation thus fails to include the effects of polyadic dependencies. The net re
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physics Letters A
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.physleta.2016.02.052
Volume: 380 Issue: 17 First Page #: 1517
Date Submitted: 8/22/17 12:00AM Date Published: 4/1/16 7:00AM
Publication Location:
**Article Title:** Statistical signatures of structural organization: The case of long memory in renewal processes
**Authors:** Sarah E. Marzen, James P. Crutchfield
**Keywords:** Fractal renewal process; Statistical complexity; Excess entropy; Power-law scaling; 1/f noise; Zipf's law
**Abstract:** Identifying and quantifying memory are often critical steps in developing a mechanistic understanding of stochastic processes. These are particularly challenging and necessary when exploring processes that exhibit long-range correlations. The most common signatures employed rely on second-order temporal statistics and lead, for example, to identifying long memory in processes with power-law autocorrelation function and Hurst exponent greater than 1/2. However, most stochastic processes hide their memory in higher-order temporal correlations. Information measures—specifically, divergences in the mutual information between a process' past and future (excess entropy) and minimal predictive memory stored in a process' causal states (statistical complexity)—provide a different way to identify long memory in processes with higher-order temporal correlations. However, there are no ergodic stationary processes with infinite excess entropy for which information measures have been compared to...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Entropy
Publication Identifier Type: DOI Publication Identifier: 10.3390/e19050214
Volume: 19 Issue: 5 First Page #: 214
Date Submitted: 8/22/17 12:00AM Date Published: 5/8/17 7:00AM
Publication Location:
**Article Title:** Anatomy of a Spin: The Information-Theoretic Structure of Classical Spin Systems
**Authors:** Vikram S. Vijayaraghavan, Ryan G. James, James P. Crutchfield
**Keywords:** Ising spin model; thermodynamic entropy density; dual total correlation; entropy rate; elusive information; enigmatic information; predictable information rate; complex system
**Abstract:** Collective organization in matter plays a significant role in its expressed physical properties. Typically, it is detected via an order parameter, appropriately defined for each given system's observed emergent patterns. Recent developments in information theory, however, suggest quantifying collective organization in a system- and phenomenon-agnostic way: decomposing the system's thermodynamic entropy density into a localized entropy, that is solely contained in the dynamics at a single location, and a bound entropy, that is stored in space as domains, clusters, excitations, or other emergent structures. As a concrete demonstration, we compute this decomposition and related quantities explicitly for the nearest-neighbor Ising model on the 1D chain, on the Bethe lattice with coordination number k=3 , and on the 2D square lattice, illustrating its generality and the functional insights it gives near and away from phase transitions. In particular, we consider the roles that different ...
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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.93.022143
Volume: 93 Issue: 2 First Page #:
Date Submitted: 8/22/17 12:00AM Date Published: 2/1/16 8:00AM
Publication Location:
**Article Title:** Elusive present: Hidden past and future dependency and why we build models
**Authors:** Pooneh M. Ara, Ryan G. James, James P. Crutchfield
**Keywords:** Stochastic processes; Information theory; Markovian processes; Time series analysis
**Abstract:** Modeling a temporal process as if it is Markovian assumes that the present encodes all of a process's history. When this occurs, the present captures all of the dependency between past and future. We recently showed that if one randomly samples in the space of structured processes, this is almost never the case. So, how does the Markov failure come about? That is, how do individual measurements fail to encode the past? and How many are needed to capture dependencies between the past and future? Here, we investigate how much information can be shared between the past and the future but not reflected in the present. We quantify this elusive information, give explicit calculational methods, and outline the consequences, the most important of which is that when the present hides past-future correlation or dependency we must move beyond sequence-based statistics and build state-based models.
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**Journal:** Physics Letters A
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.physleta.2016.01.008
Volume: 380 Issue: First Page #: 998
Date Submitted: 8/22/17 12:00AM Date Published: 3/1/16 8:00AM
Publication Location:
**Article Title:** Exact complexity: The spectral decomposition of intrinsic computation
**Authors:** James P. Crutchfield, Christopher J. Ellison, Paul M. Riechers
**Keywords:** Excess entropy; Statistical complexity; Projection operator; ResolventEntropy rate; Predictable information
**Abstract:** We give exact formulae for a wide family of complexity measures that capture the organization of hidden nonlinear processes. The spectral decomposition of operator-valued functions leads to closed-form expressions involving the full eigenvalue spectrum of the mixed-state presentation of a process's ?-machine causal-state dynamic. Measures include correlation functions, power spectra, past-future mutual information, transient and synchronization informations, and many others. As a result, a direct and complete analysis of intrinsic computation is now available for the temporal organization of finitary hidden Markov models and nonlinear dynamical systems with generating partitions and for the spatial organization in one-dimensional systems, including spin systems, cellular automata, and complex materials via chaotic crystallography.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Chaos
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5003041
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Prediction and Generation of Binary Markov Processes: Can a Finite-State Fox Catch a Markov Mouse?
**Authors:** Joshua Ruebeck, Ryan G. James, John R. Mahoney, James P. Crutchfield
**Keywords:** Statistical Mechanics; Computational Complexity; Information Theory; Chaotic Dynamics
**Abstract:** Understanding the generative mechanism of a natural system is a vital component of the scientific method. Here, we investigate one of the fundamental steps toward this goal by presenting the minimal generator of an arbitrary binary Markov process. This is a class of processes whose predictive model is well known. Surprisingly, the generative model requires three distinct topologies for different regions of parameter space. We show that a previously proposed generator for a particular set of binary Markov processes is, in fact, not minimal. Our results shed the first quantitative light on the relative (minimal) costs of prediction and generation. We find, for instance, that the difference between prediction and generation is maximized when the process is approximately independently, identically distributed.
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**Journal:** Physical Review X
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Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published: 8/22/18 7:00AM
Publication Location:
**Article Title:** Extreme Quantum Memory Advantage for Rare-Event Sampling
**Authors:** Cina Aghamohammadi, Samuel P. Loomis, John R. Mahoney, James P. Crutchfield
**Keywords:** quantum algorithm; large deviation theory; biased sampling; quantum memory; quantum advantage; stochastic process; hidden Markov model
**Abstract:** We introduce a quantum algorithm for efficient biased sampling of the rare events generated by classical memoryful stochastic processes. We show that this quantum algorithm gives an extreme advantage over known classical biased sampling algorithms in terms of the memory resources required. The quantum memory advantage ranges from polynomial to exponential and when sampling the rare equilibrium configurations of spin systems the quantum advantage diverges.
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**Publication Type:** Journal Article Peer Reviewed: N **Publication Status:** 5-Submitted
**Journal:** arXiv Preprint
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/17 12:00AM Date Published:
Publication Location:
**Article Title:** Islands in the Gap: Intertwined Transport and Localization in Structurally Complex Materials
**Authors:** Xincheng Lei, Dowman P. Varn, James P. Crutchfield
**Keywords:** Anderson localization; hidden Markov process; structured disorder; ϵ-machines; computational mechanics
**Abstract:** Localized waves in disordered one-dimensional materials have been studied for decades, including white-noise and correlated disorder, as well as quasi-periodic disorder. How these wave phenomena relate to those in crystalline (periodic ordered) materials---arguably the better understood setting---has been a mystery ever since Anderson discovered disorder-induced localization. Nonetheless, together these revolutionized materials science and technology and led to new physics far beyond the solid state. We introduce a broad family of structurally complex materials---chaotic crystals---that interpolate between these organizational extremes---systematically spanning periodic structures and random disorder. Within the family one can tune the degree of disorder to sweep through an intermediate structurally disordered region between two periodic lattices. This reveals new transport and localization phenomena reflected in a rich array of energy-dependent localization degree and density of ...
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**Journal:** Chaos
Publication Identifier Type: Publication Identifier: 10.1063/1.4986248
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published: 8/22/18 7:00AM
Publication Location:
**Article Title:** Spectral Simplicity of Apparent Complexity, Part II: Exact Complexities and Complexity Spectra
**Authors:** Paul M. Riechers, James P. Crutchfield
**Keywords:** hidden Markov model; entropy rate; excess entropy; predictable information; statistical complexity; projection operator; complex analysis; resolvent; Drazin inverse
**Abstract:** The meromorphic functional calculus developed in Part I overcomes the nondiagonalizability of linear operators that arises often in the temporal evolution of complex systems and is generic to the metadynamics of predicting their behavior. Using the resulting spectral decomposition, we derive closed-form expressions for correlation functions, finite-length Shannon entropy-rate approximates, asymptotic entropy rate, excess entropy, transient information, transient and asymptotic state uncertainty, and synchronization information of stochastic processes generated by finite-state hidden Markov models. This introduces analytical tractability to investigating information processing in discrete-event stochastic processes, symbolic dynamics, and chaotic dynamical systems. Comparisons reveal mathematical similarities between complexity measures originally thought to capture distinct informational and computational properties. We also introduce a new kind of spectral analysis via coronal ...
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**Journal:** Chaos
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Spectral Simplicity of Apparent Complexity, Part I: The Nondiagonalizable Metadynamics of Prediction
**Authors:** Paul M. Riechers, James P. Crutchfield
**Keywords:** hidden Markov model; entropy rate; excess entropy; predictable information, statistical complexity; projection operator; complex analysis; resolvent; Drazin inverse
**Abstract:** Virtually all questions that one can ask about the behavioral and structural complexity of a stochastic process reduce to a linear algebraic framing of a time evolution governed by an appropriate hidden-Markov process generator. Each type of question---correlation, predictability, predictive cost, observer synchronization, and the like---induces a distinct generator class. Answers are then functions of the class-appropriate transition dynamic. Unfortunately, these dynamics are generically nonnormal, nondiagonalizable, singular, and so on. Tractably analyzing these dynamics relies on adapting the recently introduced meromorphic functional calculus, which specifies the spectral decomposition of functions of nondiagonalizable linear operators, even when the function poles and zeros coincide with the operator's spectrum. Along the way, we establish special properties of the projection operators that demonstrate how they capture the organization of subprocesses within a complex system...
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**Journal:** arXiv Preprint
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/17 12:00AM Date Published:
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**Article Title:** Not All Fluctuations are Created Equal: Spontaneous Variations in Thermodynamic Function
**Authors:** James P. Crutchfield, Cina Aghamohammadi
**Keywords:** large deviation theory; thermodynamic formalism; fluctuation spectrum; entropy rate; fluctuation relations; nonequilibrium steady state; Maxwell's Demon; information ratchet; Second Law of Thermodynamics
**Abstract:** Almost all processes -- highly correlated, weakly correlated, or correlated not at all---exhibit statistical fluctuations. Often physical laws, such as the Second Law of Thermodynamics, address only typical realizations -- as highlighted by Shannon's asymptotic equipartition property and as entailed by taking the thermodynamic limit of an infinite number of degrees of freedom. Indeed, our interpretations of the functioning of macroscopic thermodynamic cycles are so focused. Using a recently derived Second Law for information processing, we show that different subsets of fluctuations lead to distinct thermodynamic functioning in Maxwellian Demons. For example, while typical realizations may operate as an engine -- converting thermal fluctuations to useful work -- even "nearby" fluctuations (nontypical, but probable realizations) behave differently, as Landauer erasers -- converting available stored energy to dissipate stored information. One concludes that ascribing a single, unique ...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Entropy
Publication Identifier Type: DOI Publication Identifier: 10.3390/e19100531
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Multivariate Dependence Beyond Shannon Information
**Authors:** Ryan G. James, James P. Crutchfield
**Keywords:** stochastic process; transfer entropy; causation entropy; partial information decomposition; network science; causality
**Abstract:** Accurately determining dependency structure is critical to discovering a system's causal organization. We recently showed that the transfer entropy fails in a key aspect of this---measuring information flow---due to its conflation of dyadic and polyadic relationships. We extend this observation to demonstrate that this is true of all such Shannon information measures when used to analyze multivariate dependencies. This has broad implications, particularly when employing information to express the organization and mechanisms embedded in complex systems, including the burgeoning efforts to combine complex network theory with information theory. Here, we do not suggest that any aspect of information theory is wrong. Rather, the vast majority of its informational measures are simply inadequate for determining the meaningful dependency structure within joint probability distributions. Therefore, such information measures are inadequate for discovering intrinsic causal relations. We close...
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**Journal:** AIP Advances
Publication Identifier Type: Publication Identifier: 10.1063/1.5040705
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Beyond the Spectral Theorem: Spectrally Decomposing Arbitrary Functions of Nondiagonalizable Operators
**Authors:** Paul M. Riechers, James P. Crutchfield
**Keywords:** Statistical Mechanics; Spectral Theory; Chaotic Dynamics; Quantum Physics
**Abstract:** Nonlinearities in finite dimensions can be linearized by projecting them into infinite dimensions. Unfortunately, often the linear operator techniques that one would then use simply fail since the operators cannot be diagonalized. This curse is well known. It also occurs for finite-dimensional linear operators. We circumvent it by developing a meromorphic functional calculus that can decompose arbitrary functions of nondiagonalizable linear operators in terms of their eigenvalues and projection operators. It extends the spectral theorem of normal operators to a much wider class, including circumstances in which poles and zeros of the function coincide with the operator spectrum. By allowing the direct manipulation of individual eigenspaces of nonnormal and nondiagonalizable operators, the new theory avoids spurious divergences. As such, it yields novel insights and closed-form expressions across several areas of physics in which nondiagonalizable dynamics are relevant, including ...
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.96.012317
Volume: 96 Issue: 1 First Page #:
Date Submitted: 8/24/17 12:00AM Date Published: 7/1/17 7:00AM
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:** Explosive percolation; Collective behavior in networks; Discontinuous phase transition; Directed networks; Social networks
**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. We present analysis with branching process
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**Journal:** Chaos
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Volume: 99 Issue: First Page #: 012304
Date Submitted: 9/3/20 12:00AM Date Published: 1/3/19 8:00AM
Publication Location:
**Article Title:** Master stability functions for complete, intra-layer and inter-layer synchronization in multiplex networks
**Authors:** Longkun Tang, Xiaoqun Wu, Jinhu Lu, Jun-an Lu, Raissa M. D'Souza
**Keywords:** Multiplex networks; master stability function; intra-layer synchronization; inter-layer synchronization; synchronized region
**Abstract:** Synchronization phenomena are of broad interest across disciplines and increasingly of interest in a multiplex network setting. Here we show how the Master Stability Function, a celebrated framework for analyzing synchronization on a single network, can be extended to certain classes of multiplex networks with different intra-layer and inter-layer coupling functions. We derive three master stability equations that determine respectively the necessary regions of complete synchronization, intra-layer synchronization and inter-layer synchronization. We calculate these three regions explicitly for the case of a two-layer network of Rossler oscillators and show that the overlap of the regions determines the type of synchronization achieved. In particular, if the inter- or intra-layer coupling function is such that the inter-layer or intra-layer synchronization region is empty, complete synchronization cannot be achieved regardless of the coupling strength. Furthermore, ...
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.98.022127
Volume: 98 Issue: 022127 First Page #:
Date Submitted: 8/27/18 12:00AM Date Published:
Publication Location:
**Article Title:** Self-organization of dragon king failures
**Authors:** Yuansheng Lin, Keith Burghardt, Martin Rohden, Pierre-Andre Noel, Raissa M. D'Souza
**Keywords:** Self-organized criticality; Large deviation theory; Network control
**Abstract:** The mechanisms underlying cascading failures are often modeled via the paradigm of self-organized criticality. Here we introduce a simple network model where nodes self-organize to be either weakly or strongly protected against failure in a manner that captures the trade-off between degradation and reinforcement of nodes inherent in many network systems. If strong nodes cannot fail, any failure is contained to a single, isolated cluster of weak nodes and the model produces power-law distributions of failure sizes. We classify the large, rare events that involve the failure of only a single cluster as “black swans.” In contrast, if strong nodes fail once a sufficient fraction of their neighbors fail, then failure can cascade across multiple clusters of weak nodes. If over 99.9% of the nodes fail due to this cluster hopping mechanism, we classify this as a “dragon king,” which are massive failures caused by mechanisms distinct from smaller failures. The dragon kings observed are self-org
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**Journal:** Chaos
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.4994567
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Stability of entrainment of a continuum of coupled oscillators
**Authors:** Jordan Snyder, Anatoly Zlotnik, and Aric Hagberg
**Keywords:** Synchronization; Control; Nonlinear dynamics
**Abstract:** Two well-understood approaches can be applied to impose coherent behavior in a diverse population of dynamical systems: the “top-down” approach of applying a common driving signal, and the “bottom-up” approach of imposing pairwise coupling. While these approaches yield similar behaviors, their precise characteristics can put them in opposition. In this article we study a situation that high- lights both the synergy and tension that can exist between driving and coupling in collections of oscillators.
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**Journal:** arXiv Preprint
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Volume: 1 Issue: First Page #: 033125
Date Submitted: 9/3/20 12:00AM Date Published: 11/22/19 8:00AM
Publication Location:
**Article Title:** Susceptible individuals drive active social contagion
**Authors:** N. N. Chung, L. Y. Chew, W. Chen, R. M. D'Souza, and C. H. Lai
**Keywords:** Social influence; Opinion dynamics; Complex networks; Terse messages; Active versus Passive influence
**Abstract:** That influential individuals play a catalyzing role in driving large- scale social contagion has been the focus of many recent empirical and theoretical studies. Yet, complementary studies suggest that the success of social contagion depends largely on having a group of highly susceptible individuals. Here we show that being influen- tial is not due solely to having susceptible peers and that the relative importance of influential versus susceptible individuals depends on the underlying mechanism driving the contagion. Our mathematical models show that for passive social influence both influential and susceptible individuals catalyze the spread of the contagion progres- sively and equitably. In contrast, for active social influence, suscep- tible individuals facilitate rapid initial contagion, but then influential individuals are necessary for sustaining the growth of the contagion. We show that active influence characterizes certain online social net- works, like retweeting ...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** American Control Conference (ACC), 2016
Publication Identifier Type: DOI Publication Identifier: 10.1109/ACC.2016.7526542
Volume: Issue: First Page #:
Date Submitted: 8/24/17 12:00AM Date Published: 7/7/17 1:22AM
Publication Location:
**Article Title:** Multiple time-scales in network-of-networks
**Authors:** Airlie Chapman, Mehran Mesbahi
**Keywords:** Network-of-networks; Time-Scale Separation; Networked Dynamic Systems; State-Dependent Networks
**Abstract:** This paper examines a multiple time-scale system where each layer of time-scale dynamics corresponds to a net- work. Coupling between layers induces a network-of-networks dynamic system. Assuming a hierarchical interaction structure between network time-scale layers with sufficient time-scale differences, layers can be studied under a separation principle. We describe stability of the network-of-networks through a composite Lyapunov function and provide a bilinear matrix inequality condition to guarantee asymptotic stability. Tech- niques are proposed to adapt this inequality into a linear matrix inequality condition making it computationally efficient to solve as a convex optimization problem. We examine estimates of the dynamics' domain of attraction and provide conservative bounds on the time-scale separation required to guarantee stability. A class of network-of-networks dynamics with modified consensus dynamics and a state-dependent network structure is then explored...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** International Federation for Automatic Control (IFAC)
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.ifacol.2017.08.2268
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published: 7/2/17 8:23AM
Publication Location:
**Article Title:** Large-Scale Distributed Kalman Filtering via an Optimization Approach
**Authors:** Mathias Hudoba de Badyn, Mehran Mesbahi
**Keywords:** Machine learning; Fast Kalman algorithms; State estimation; Gradient methods
**Abstract:** Large-scale distributed systems such as sensor networks, often need to achieve filtering and consensus on an estimated parameter from high-dimensional measurements. Running a Kalman filter on every node in such a network is computationally intensive; in particular the matrix inversion in the Kalman gain update step is expensive. In this paper, we extend previous results in distributed Kalman filtering and large-scale machine learning to propose a gradient descent step for updating an estimate of the error covariance matrix; this is then embedded and analyzed in the context of distributed Kalman filtering. We provide properties of the resulting filters, in addition to a number of applications throughout the paper.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Transactions on Network Science and Engineering
Publication Identifier Type: DOI Publication Identifier: 10.1109/TNSE.2017.2754944
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Weighted Bearing-Compass Dynamics: Edge and Leader Selection
**Authors:** Eric Schoof, Airlie Chapman, Mehran Mesbahi
**Keywords:** Bearing rigidity; Formation control; Submodularity, Network design, Leader selection
**Abstract:** This paper considers the design and effective interfaces of a distributed robotic formation running planar weighted bearing-compass dynamics. We present results which support methodologies to construct formation topologies using submodular optimization techniques. Further, a convex optimization framework is developed for the selection of edge weights which increase performance. We explore a method to select leader agents which can translate and scale the formation, and a corresponding controller that promotes the formation keeping its overall shape intact during manipulation. The results are supported with examples that illustrate the approach and their differing levels of performance.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** IEEE Transactions on Control of Network Systems
Publication Identifier Type: DOI Publication Identifier: 10.1109/TCNS.2018.2800401
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Time-Scale Separation in Networks: State-Dependent Graphs and Consensus Tracking
**Authors:** Armand Awad, Airlie Chapman, Eric Schoof, Anshu Narang-Siddarth, Mehran Mesbahi
**Keywords:** Time-Scale Separation; Networked Dynamic Systems; State-Dependent Networks
**Abstract:** This paper studies the coupled dynamics spanning multiple time-scales that arise in networked systems. Two particular cases are examined. In the first, agents evolve according to the consensus dynamics over state-dependent graphs whose weight dynamics are slow-varying. In the second, the consensus dynamics are coupled to rapidly evolving nonlinear node dynamics. In both instances, graph-based guarantees are provided that certify the existence of a separation principle across time-scales. Further, the effect of the network's structure on the composite multiple time-scale system's stability and basin of attraction is quantified in each case. As illustrated by specific numeric examples, these results provide designers with a network-centric approach to improve the performance and stability of such coupled systems.
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**Journal:** Reliability Engineering & System Safety
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.ress.2016.11.010
Volume: 160 Issue: First Page #: 89
Date Submitted: 8/28/17 12:00AM Date Published: 4/1/17 7:00AM
Publication Location:
**Article Title:** AC power flow importance measures considering multi-element failures
**Authors:** Jian Li, Leonardo Dueñas-Osorio, Changkun Chen, Congling Shi
**Keywords:** AC power flow; N-k reliability; Importance ranking; Cascading failure; Functional reliability
**Abstract:** Quantifying the criticality of individual components of power systems is essential for overall reliability and management. This paper proposes an AC-based power flow element importance measure, while considering multi-element failures. The measure relies on a proposed AC-based cascading failure model, which captures branch overflow, bus load shedding, and branch failures, via AC power flow and optimal power flow analyses. Taking the IEEE 30, 57 and 118-bus power systems as case studies, we find that N-3 analyses are sufficient to measure the importance of a bus or branch. It is observed that for a substation bus, its importance is statistically proportional to its power demand, but this trend is not observed for power plant buses. While comparing with other reliability, functionality, and topology-based importance measures popular today, we find that a DC power flow model, although better correlated with the benchmark AC model as a whole, still fails to locate some critical elements...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Water Resources Planning and Management
Publication Identifier Type: DOI Publication Identifier: 10.1061/(ASCE)WR.1943-5452.0000709
Volume: 143 Issue: 1 First Page #: 04016068
Date Submitted: 8/28/17 12:00AM Date Published: 1/1/17 8:00AM
Publication Location:
**Article Title:** Exploring Topological Effects on Water Distribution System Performance Using Graph Theory and Statistical Models
**Authors:** Jacob M. Torres, Leonardo Duenas-Osorio, Qilin Li, Alireza Yazdani
**Keywords:** Water distribution systems; Graph theory; Network topology; Random pipe networks; Statistical modeling; Generalized additive models; Percolation theory; EPANET
**Abstract:** Water distribution system (WDS) pipe networks can vary widely in topological layout. The variations in branch and loop combinatorics across large pipe network data sets are ideal for exploring graph-based structural patterns and linkages with engineered performance. To facilitate this exploration, a library of 10,001 lattice-like pipe networks is developed. Each network is equipped with hydraulic, water quality, and diurnal demand information for extended period simulations. Results show strong correlations exist among graph theory metrics (e.g., geodesic, spectral, and combinatorics-based) and performance measures (e.g., maximum hourly unit headloss, average water age, and average chemical concentration). These trends are extended with performance predictions using parametric and semiparametric statistical models. Predictive accuracies are evident for processes that follow diffusion-like behaviors, indicating coupled applications of graph theory and statistical methods may have ...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Structural Safety
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Quantum-Inspired Boolean States for Bounding Engineering Network Reliability Assessment
**Authors:** Leonardo Dueñas-Osorio, Moshe Vardi, Javier Rojo
**Keywords:** Network reliability; Tensor networks; Satisfiability; Counting; Boolelan logic; Quantum computing
**Abstract:** Significant methodological progress has taken place to quantify the reliability of networked systems over the past decades. Both numerical and analytical methods have enjoyed improvements via a host of advanced Monte Carlo simulation strategies, state space partition methods, statistical learning, and Boolean functions among others. The latter approach exploits logic to approximate network reliability assessments efficiently while offering theoretical error guarantees. In parallel, physicists have made progress modeling complex systems via tensor networks (TNs), particularly quantum many-body systems. Inspired by the representation power of quantum TNs, this paper offers a new approach to efficiently bound network reliability (REL) classically. It does so by exactly solving a related network Boolean satisfiability counting problem (or #SAT_{NET}), represented as a TN, which upper-bounds general all-terminal reliability (ATR) problems by counting configurations in which all network...
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Computer-Aided Civil and Infrastructure Engineering
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Efficient Infrastructure Restoration Strategies using the Recovery Operator
**Authors:** Andres Gonzalez, Airlie Chapman, Leonardo Duenas-Osorio, Mehran Mesbahi, Raissa M. D'Souza
**Keywords:** Infrastructure vulnerability; Interdependent networks; Model; Recovery dynamics
**Abstract:** Infrastructure systems are critical for so- ciety's resilience, government operation and overall de- fense. Thereby, it is imperative to develop informative and computationally e♂cient analysis methods for infrastruc- ture systems, while revealing their vulnerability and reco- verability. To capture practical constraints in systems ana- lyses, various di♂erent layers of complexity are required, such as limited element capacities, restoration resources, and the presence of interdependence among systems. High- ♀delity modeling such as mixed integer programming and physics-based modeling can often be computationally expen- sive, making time-sensitive analyses challenging. Further- more, the complexity of recovery solutions can reduce ana- lysis transparency. An alternative, presented in this work, is a reduced-order representation, dubbed a recovery opera- tor, of a high-♀ delity time-dependent recovery model of a system of interdependent networks. The form of the opera- tor is assumed ...
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**Journal:** Nano Letters
Publication Identifier Type: Publication Identifier: 10.1021/acs.nanolett.7b02026
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Complex dynamical networks constructed with fully controllable nonlinar nanomechanical oscillators
**Authors:** Warren Fon, Matt Matheny, Jarvis Li, Lev Krayzman, Michael Cross, Raissa D'Souza, James Crutchfiel
**Keywords:** nanoscale oscillators, complex networks
**Abstract:** Control of the global parameters of complex networks has been explored experimentally in a variety of contexts. Yet, the more difficult prospect of realizing arbitrary network architectures, especially analog physical networks, that provide dynamical control of individual nodes and edges has remained elusive. It also proves challenging to measure a complex network's full internal dynamics given the vast hierarchy of timescales involved. These span from the fastest nodal dynamics to very slow epochs over which emergent global phenomena, including network synchronization and the manifestation of exotic steady states, eventually emerge. Here, we demonstrate an experimental system that satisfies these requirements. It is based upon modular, fully controllable, nonlinear radio-frequency nanomechanical oscillators, designed to form the nodes of complex dynamical networks with edges configured with arbitrary topology. The dynamics of these oscillators and their surrounding network are analog,
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Reliability Engineering and System Safety
Publication Identifier Type: DOI Publication Identifier: http://dx.doi.org/10.1016/j.ress.2016.07.003
Volume: 156 Issue: First Page #: 24
Date Submitted: 8/31/17 12:00AM Date Published: 7/6/17 7:00AM
Publication Location:
**Article Title:** Connectivity reliability and topological controllability of infrastructure networks: A comparative assessment
**Authors:** Jian Li, Leonardo Dueñas-Osorio, Changkun Chen, Congling Shi
**Keywords:** Reliability, controllability of infrastructure
**Abstract:** As infrastructure systems evolve, their design, maintenance, and optimal performance require mature tools from system reliability theory, as well as principles to handle emerging system features, such as controllability. This paper conducts a comparative study of the connectivity reliability (CR) and topolo- gical controllability (TC) of infrastructure systems in terms of three aspects: topology, robustness, and node importance. Taking eight city-level power transmission networks and thousands of artificial net- works as examples, this paper reveals that a dense and homogeneous network topology is better to satisfy CR and TC requirements, than more common sparse and heterogeneous networks when node attributes are generic. It is observed that the average degree's impact on CR is more significant than on TC, while degree heterogeneity is more significant on TC. When node attributes are accounted for, for generators the reliability-based node importance measure may underestimate some impo
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**Journal:** Journal of Risk Assessment
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Interdependent Network Recovery Games
**Authors:** Andrew M. Smith, Andr ?es Gonza ?lez, Leonardo Duenas-Osorio, Raissa D'Souza
**Keywords:** infrastructure recovery, game theory, optimization
**Abstract:** Recovery of interdependent infrastructure networks in the presence of catastrophic failure is crucial to the economy and welfare of society. Recently, centralized methods have been developed to address optimal resource allocation in post-disaster recovery scenarios of interdependent infrastructure systems that minimize total cost. In real-world systems, however, multiple independent, possibly noncooperative, utility network controllers are responsible for making recovery decisions, resulting in suboptimal decentralized processes. With the goal of minimizing recovery cost, a best-case decentralized model allows controllers to develop a full recovery plan and negotiate until all parties are satisfied (an equilibrium is reached). Such a model is computationally intensive for planning and negotiating, and time is a crucial resource in post-disaster recovery scenarios. Furthermore, in this work, we prove this best-case decentralized negotiation process could continue indefinitely under cert
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Chaos: An Interdisciplinary Journal of Nonlinear Science
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5017534
Volume: 28 Issue: 7 First Page #: 075306
Date Submitted: 8/22/18 12:00AM Date Published: 7/1/18 7:00AM
Publication Location:
**Article Title:** Inter-scale information flow as a surrogate for downward causation that maintains spiral waves
**Authors:** Hiroshi Ashikaga, Ryan G. James
**Keywords:** Diseases and conditions, Electrochemistry, Pathology, Entropy
**Abstract:** A rotor, the rotation center of spiral waves, has been proposed as a causal mechanism to maintain atrial fibrillation (AF) in human. However, our current understanding of the causality between rotors and spiral waves remains incomplete. One approach to improving our understanding is to determine the relationship between rotors and downward causation from the macro-scale collective behavior of spiral waves to the micro-scale behavior of individual components in a cardiac system. This downward causation is quantifiable as inter-scale information flow that can be used as a surrogate for the mechanism that maintains spiral waves. We used a numerical model of a cardiac system and generated a renormalization group with system descriptions at multiple scales. We found that transfer entropy quantified the upward and downward inter-scale information flow between micro- and macro-scale descriptions of the cardiac system with spiral waves. In addition, because the spatial profile of transfer entr
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**Journal:** ArXiv preprint
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** The Origins of Computational Mechanics: A Brief Intellectual History and Several Clarifications
**Authors:** James P. Crutchfield
**Keywords:** Statistical Mechanics, Information Theory, Machine Learning
**Abstract:** The principle goal of computational mechanics is to define pattern and structure so that the organization of complex systems can be detected and quantified. Computational mechanics developed from efforts in the 1970s and early 1980s to identify strange attractors as the mechanism driving weak fluid turbulence via the method of reconstructing attractor geometry from measurement time series and in the mid-1980s to estimate equations of motion directly from complex time series. In providing a mathematical and operational definition of structure it addressed weaknesses of these early approaches to discovering patterns in natural systems. Since then, computational mechanics has led to a range of results from theoretical physics and nonlinear mathematics to diverse applications---from closed-form analysis of Markov and non-Markov stochastic processes that are ergodic or nonergodic and their measures of information and intrinsic computation to complex materials and deterministic chaos and in
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Earthquake Engineering & Structural Dynamics
Publication Identifier Type: DOI Publication Identifier: 10.1002/eqe.3071
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published: 8/1/18 7:00AM
Publication Location:
**Article Title:** Decomposition algorithms for system reliability estimation with applications to interdependent lifeline networks
**Authors:** Roger Paredes, Leonardo Dueñas-Osorio, Isaac Hernandez-Fajardo, Masayoshi Nakashima
**Keywords:** algorithms, analytical methods, interdependence, network reliability, risk, state-space partition
**Abstract:** Reliability and risk assessment of lifeline systems call for efficient methods that integrate hazard and interdependencies. Such methods are computationally challenged when the probabilistic response of systems is tied tomultiple events, as performance quantification requires a large catalog of groundmotions. Available methods to address this issue use catalog reductions and importance sampling. However, besides comparisons against baseline Monte Carlo trials in select cases, there is no guarantee that suchmethodswill perform or scalewell in practice. This paper proposes a new efficientmethod for reliability assessment of interdependent lifeline systems, termed RAILS, that considers systemic performance and is particularly effective when dealing with large catalogs of events. RAILS uses the state-space partition method to estimate systemic reliabilitywith theoretical bounds and, for the first time, supports cyclic interdependencies among lifeline systems. Recycling computations across
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**Journal:** Physica A: Statistical Mechanics and its Applications
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.physa.2018.05.081
Volume: 508 Issue: First Page #: 313
Date Submitted: 8/22/18 12:00AM Date Published: 10/1/18 7:00AM
Publication Location:
**Article Title:** A cascading failure model based on AC optimal power flow: Case study
**Authors:** Jian Li, Congling Shi, Changkun Chen, Leonardo Dueñas-Osorio
**Keywords:** AC-based cascading failure model, Case study, Nodes failure, Branches failure
**Abstract:** Simulating the grids cascading failure process is an essential means of preventing cascading failures. In traditional cascading failure models, DC power flow models are applied widely, but reactive power characteristic cannot be reflected. This study improves and applies an AC-based Cascading Failure model (called ACCF model), which captures bus load shedding and branch failures, all via AC power flow and optimal power flow analyses. Taking the IEEE 30- and 118-bus power systems as case studies, the ACCF model is proved feasible. With case studies, this study reveals that during the cascading failure, the broken branches are not necessarily close to the initial faulty elements, and some of the affected nodes/branches are ‘‘far’’ away from the initial faulty nodes. And as the initial branch failure probability increases, the system real power loss probability function gradually changes from approximate power distribution to a normal distribution. Meanwhile, the study also discovers that
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Reliability Engineering & System Safety
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.ress.2018.03.011
Volume: 175 Issue: First Page #: 196
Date Submitted: 8/22/18 12:00AM Date Published: 7/1/18 2:00PM
Publication Location:
**Article Title:** Electrical and topological drivers of the cascading failure dynamics in power transmission networks
**Authors:** Alberto Azzolin, Leonardo Dueñas-Osorio, Francesco Cadini, Enrico Zio
**Keywords:** Power grids, Vulnerability assessment, Cascading failures, DC power flow
**Abstract:** To systematically study key factors affecting cascading failures in power systems, this paper advances algorithms for generating synthetic power grids with realistic topological and electrical features, while computationally quantifying how such factors influence system performance probabilistically. Key parameters affecting line out- ages and power losses during cascading failures include line redundancy, load/generator layout and re-dispatch strategies. Our study combines a synthetic power grid generator with a direct current (DC) cascading failure simulator. The impact of each of the factors and their interactions unravel useful insights for interventions aimed at reducing the probabilities of large blackouts on existing and future power systems. Moreover, conclusions drawn from a spectrum of different power grid topologies and electrical configurations offer more generality than typically attained when studying specific test cases. Line redundancy and distributed generation appear
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**Journal:** arXiv preprint
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Network Reliability Estimation in Theory and Practice
**Authors:** R. Paredes, L. Dueñas-Osorio, K.S. Meel, M.Y. Vardi
**Keywords:** network reliability, bounds, FPRAS, PAC, relative variance, uncertainty
**Abstract:** As engineered systems expand, become more interdependent, and operate in real-time, reliability assessment is indispensable to support investment and decision making. However, network reliability problems are known to be #P-complete, a computational complexity class largely believed to be intractable. The computational intractability of network reliability motivates our quest for reliable approximations. Based on their theoretical foundations, available methods can be grouped as follows: (i) exact or bounds, (ii) guarantee-less sampling, and (iii) probably approximately correct (PAC). Group (i) is well regarded due to its useful byproducts, but it does not scale in practice. Group (ii) scales well and verifies desirable properties, such as the bounded relative error, but it lacks error guarantees. Group (iii) is of great interest when precision and scalability are required, as it harbors computationally feasible approximation schemes with PAC-guarantees. We give a comprehensive review
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**Journal:** arXiv preprint
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/22/18 12:00AM Date Published:
Publication Location:
**Article Title:** Influence Models on Layered Uncertain Networks: A Guaranteed-Cost Design Perspective
**Authors:** Siavash Alemzadeh, Mehran Mesbahi
**Keywords:** Layered social networks, composite networks, distributed systems, guaranteed-cost design
**Abstract:** Control and estimation on large-scale social networks often necessitate the availability of models for the interactions amongst the agents in the network. However characterizing accurate models of social interactions pose new challenges due to their inherent complexity and unpredictability. Moreover, model uncertainty on the interaction dynamics becomes more pronounced for large-scale networks. For certain classes of social networks, in the meantime, the layering structure allows a compositional approach for modeling as well as control and estimation. The layering can be induced in the network, for example, due to the presence of distinct social types and other indicators, such as geography and financial ties. In this paper, we present a compositional approach to determine performance guarantees on layered networks with inherent model uncertainties induced by the network. To this end, we use a factorization approach to determine robust stability and performance of the composite network
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.98.020302
Volume: 98 Issue: 2 First Page #:
Date Submitted: 8/27/18 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:** Self-organized systems, social systems, network structure
**Abstract:** Hierarchy of social organization is a ubiquitous property of animal and human groups, linked to resource allocation, collective decisions, individual health, and even to social instability. Experimental evidence shows that both intrinsic abilities of individuals and social reinforcement processes impact hierarchies; existing mathematical models, however, focus on the latter. Here, we develop a rigorous model that incorporates both features and explore their synergistic effect on stability and the structure of hierarchy. 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
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Chaos: An Interdisciplinary Journal of Nonlinear Science
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5008955
Volume: 28 Issue: 1 First Page #: 013110
Date Submitted: 8/27/18 12:00AM Date Published: 1/1/18 8:00AM
Publication Location:
**Article Title:** Maximizing synchronizability of duplex networks
**Authors:** Xiang Wei, Jeffrey Emenheiser, Xiaoqun Wu, Jun-an Lu, Raissa M. D'Souza
**Keywords:** Phase transitions, social networks, graph theory
**Abstract:** We study the synchronizability of duplex networks formed by two randomly generated network layers with different patterns of interlayer node connections. According to the master stability function, we use the smallest nonzero eigenvalue and the eigenratio between the largest and the second smallest eigenvalues of supra-Laplacian matrices to characterize synchronizability on various duplexes. We find that the interlayer linking weight and linking fraction have a profound impact on synchronizability of duplex networks. The increasingly large inter-layer coupling weight is found to cause either decreasing or constant synchronizability for different classes of network dynamics. In addition, negative node degree correlation across interlayer links outperforms positive degree correlation when most interlayer links are present. The reverse is true when a few interlayer links are present. The numerical results and understanding based on these representative duplex networks are illustrative and
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**Journal:** Science
Publication Identifier Type: DOI Publication Identifier: 10.1126/science.aaq0474
Volume: 358 Issue: 6365 First Page #: 860
Date Submitted: 8/27/18 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.
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**Journal:** arXi
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/28/18 12:00AM Date Published:
Publication Location:
**Article Title:** A Perspective on Unique Information: Directionality, Intuitions, and Secret Key Agreement
**Authors:** Ryan James, Jeff Emenheiser, James Crutchfield
**Keywords:** information theory, partial information decomposition, secret key agreement, cryptography
**Abstract:** Recently, the partial information decomposition emerged as a promising framework for identifying the meaningful components of the information contained in a joint distribution. Its adoption and practical application, however, have been stymied by the lack of a generally-accepted method of quantifying its components. Here, we briefly discuss the bivariate (two-source) partial information decomposition and two implicitly directional interpretations used to intuitively motivate alternative component definitions. Drawing parallels with secret key agreement rates from information-theoretic cryptography, we demonstrate that these intuitions are mutually incompatible and suggest that this underlies the persistence of competing definitions and interpretations. Having highlighted this hitherto unacknowledged issue, we outline several possible solutions.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
**Journal:** Automatica
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** Nonlinear Observability via Koopman Analysis: Characterizing the Role of Symmetry
**Authors:** Afshin Mesbahi, Jingjing Bu, Mehran Mesbahi
**Keywords:** Nonlinear control, symmetry, Koopman, complex networks, network science
**Abstract:** This paper considers the observability of nonlinear systems from a Koopman operator theoretic perspective–and in particular– the effect of symmetry on observability. We first examine an infinite-dimensional linear system (constructed using independent Koopman eigenfunctions) such that its observability is equivalent to the observability of the original nonlinear system. Next, we derive an analytic relation between symmetry and nonlinear observability; it is shown that symmetry in the nonlinear dynamics is reflected in the symmetry of the corresponding Koopman eigenfunctions, as well as presence of repeated Koopman eigenvalues. We then proceed to show that the loss of observability in symmetric nonlinear systems can be traced back to the presence of these repeated eigenvalues. In the case where we have a sufficient number of measurements, the nonlinear system remains unobservable when these functions have symmetries that mirror those of the dynamics. The proposed observability framework
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
**Journal:** TRANSACTIONS ON CONTROL OF NETWORKED SYSTEMS
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** Performance and Design of Consensus on Matrix-Weighted and Time Scaled Graphs
**Authors:** Mathias Hudoba de Badyn, Dillon R. Foight, Mehran Mesbahi
**Keywords:** network control, symmetry, network science
**Abstract:** In this paper, we consider the H2-norm of networked systems with multi-time scale consensus dynamics and matrix weights for vector-valued agent states. We develop a general framework for such systems that allows for matrix valued edge weighting, independent agent-based time scales, as well as measurement and process noise. This allows us to explore how these noise contributions affect consensus on matrix-weighted graphs, specifically by examining consensus on the edge states. In particular, we highlight an interesting case where the influences of the weighting and scaling on the H2 norm can be separated in the design problem. We then consider distributed opti- mization algorithms for updating the time scale parameters and matrix weights in order to suppress network response to injected process and measurement noise. Finally, we present an application to formation control for multi-vehicle systems.
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**Journal:** TRANSACTIONS ON AUTOMATIC CONTROL
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** H2 Performance of Series-Parallel Networks: A Compositional Perspective
**Authors:** Mathias Hudoba de Badyn, Mehran Mesbahi
**Keywords:** network control
**Abstract:** Series-parallel networks are a class of graphs on which many NP-hard problems have tractable solutions. In this paper, we examine performance measures on matrix- weighted leader-follower consensus on series-parallel net- works. By using an extension of electrical network theory on matrix-valued resistances, voltages, and currents, we show that the computation of the H2 norm can be per- formed in a rather efficient manner. This is done by using the decomposition of the network into atomic elements and composition rules, facilitating a dynamic programming type algorithm for H2 computation over a binary decision tree. Lastly, we examine the problem of adapting the matrix- valued edge weights to optimize the H2 norm of the net- work, and show that it can be done with similar computa- tional complexity.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Reliability Engineering & System Safety
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.ress.2019.04.025
Volume: 191 Issue: First Page #: 106472
Date Submitted: 8/25/19 12:00AM Date Published: 11/1/19 7:00AM
Publication Location:
**Article Title:** Principled network reliability approximation: A counting-based approach
**Authors:** R. Paredes, L. Dueñas-Osorio, K.S. Meel, M.Y. Vardi
**Keywords:** Network science, systems reliability theory
**Abstract:** As engineered systems expand, become more interdependent, and operate in real-time, reliability assessment is key to inform investment and decision making. However, network reliability problems are known to be #P- complete, a computational complexity class believed to be intractable, and thus motivate the quest for approximations. Based on their theoretical foundations, reliability evaluation methods can be grouped as: (i) exact or bounds, (ii) guarantee-less sampling, and (iii) probably approximately correct (PAC). Group (i) is well regarded due to its useful byproducts, but it does not scale in practice. Group (ii) scales well and veri es desirable properties, such as the bounded relative error, but it lacks error guarantees. Group (iii) is of great interest when precision and scalability are required. We introduce -RelNet, an extended counting-based method that delivers PAC guarantees for the -terminal reliability problem. We also put our developments in context relative to cl
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 3-Accepted
**Journal:** Journal of Risk and Uncertainty in Engineering Systems,
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** Decentralized Decision-Making for the Restoration of Interdependent Networks
**Authors:** H. Talebiyan, L. Dueñas-Osorio
**Keywords:** Network science, systems reliability
**Abstract:** This study introduces tractable algorithms to model the decentralized decision-making process for post-disaster restoration of interdependent networks. The restoration strategies are devised by a host of agents, who control different layers of the interdependent network. Due to interdependency, each agent's decision is impacted by others' decisions. However, agents communicate poorly in real-world settings, particularly after contingencies, as they cannot access all the information that is necessary to make a decision, and compensate with their expert judgment.We propose the notion of "Judgment Call" to model this practical human contrivance. We explore several assumptions on judgments including pure random judgment, optimistic judgment, and judgments guided by importance measures. The performance of the method is compared to optimal solutions applied to a database of ideal networks that contains different configurations of random, scale-free, and grid networks. Also, we apply the meth
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Scientific Reports
Publication Identifier Type: DOI Publication Identifier: 10.1038/s41598-019-46799-0
Volume: 9 Issue: 1 First Page #:
Date Submitted: 8/25/19 12:00AM Date Published: 7/1/19 7:00AM
Publication Location:
**Article Title:** Macaques preferentially attend to visual patterns with higher fractal dimension contours
**Authors:** Kelly R. Finn, James P. Crutchfield, Eliza Bliss-Moreau
**Keywords:** Network science, vision
**Abstract:** Animals' sensory systems evolved to effiently process information from their environmental niches. Niches often include irregular shapes and rough textures (e.g., jagged terrain, canopy outlines) that must be navigated to nd food, escape predators, and master other tness-related challenges. For most primates, vision is the dominant sensory modality and thus, primates have evolved systems for processing complicated visual stimuli. one way to quantify information present in visual stimuli in natural scenes is evaluating their fractal dimension. We hypothesized that sensitivity to complicated geometric forms, indexed by fractal dimension, is an evolutionarily conserved capacity, and tested this capacity in rhesus macaques (Macaca mulatta). Monkeys viewed paired black and white images of simulated self-similar contours that systematically varied in fractal dimension while their attention to the stimuli was measured using noninvasive infrared eye tracking. They xated more frequently on,
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Entropy
Publication Identifier Type: DOI Publication Identifier: 10.3390/e21010012
Volume: 21 Issue: 1 First Page #: 12
Date Submitted: 8/25/19 12:00AM Date Published: 12/1/18 8:00AM
Publication Location:
**Article Title:** Unique Information and Secret Key Agreement
**Authors:** Ryan James, Jeffrey Emenheiser, James Crutchfield
**Keywords:** Network information
**Abstract:** The partial information decomposition (PID) is a promising framework for decomposing a joint random variable into the amount of influence each source variable Xi has on a target variable Y, relative to the other sources. For two sources, influence breaks down into the information that both X0 and X1 redundantly share with Y, what X0 uniquely shares with Y, what X1 uniquely shares with Y, and finally what X0 and X1 synergistically share with Y. Unfortunately, considerable disagreement has arisen as to how these four components should be quantified. Drawing from cryptography, we consider the secret key agreement rate as an operational method of quantifying unique information. Secret key agreement rate comes in several forms, depending upon which parties are permitted to communicate. We demonstrate that three of these four forms are inconsistent with the PID. The remaining form implies certain interpretations as to the PID's meaning
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Open Source Software
Publication Identifier Type: DOI Publication Identifier: 10.21105/joss.00738
Volume: 3 Issue: 25 First Page #: 738
Date Submitted: 8/25/19 12:00AM Date Published: 5/1/18 7:00AM
Publication Location:
**Article Title:** dit: a Python package for discrete information theory
**Authors:** Ryan G. James, Christopher J. Ellison, James P. Crutchfield
**Keywords:** network information theory
**Abstract:** dit ("Dit: A Python Package for Discrete Information Theory. Available at: Https://Github.com/Dit/Dit" n. d.) is a Python package for the study of discrete information theory. Information theory is a mathematical framework for the study of quantifying, compressing, and communicating random variables (Cover and Thomas 2006)(MacKay 2003)(Yeung 2008). More recently, information theory has been utilized within the physical and social sciences to quantify how different components of a system interact. dit is primarily concerned with this aspect of the theory.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Physical Review X
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevX.8.031013
Volume: 8 Issue: 3 First Page #:
Date Submitted: 8/25/19 12:00AM Date Published: 7/1/18 7:00AM
Publication Location:
**Article Title:** Causal Asymmetry in a Quantum World
**Authors:** Jayne Thompson, Andrew J.?P. Garner, John R. Mahoney, James P. Crutchfield, Vlatko Vedral, Mile G
**Keywords:** Quantum information
**Abstract:** Causal asymmetry is one of the great surprises in predictive modeling: The memory required to predict the future differs from the memory required to retrodict the past. There is a privileged temporal direction for modeling a stochastic process where memory costs are minimal. Models operating in the other direction incur an unavoidable memory overhead. Here, we show that this overhead can vanish when quantum models are allowed. Quantum models forced to run in the less-natural temporal direction not only surpass their optimal classical counterparts but also any classical model running in reverse time. This holds even when the memory overhead is unbounded, resulting in quantum models with unbounded memory advantage.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Journal of Physics A
Publication Identifier Type: DOI Publication Identifier: 10.1088/1751-8121/aaed53
Volume: 52 Issue: First Page #: 014002
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** Unique Information via Dependency Constraints
**Authors:** Ryan G. James, Jeffrey Emenheiser, James P. Crutchfield
**Keywords:** mutual information, statistical dependence
**Abstract:** The partial information decomposition (PID) is perhaps the leading proposal for resolving information shared between a set of sources and a target into redundant, synergistic, and unique constituents. Unfortunately, the PID framework has been hindered by a lack of a generally agreed-upon, multivariate method of quantifying the constituents. Here, we take a step toward rectifying this by developing a decomposition based on a new method that quantifies unique information. We first develop a broadly applicable method—the dependency decomposition—that delineates how statistical dependencies influence the structure of a joint distribution. The dependency decomposition then allows us to define a measure of the information about a target that can be uniquely attributed to a particular source as the least amount which the source-target statistical dependency can influence the information shared between the sources and the target. The result is the first measure that satisfies the core axiom
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Science
Publication Identifier Type: DOI Publication Identifier: 10.1126/science.aav7932
Volume: 363 Issue: 6431 First Page #:
Date Submitted: 8/25/19 12:00AM Date Published: 3/1/19 8:00AM
Publication Location:
**Article Title:** Exotic states in a simple network of nanoelectromechanical oscillators
**Authors:** Matthew H. Matheny, Jeffrey Emenheiser, Warren Fon, Airlie Chapman, Anastasiya Salova, Martin Roh
**Keywords:** Synchronization, nonlinear control, emergent coupling
**Abstract:** Synchronization of oscillators, a phenomenon found in a wide variety of natural and engineered systems, is typically understood through a reduction to a first-order phase model with simplified dynamics. Here, by exploiting the precision and flexibility of nanoelectromechanical systems, we examined the dynamics of a ring of quasi-sinusoidal oscillators at and beyond first order. Beyond first order, we found exotic states of synchronization with highly complex dynamics, including weak chimeras, decoupled states, traveling waves, and inhomogeneous synchronized states. Through theory and experiment, we show that these exotic states rely on complex interactions emerging out of networks with simple linear nearest-neighbor coupling. This work provides insight into the dynamical richness of complex systems with weak nonlinearities and local interactions.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
**Journal:** arXiv
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** Efficient Contraction of Large Tensor Networks for Weighted Model Counting through Graph Decompositions
**Authors:** Jeffrey M. Dudek, Leonardo Duenas-Osorio, Moshe Y. Vardi
**Keywords:** tensor networks
**Abstract:** Constrained counting is a fundamental problem in artificial intelligence. A promising new algebraic approach to constrained count- ing makes use of tensor networks, following a reduction from constrained counting to the problem of tensor-network contraction. Contracting a tensor network efficiently requires determining an efficient order to con- tract the tensors inside the network, which is itself a difficult problem. In this work, we apply graph decompositions to find contraction orders for tensor networks. We prove that finding an efficient contraction order for a tensor network is equivalent to the well-known problem of finding an optimal carving decomposition. Thus memory-optimal contraction orders for planar tensor networks can be found in cubic time. We show that tree decompositions can be used both to find carving decompositions and to factor tensor networks with high-rank, structured tensors. We implement these algorithms on top of state-of-the-art solvers for tree decompositi
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 4-Under Review
**Journal:** ArXiv
Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 8/25/19 12:00AM Date Published:
Publication Location:
**Article Title:** A quantum algorithm to count weighted ground states of classical spin Hamiltonians
**Authors:** Bhuvanesh Sundar, Roger Paredes, David T. Damanik, Leonardo Duenas-Osorio, Kaden R. A. Hazzarc
**Keywords:** Quantum algorithms
**Abstract:** Ground state counting plays an important role in several applications in science and engineering, from estimating residual entropy in physical systems, to bounding engineering reliability and solving combinatorial counting problems. While quantum algorithms such as adiabatic quantum optimization (AQO) and quantum approximate optimization (QAOA) can minimize Hamiltonians, they are inadequate for counting ground states. We modify AQO and QAOA to count the ground states of arbitrary classical spin Hamiltonians, including counting ground states with arbitrary nonnegative weights attached to them. As a concrete example, we show how our method can be used to count the weighted fraction of edge covers on graphs, with user-specified confidence on the relative error of the weighted count, in the asymptotic limit of large graphs. We find the asymptotic computational time complexity of our algorithms, via analytical predictions for AQO and numerical calculations for QAOA.
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**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** IEEE Transactions on Network Science and Engineering
Publication Identifier Type: DOI Publication Identifier: 10.1109/TNSE.2018.2885163
Volume: Issue: First Page #: 1
Date Submitted: 8/26/19 12:00AM Date Published:
Publication Location:
**Article Title:** Topology identification in two-layer complex dynamical networks
**Authors:** Yingfei Wang, Xiaoqun Wu, Jinhu Lu, Jun-an Lu, Raissa DSouza
**Keywords:** layered networks, synchronization
**Abstract:** This study focuses on topology identification in two-layer networks with peer-to-peer unidirectional couplings, where one layer (the response layer) receives information from the other layer (the drive layer). The goal is to construct a theoretical framework for identifying the topology of the response layer based on the dynamics observed in both layers. In particular, an auxiliary layer is constructed. Based on the LaSalle-type invariance principle, simple control inputs and updating laws are designed to enable nodes in the auxiliary layer to reach complete synchronization with their counterparts in the response layer. Simultaneously, the topology of the response layer is adaptively identified. Numerical simulations are conducted to illustrate the effectiveness of the method. The impact of the inter-layer information transmission speed on the identification performance is further investigated. It is revealed that neither too slow or too fast information transmission favors efficient
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**Journal:** Science
Publication Identifier Type: DOI Publication Identifier: 10.1126/science.aav7140
Volume: 362 Issue: 6420 First Page #: 1253
Date Submitted: 8/26/19 12:00AM Date Published: 12/1/18 8:00AM
Publication Location:
**Article Title:** Unlocking the science of success
**Authors:** Raissa M. D'Souza
**Keywords:** Social networks, book review
**Abstract:** Want to master your professional and social networks to maximize recognition? Want to learn how to build productive teams that create lasting impact? In his new book, The Formula: The Universal Laws of Success, Albert-László Barabási translates almost a decade of scholarly research on the science of success into a lively and compelling narrative woven together with captivating stories and his own deeply personal experiences.
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
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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.99.012304
Volume: 99 Issue: 1 First Page #:
Date Submitted: 8/26/19 12:00AM Date Published: 1/1/19 8:00AM
Publication Location:
**Article Title:** Master stability functions for complete, intralayer, and interlayer synchronization in multiplex networks of coupled Rössler oscillators
**Authors:** Longkun Tang, Xiaoqun Wu, Jinhu Lü, Jun-an Lu, Raissa M. D'Souza
**Keywords:** Synchronization, complex networks, non-linear dynamics
**Abstract:** Synchronization phenomena are of broad interest across disciplines and increasingly of interest in a multiplex network setting. For the multiplex network of coupled Rössler oscillators, here we show how the master stability function, a celebrated framework for analyzing synchronization on a single network, can be extended to certain classes of multiplex networks with different intralayer and interlayer coupling functions. We derive three master stability equations that determine, respectively, the necessary regions of complete synchronization, intralayer synchronization, and interlayer synchronization. We calculate these three regions explicitly for the case of a two-layer network of Rössler oscillators and show that the overlap of the regions determines the type of synchronization achieved. In particular, if the interlayer or intralayer coupling function is such that the interlayer or intralayer synchronization region is empty, complete synchronization cannot be achieved regardless
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**Journal:** Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.99.032308
Volume: 99 Issue: 3 First Page #:
Date Submitted: 8/26/19 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:** Cascading failures, complex networks, ARL collaboration
**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.
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**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: 8/26/19 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:** multiplex networks, node ranking, centrality measures
**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. 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
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**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2014 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)
Date Received: 23-Aug-2018 Conference Date: 10-Jul-2014 Date Published:
Conference Location: Durham, UK
**Paper Title:** Outage Predictions of Electric Power Systems under Hurricane Winds by Bayesian Networks
**Authors:** Akwasi F. Mensah, Leonardo Dueñas-Osorio
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering
Date Received: 23-Aug-2018 Conference Date: 21-Jul-2014 Date Published:
Conference Location: Anchorage, Alaska, USA
**Paper Title:** UNCOVERING THE HETEROGENEITY OF SPATIAL LIFELINE SYSTEM INTERDEPENDENCIES
**Authors:** R. Paredes-Toro, L. Dueñas-Osorio, G. P. Cimellaro
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Second International Conference on Vulnerability and Risk Analysis and Management (ICVRAM) and the Sixth International Symposium on Uncertainty, Modeling, and Analysis (ISUMA)
Date Received: 16-Aug-2016 Conference Date: 14-Jul-2014 Date Published:
Conference Location: Liverpool, UK
**Paper Title:** Lifeline System Interdependencies—Key for Resilience in Practice
**Authors:** Alex K. Tang, Jian Li, and Leonardo Duenas-Osorio
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**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Second International Conference on Vulnerability and Risk Analysis and Management (ICVRAM) and the Sixth International Symposium on Uncertainty, Modeling, and Analysis (ISUMA)
Date Received: 16-Aug-2016 Conference Date: 13-Jul-2014 Date Published:
Conference Location: Liverpool, UK
**Paper Title:** Mitigation Strategies for Lifeline Systems Based on the Interdependent Network Design Problem
**Authors:** Andre ?s D. Gonza ?lez, Mauricio Sa ?nchez-Silva, Leonardo Duen ?as-Osorio, Andre ?s L. Medaglia
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 12th International Conference on Applications of Statistics and Probability in Civil Engineering, Vancouver, Canada, July 12-15
Date Received: 16-Aug-2016 Conference Date: 12-Jul-2015 Date Published:
Conference Location: Vancouver
**Paper Title:** Reliability and Controllability of Infrastructure Networks: DoThey Match?
**Authors:** Jian Li, Leonardo Dueñas-Osorio, and Changkun Chen
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Computational complexity, time complexity, Interdependent Networks, Network Design ProblemJournal: 12th International Conference on Applications of Statistics and Probability in Civil Engineering, Vancouver, Canada, July 12-15
Date Received: 16-Aug-2016 Conference Date: 12-Jul-2015 Date Published:
Conference Location: Vancouver
**Paper Title:** The Computational Complexity of Probabilistic InterdependentNetwork Design Problems
**Authors:** Andres D. Gonzalez, Leonardo Duen?as-Osorio, Mauricio Sa?nchez-Silva, Andre?s L. Medaglia
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2014 IEEE 53rd Annual Conference on Decision and Control (CDC)
Date Received: 16-Aug-2016 Conference Date: 14-Dec-2014 Date Published:
Conference Location: Los Angeles, CA, USA
**Paper Title:** On symmetry and controllability of multi-agent systems
**Authors:** Airlie Chapman, Mehran Mesbahi
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**Conference Name:** IEEE Conference on Decision and Control, 2015
Date Received: 16-Aug-2016 Conference Date: 15-Dec-2015 Date Published:
Conference Location: Osaka
**Paper Title:** Network Entropy: A System-Theoretic Perspective
**Authors:** Mathias Hudoba de Badyn, Airlie Chapman, Mehran Mesbahi
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**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2016 American Control Conference (ACC)
Date Received: 16-Aug-2016 Conference Date: 06-Jul-2016 Date Published:
Conference Location: Boston, MA, USA
**Paper Title:** Multiple time-scales in network-of-networks
**Authors:** Airlie Chapman and Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2015 54th IEEE Conference on Decision and Control (CDC)
Date Received: 16-Aug-2016 Conference Date: 15-Dec-2015 Date Published:
Conference Location: Osaka
**Paper Title:** State controllability, output controllability and stabilizability of networks: A symmetry perspective
**Authors:** Airlie Chapman and Mehran Mesbahi
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**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2015 54th IEEE Conference on Decision and Control (CDC)
Date Received: 16-Aug-2016 Conference Date: 15-Dec-2015 Date Published:
Conference Location: Osaka
**Paper Title:** Time-scale separation on networks: Consensus, tracking, and state-dependent interactions
**Authors:** Armand Awad, Airlie Chapman, Eric Schoof, Anshu Narang-Siddarth, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** IEEE Conference on Decision and Control
Date Received: 16-Aug-2016 Conference Date: 16-Aug-2016 Date Published: 16-Aug-2016
Conference Location: Las Vegas NV
**Paper Title:** Pattern Control for Networks of Ginzburg-Landau Oscillators via Markov Decision Processes (Invited paper)
**Authors:** Airlie Chapman, Eric Schoof and Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** The 6th Asian-Pacific Symposium on Structural Reliability and its Applications (APSSRA6)
Date Received: 16-Aug-2016 Conference Date: 17-Aug-2016 Date Published: 17-Aug-2016
Conference Location: Shanghai
**Paper Title:** The time-dependent interdependent network design problem (td-INDP) and the evaluation of multi-system recovery strategies in polynomial time
**Authors:** A. D. González, L. Dueñas-Osorio, A. L. Medaglia, M. Sánchez-Silva
Acknowledged Federal Support: **Y**

# RPPR Final Report
as of 29-Sep-2020

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** The 6th EAI Intnl. Conf. on Game Theory for Networks
Date Received: 23-Aug-2018 Conference Date: 17-Aug-2016 Date Published: 17-Aug-2016
Conference Location: Kelowna, BC, Canada
**Paper Title:** Strategic Seeding of Rival Opinions
**Authors:** Samuel D. Johnson, Jemin George, and Raissa M. D'Souza
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2016 IEEE 55th Conference on Decision and Control (CDC)
Date Received: 24-Aug-2017 Conference Date: 12-Dec-2016 Date Published:
Conference Location: Las Vegas, NV, USA
**Paper Title:** Growing controllable networks via whiskering and submodular optimization
**Authors:** Mathias Hudoba de Badyn, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2016 IEEE 55th Conference on Decision and Control (CDC)
Date Received: 24-Aug-2017 Conference Date: 12-Dec-2016 Date Published:
Conference Location: Las Vegas, NV, USA
**Paper Title:** Pattern control for networks of Ginzburg-Landau oscillators via Markov Decision Processes
**Authors:** Airlie Chapman, Eric Schoof, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2017 American Control Conference (ACC)
Date Received: 22-Aug-2018 Conference Date: 24-May-2017 Date Published:
Conference Location: Seattle, WA, USA
**Paper Title:** Parallel probabilistic swarm guidance by exploiting Kronecker product structures in discrete-time Markov chains
**Authors:** King Keung Wu, Yeung Yam, Helen Meng, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2017 American Control Conference (ACC)
Date Received: 22-Aug-2018 Conference Date: 24-May-2017 Date Published:
Conference Location: Seattle, WA, USA
**Paper Title:** Adaptive communication networks with privacy guarantees
**Authors:** Atiye Alaeddini, Kristi Morgansen, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** IEEE Conference on Decision and Control
Date Received: 22-Aug-2018 Conference Date: 13-Dec-2017 Date Published: 13-Dec-2017
Conference Location: Melbourne, Australia
**Paper Title:** Data-guided Control: Clustering, Graph Products, and Decentralized Control
**Authors:** Airlie Chapman, Andrés D. González, Mehran Mesbahi, Leonardo Dueñas-Osorio, and Raissa M. D'Sou
Acknowledged Federal Support: **Y**

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**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 12th International Conference on Structural Safety & Reliability (ICOSSAR2017),
Date Received: 28-Aug-2017 Conference Date: 06-Aug-2017 Date Published: 06-Aug-2017
Conference Location: Vienna, Austria
**Paper Title:** Optimizing the Resilience of Infrastructure Systems under Uncertainty using the Interdependent Network Design Problem
**Authors:** Andrés D. González, Leonardo Dueñas-Osorio, Mauricio Sánchez-Silva, Andrés L. Medaglia, Andrew J.
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 12th Int. Conf. on Structural Safety and Reliability
Date Received: 28-Aug-2017 Conference Date: 06-Aug-2017 Date Published: 06-Aug-2017
Conference Location: Vienna, Austria
**Paper Title:** Reliability Assessment of Interdependent Lifeline Systems (RAILS) and Systemic Importance Measures Using a Non-Simulation Method
**Authors:** Roger Paredes, Leonardo Dueñas-Osorio
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2017 IEEE Conference on Control Technology and Applications (CCTA)
Date Received: 22-Aug-2018 Conference Date: 27-Aug-2017 Date Published:
Conference Location: Mauna Lani Resort, HI, USA
**Paper Title:** Controllability and stabilizability analysis of signed consensus networks
**Authors:** Siavash Alemzadeh, Mathias Hudoba de Badyn, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2017 IEEE 56th Annual Conference on Decision and Control (CDC)
Date Received: 22-Aug-2018 Conference Date: 12-Dec-2017 Date Published:
Conference Location: Melbourne, Australia
**Paper Title:** Controllability and data-driven identification of bipartite consensus on nonlinear signed networks
**Authors:** Mathias Hudoba de Badyn, Siavash Alemzadeh, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** Proceedings of the 6th International Symposium on Reliability Engineering and Risk Management
Date Received: 22-Aug-2018 Conference Date: 31-May-2018 Date Published:
Conference Location: Singapore
**Paper Title:** Beyond the Interdependent Network Design Problem
**Authors:** ANDRÉS D. GONZÁLEZ1, MAURICIO SÁNCHEZ-SILVA2, LEONARDO DUEÑASOSORIO3 and ANDF
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 12th Int. Conf. on Structural Safety and Reliability
Date Received: 22-Aug-2018 Conference Date: 06-Aug-2017 Date Published:
Conference Location: Vienna
**Paper Title:** Improvement of a fully polynomial randomized approximation scheme (FPRAS) for infrastructure system reliability assessment
**Authors:** Bowen Fu, Leonardo Duenas-Osorio
Acknowledged Federal Support: **Y**

# RPPR Final Report
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**Publication Type:** Conference Paper or Presentation **Publication Status:** 5-Submitted
**Conference Name:** 57th IEEE Conference on Decision and Control.
Date Received: 22-Aug-2018 Conference Date: 17-Dec-2018 Date Published:
Conference Location: Miami Beach, USA
**Paper Title:** Density Control of State-Dependent Networked Dynamical Systems Using Optimal Mass Transport and Kernel Density Estimation
**Authors:** Mathias Hudoba de Badyn, Utku Eren, Behc¸et Ac¸?kmes¸e and Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2019 American Control Conference
Date Received: 25-Aug-2019 Conference Date: 10-Jul-2019 Date Published: 10-Jul-2019
Conference Location: Philadelphia, USA
**Paper Title:** Identification of the Laplacian Spectrum from Sparse Local Measurements
**Authors:** Afshin Mesbahi, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2019 American Control Conference
Date Received: 25-Aug-2019 Conference Date: 10-Jul-2019 Date Published: 10-Jul-2019
Conference Location: Philadelphia, USA
**Paper Title:** Efficient Computation of H2 Performance on Series-Parallel Networks
**Authors:** Mathias Hudoba de Badyn, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 3-Accepted
**Conference Name:** 2019 IEEE Conference on Decision and Control
Date Received: 25-Aug-2019 Conference Date: 11-Dec-2019 Date Published: 11-Dec-2019
Conference Location: Nice, France
**Paper Title:** Time Scale Design for Network Resilience
**Authors:** Dillon R. Foight, Mathias Hudoba de Badyn, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2019 American Control Conference
Date Received: 25-Aug-2019 Conference Date: 10-Jul-2019 Date Published: 10-Jul-2019
Conference Location: Philadelpiha, USA
**Paper Title:** On Modal Properties of the Koopman Operator for Nonlinear Systems with Symmetry
**Authors:** Afshin Mesbahi, Jingjing Bu, Mehran Mesbahi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 13th international conference on applications of statistics and probability in civil engineering (ICASP13)
Date Received: 25-Aug-2019 Conference Date: 26-May-2019 Date Published: 26-May-2019
Conference Location: Seoul
**Paper Title:** Recovery of infrastructure networks via importance-based multicentric percolation processes
**Authors:** B. Fu, L. Dueñas-Osorio
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 0-Other
**Conference Name:** 13th international conference on applications of statistics and probability in civil engineering (ICASP13)
Date Received: 25-Aug-2019 Conference Date: 26-May-2019 Date Published: 26-May-2019
Conference Location: Seoul
**Paper Title:** A weighted model counting approach for critical infrastructure reliability
**Authors:** R. Paredes, L. Dueñas-Osorio, K.S. Meel, M.Y. Vardi
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 13th international conference on applications of statistics and probability in civil engineering (ICASP13)
Date Received: 25-Aug-2019 Conference Date: 26-May-2019 Date Published: 26-May-2019
Conference Location: Seoul
**Paper Title:** Probabilistic assessment of decentralized decision-making for interdependent network restoration
**Authors:** H. Talebiyan, L. Dueñas-Osorio
Acknowledged Federal Support: **Y**

**DISSERTATIONS:**

**Publication Type:** Thesis or Dissertation
**Institution:**
Date Received: 20-Aug-2014 Completion Date:
**Title:** Models of systemic events: interdependence, contagion, and innovation
**Authors:**
Acknowledged Federal Support:

**Publication Type:** Thesis or Dissertation
**Institution:**
Date Received: 27-Aug-2015 Completion Date:
**Title:** Phase Transitions on Static and Evolving Networks
**Authors:**
Acknowledged Federal Support:

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 16-Aug-2016 Completion Date: 1/10/16 11:58PM
**Title:** On Strategic Behavior in Networks
**Authors:** Samuel Johnson
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 16-Aug-2016 Completion Date: 11/16/15 11:58PM
**Title:** Growth And Interdependence Of Complex Networks
**Authors:** Vikram Vijayaraghavan
Acknowledged Federal Support: **Y**

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**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 16-Aug-2016 Completion Date: 6/15/16 7:00AM
**Title:** Mechanisms within the Black Box: Prediction, Computation, Randomness, and Complexity of Input-Output Processes via the epsilon-Transducer
**Authors:** Nix Barnett
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** Rice University/Central South University of China
Date Received: 17-Aug-2016 Completion Date: 6/15/16 4:54PM
**Title:** Structural Controllability and Key Nodes Identification Methodology for City-level Power Transmission Networks
**Authors:** Jian Li
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 30-Aug-2018 Completion Date: 3/15/18 4:58PM
**Title:** Strategic Security and Recovery on Interdependent Networks
**Authors:** Andrew Smith
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** University of Washington
Date Received: 30-Aug-2018 Completion Date: 8/29/18 8:15PM
**Title:** Distributed Protocols, Nonlinear State-Dependent Networks, and Human-Swarm Interactions
**Authors:** Eric Alan Schoof
Acknowledged Federal Support: **N**

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 03-Sep-2020 Completion Date: 11/19/19 7:40PM
**Title:** Quantifying and Modeling Layer-level Interactions in Multiplex Networks
**Authors:** Haochen Wu
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 03-Sep-2020 Completion Date: 5/17/19 7:00AM
**Title:** Collective Behavior in Dynamics on Networks
**Authors:** Jordan Snyder
Acknowledged Federal Support: **Y**

**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 03-Sep-2020 Completion Date: 2/15/19 8:00AM
**Title:** Rank Aggregation Methods For Consensus Ranking in Multilayer Networks
**Authors:** Niklaus Braun
Acknowledged Federal Support: **N**

# RPPR Final Report
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**Publication Type:** Thesis or Dissertation
**Institution:** UC Davis
Date Received: 03-Sep-2020 Completion Date: 6/7/19 8:37PM
**Title:** Studying Animals as Complex Systems: From Perception to Social Structure
**Authors:** Kelly Finn
Acknowledged Federal Support: **Y**

# Final Report: Predicting and controlling systems of interdependent networks

*Network Control MURI team, PI D'Souza, award W911NF-13-1-0340*
**Accomplishments, Sep. 1, 2013 – May 31, 2020**

***Goal:*** **To develop general theory for the control of multi-scale systems composed of heterogeneous nonlinear agents interacting via complex interdependent networks.**

## I. Overview and key highlights:

Our team was created to respond to the call for a MURI topic on controlling complex networks. We created a multidisciplinary team, who had not worked together previously, bringing together expertise in theoretical physics, dynamical systems, control theory, infrastructure engineering, nano-scale device physics and finally (to capture the social network aspect) macaque monkey societies. We achieved a tremendous amount. A few highlights are given here.

- Over 90 peer-reviewed journal papers published, primarily in the highest-impact journals. Highlights include:
  - "Exotic states in a simple network of nanoelectromechanical oscillators" published in ***Science***, 363 (6431), Jan 2019. The results were featured in popular press articles in *Wired* Magazine and *Quanta* Magazine.
  - "Consensus ranking for multi-objective interventions in multiplex networks", ***New Journal of Physics****,* 21 (055001), 2019.
  - "Causal asymmetry in a quantum world", ***Physical Review X***, 8(3), 031013, 2018.
  - "Curtailing cascading failures", ***Science***, 358 (6365), 2017.
  - "Complex dynamical networks constructed with fully controllable nonlinear nanomechanical oscillators", ***Nano Letters***, 17 (10), 2017.
  - "Control of finite critical behaviour in a small-scale social system". ***Nature Communications*** 8, 14301, 2017.
  - "Efficient infrastructure restoration strategies using the recovery operator", ***Computer-Aided Civil and Infrastructure Engineering*** 32 (12), 2017.
  - "Information flows? A critique of transfer entropies", ***Physical Review Letters***, 116, 238701, 2016.
  - "Controllability of multiplex, multi-time-scale networks", ***Physical Review E***, 94 (3), 2016.
  - *"*Anomalous critical and supercritical phenomena in explosive percolation", ***Nature Physics***, 11 (7), 2015.
  - "Target control of complex networks", ***Nature Communications*** 5 (1), 2014.
  - "Microtransition cascades to percolation", ***Physical Review Letters***, 112 (15), 2014.
  - Nine publications in ***IEEE Transactions*** journals.

- 33 peer-reviewed conference papers published primarily in the most important conferences in control theory and infrastructure engineering, including:
    - Six papers in the annual American Control Conference (ACC).
    - 11 papers in the IEEE Annual Conference of Decision and Control (CDC).
    - Best Paper Award, International Civil Engineering Risk and Reliability Association, 2015.
    - Test of Time Award at ESEC/FSE 2018.
- Team members gave over 70 Plenary/Keynote/Invited talks, disseminating this work at leading institutions and conferences around the globe.
- Overall, our research activities had direct involvement from 35 Graduate students, 7 undergraduate students, 2 REUs, 15 Postdoctoral Scholars, and 6 Staff Scientists, all of whom received significant training opportunities while working in the labs of the MURI team PIs. We graduated 11 PhD students and 1 MS student. Several students were involved with the national labs via summer internships or employment. All trainees have gone onto very successful positions including 3 who are now faculty members (at U Oklahoma, U Melbourne, and Central European University) and several received prestigious postdoctoral positions including the JMSF Fellowship in Studying Complex Systems and the Neukom Fellowship for postdoctoral studies at Dartmouth University.
- Interaction with Army and National Labs:
    - Trained a PhD student from Sandia National Lab,
    - PhD students did internships at LLNL and at the ARL Network Science Center at the ARC in Adelphi, MD.
    - Year 4 annual review held at the Network Science Center, Army Research Lab, ARC, Adelphi MD, and involved many ARL researchers as well as ARO and DTRA Program Managers.
    - Year 2 MURI Team Annual Review at the Santa Fe Institute, introducing ARO and DARPA PMs to SFI researchers and facilitating potential grant opportunities. (D'Souza received DARPA award W911NF-17-1-0077 as a follow on to this meeting.)
- MURI team research featured in popular science journals Wired (twice) and Quanta Magazine (twice).
    - “Scientists Discover Exotic New Patterns of Synchronization”, Quanta Magazine, April 4, 2019.
    - “The Math of How Crickets, Starlings, and Neurons Sync Up”, Wired Magazine, April 7, 2019.
    - “The New Laws of Explosive Networks”, Quanta Magazine, July 14, 2015.
    - “New Laws Explain Why Fast-Growing Networks Break”, Wired Magazine, Aug 1, 2015.
- Many influential conferences organized, including NetSci 2014, NetSci 2016-18, and special sessions on our MURI topic.

- Many honors and awards received including:
    - Euler Award of the Network Science Society, 2020.
    - Test of Time Award, ESEC/FSE 2018.
    - UC Davis Outstanding Postdoctoral Scholar Award, 2019.
    - PI (D'Souza) elected Fellow of the American Physical Society, 2016.
    - PI (D'Souza) elected Fellow of the Network Science Society, 2019.
    - Co-PI (Mesbahi) elected Fellow of the IEEE Society, 2015.
    - Co-PI (Duenas-Osorio) receives the 2017 IASSAR Early Achievement Research Award, given every four years by the International Association for Structural Safety and Reliability (IASSAR). The award goes to researchers who are "at early stages of their careers and generally below 40 years of age," and recognizes "contributions to and impact on the field of structural safety and reliability."
    - PI receives UC Davis College of Engineering Outstanding Midcareer Faculty Research Award, 2017.
    - PhD student, Airlie Chapman, receives Springer Outstanding Thesis Award, 2015.
    - co-PI Duenas-Osorio, 2015 Best Journal Paper award from *Earthquake Spectra*.
    - PI appointed Lead Editor and *Physical Review Research* and to the Board of Reviewing Editors at *Science.*
    - co-PI (Crutchfield), receives Best paper of 2003 in *Chaos*, awarded May 2015.

We leave a substantial legacy. We were able to meaningfully integrate our diverse research areas and develop many innovative approaches for the control of complex networks (see Figures 2 and 3), and we have also influenced the field of traditional control theory. One testament to this is that the PI (D'Souza), while extensively trained in theoretical physics and network science, had never worked in the field of control theory. She led this project and established this body of work as a new direction in control theory as evidenced by her Plenary Lecture at the 2019 European Controls Conference – a conference of over 1000 attendees with primarily parallel sessions and only 5 Plenary Lectures in total. We leave transformative impact bridging the fields of statistical physics, control theory, nonlinear dynamics and complex networks across application domains and are guiding new frontiers in control theory.

## II. Project background:

Complex interdependent networks are at the core of modern civilian and military life (see Fig 1). Critical infrastructure, for instance, is a collection of interdependent power, water, gas, and transportation networks. Human societies are comprised of a collection of social and economic networks coupled to that critical infrastructure. Each of the individual networks in these systems is itself a complex system, displaying unanticipated emergent behaviors and often consisting of

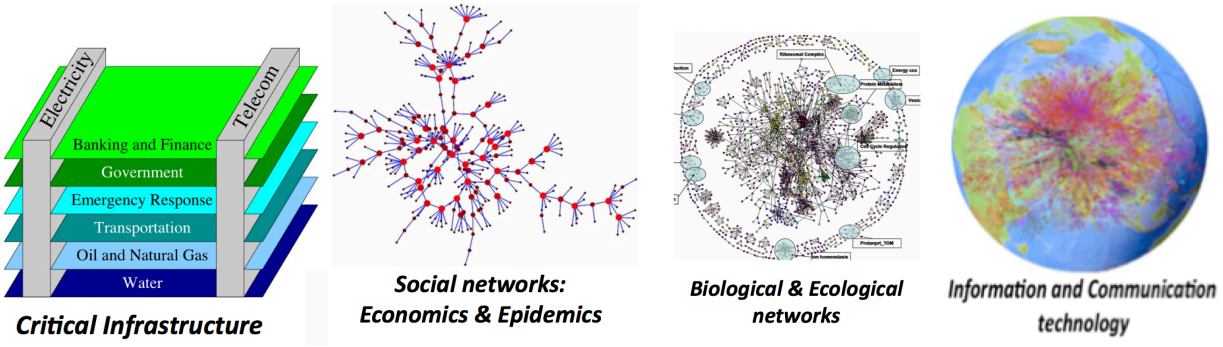


**Figure 1**. The interdependent complex networks of modern military and civilian life. They are increasingly cyber-physical and socio-technical systems with coordinated behaviors at multiple length and time scales. Having millions of degrees of freedom, unanticipated emergent properties and tipping points, the standard tools of control theory alone do not allow for their control.

millions of degrees of freedom. One key emergent behavior pervasive across domains of networks is the phenomenon of global consensus from local interactions, or for oscillatory networks, that of synchronization, when the oscillatory behavior of nodes in the network displays non-trivial coordinated activity. Full synchronization is fundamental for the operation of the electric power grid or a distributed digital communications network, yet large-scale synchrony can be pathological in other situations such as epileptic seizures or collective social aggression. Due to its importance across fields of science and engineering, synchronization of complex networks is a core focus of applied mathematics, network science, and engineering reliability. Complex interdependent networks are the paradigm we study, and synchronization is an emergent collective behavior that spans many of our empirical testbeds.

Traditional control theory cannot be directly applied to the control of modern networks because they are so large and interconnected it is typically not feasible to know the state of every element in the system. In addition, they display unanticipated emergent behaviors. To address this challenge, our MURI team has unlocked fundamental theory and understanding of processes on networks by using mathematical models from control theory, statistical physics, optimization, and information theory coupled to data driven approaches. During the duration of our MURI, the team made many fundamental advances we are now able to articulate a clear overarching understanding of what will be necessary for the control of complex networks across multiple time and length scales. This is shown in Figures 2, 3 and 4.

## II. Transformative results:

We had Major Goals I-VI involving collective phenomena, information dynamics, network controllability, infrastructure networks, NEMS oscillators and macaque monkey societies. Below are key results that came from integrating and synthesizing the expertise across the team.

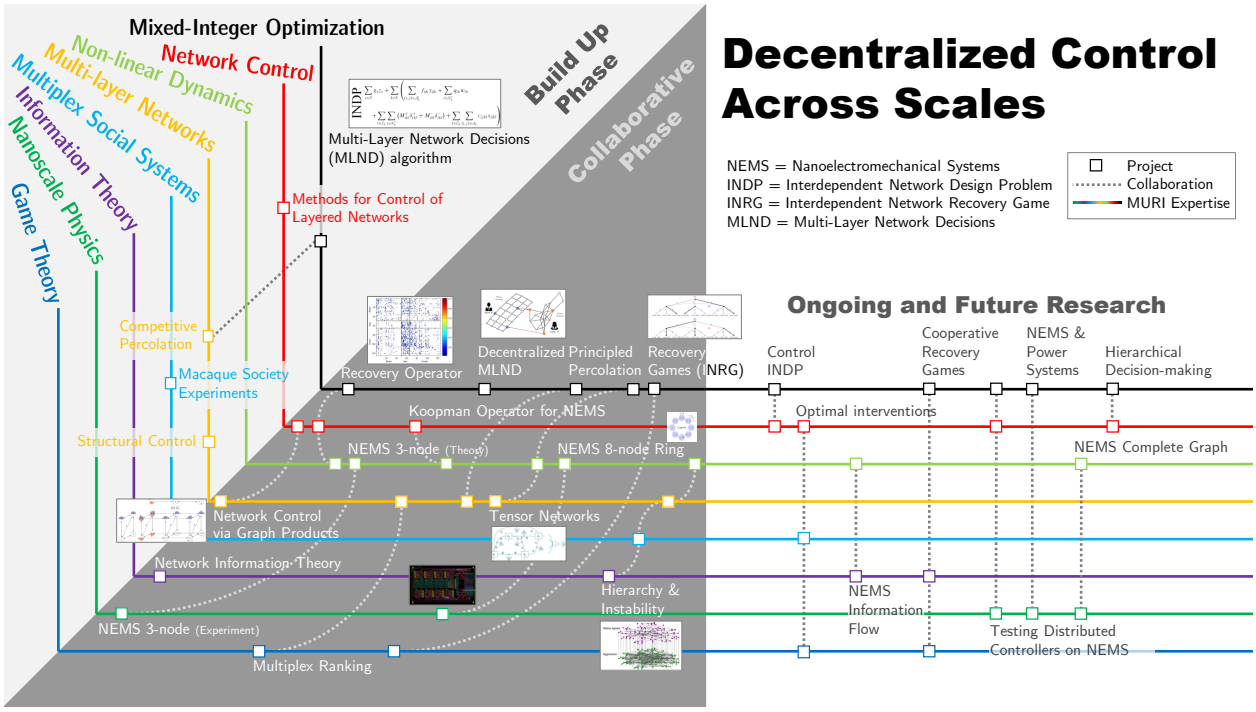


**Figure 2:** MURI research topics and crosscutting collaborations with specific methods indicated.

Figure 2 is a graphical depiction of the research topics and crosscutting collaborations with the specific methods that link them indicated, showing how they integrate across our domains of expertise. Figure 3 is the graph of research themes and crosscutting collaborations, enabling decentralized control across scales and across heterogeneous networks.

**III.A. Synchronization:** From a foundational level, we have brought together the analysis of nonlinear systems from information theory, control theory and statistical physics of networks together with innovation in nanoscale engineering to pioneer a study into the array of exotic behaviors displayed from simple collections of nonlinear nodes. We show that the dynamics of the system breaks the physical symmetry of the network connectivity pattern leading to exotic patterns of coordinated behaviors. Due to the unprecedented speed and access to the full details of the system's behavior we have been able to demonstrate behaviors that were up until now only conjectured theoretically and to analyze far more complex unanticipated behaviors. This accompanying manuscript was accepted to *Science* on Jan 17, 2019, demonstrating that we have created transformative interdisciplinary cutting-edge science, integrated across the MURI team [Science2019]. This work builds on our collaborative theoretical and experimental results

[Chaos2016, Nano2017] and positions us to now explore control interventions in high-dimensional spaces and scaling-up of fundamental theory to systems where multiple levels of synchronization are essential for proper function from critical infrastructure to eventually brain networks. Synchronization, especially exotic forms, enables decentralized coordination across scales and our NEMS platform is unique among experimental platforms in terms of its speed and precision, allowing full access to relaxation and transient effects, crucial for understanding synchronization dynamics emergent across scales.

**III.B. Control of layered networks:** Another key result concerns collections of layered networks. An underlying framework we call the Interdependent Network Design Problem (INDP), a mixed integer programming method for revealing interdependencies and optimal multi-layer coordinated recovery [CACIE2016], has won several awards and serves as our benchmark for optimal centralized recovery of interdependent networks. More generally, by bringing together data on the structure and function of a layered system with mathematical formulations of graph products and control, we have developed principled methods for control of decentralized layered networks [CACIE2017, CDC2017]. A key principle in layered networks is that differing incentives and constraints often exist in the distinct layers. Each layer can be owned by a distinct operator and we use a class of non-cooperative games on networks to capture multi-layered decision processes and reveal systemic mechanisms that block guarantees of convergence to any functioning solution [Risk2017]. We also show that simple and abstracted models of percolation dynamics are capable of approximating combinatorial-space search algorithms in multi-layered sequential decision problems [SciRep2019]. Extensions of layered networks to multiple time-scale systems have also been examined by our team [ACSNM2018]. This body of work significantly advances our understanding of the broad class of layered networks over which different types of commodities and information flow, such as power grids, transportation networks, water networks, and telecom networks.

**III.C. Control of heterogenous networks**: Beyond layered networks, we have also developed transformative results for more general heterogenous networks. We have shown how to determine the structural controllability of multiplex networks with multiple time-scales present [PRE2016]. We have developed the theory of "target control", where only some portion of the network needs to be controlled [NComm2014], which has become highly influential. We have shown now for many different systems, that heterogeneous networks can be approximated by graph products and how to analyze the controllability and observability of such systems, including building distributed controllers [IEEETAC2015, CDC2017]. This work also applies to networks-of-networks. We have shown how notions of tipping points and phase transitions can be exploited for control purposes in small heterogenous systems [NComm2017] and in large networks with heterogeneous modules [NPhys2015, AIP2019].

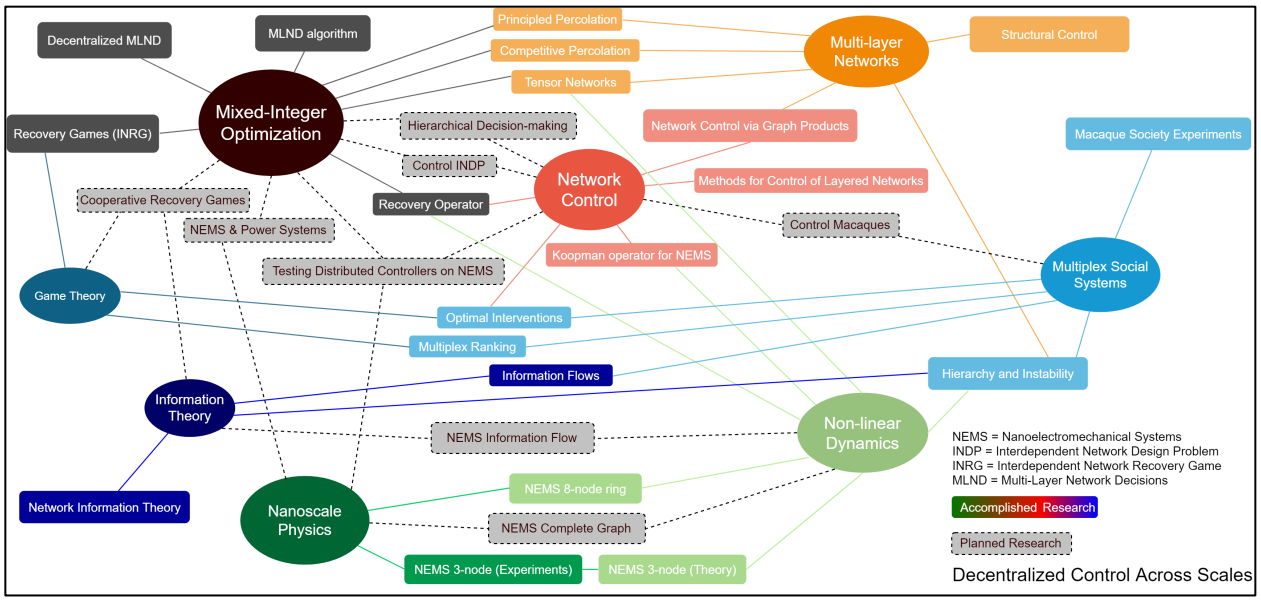


**Figure 3: MURI collaboration graph** of research themes and crosscutting collaborations, enabling decentralized control across scales and across heterogeneous networks.

**III.D. Multiplex social systems**: Humans play a key role in all of our modern systems, and human societies can be represented as a "multiplex" network, where the same set of individuals exist on multiple layers, with each layer representing a distinct type of interaction. A fundamental aspect of any human society is that some types of interactions are affiliative, like trade, alliances or huddling, while other interactions are competitive and aggressive. Imbalance between interactions can lead to social instability, and also means we may want to intervene with different goals on distinct layers, for instance preserving affiliative networks while disrupting agonistic ones. We have developed first-principles models of social instability resulting from tensions between talent and social reinforcement [PRE2018], and general methods for multi-layered networks. The latter has enabled us to develop multi-objective targeted node-removal interventions [NJPhys2019] and identify characteristics of individuals whose rank in the layered network setting is particularly important [PeerJ2020]. Information transfer in the multiplex setting is a fundamental consideration and with the Year 5 add-on funds received, we were able to accomplish important steps towards unraveling the dynamics of multi-layered information flow in social settings. In year 1-4 of the project, we had been using existing data on the macaque society that had been previously collected, but not yet analyzed. The add-on funds allowed us to conduct an experiment at the California National Primate Research Center, lead by co-PI McCowan, using visual barriers to disrupt flow of information over the multilayered networks of the macaque societies. We were able to identify keystone signaling networks, motifs of interactions, and implications across the full system. Key findings include that there are two

distinct types of grooming networks existing – political and social – which must be defined by participation in multiple networks simultaneously. Centrality in political networks is associated with increased inflammation, while participation in the social grooming is associated with decreased inflammation. From analyzing the motifs present in signaling networks we find that visual barriers enhance the presence of keystone signaling, as animals use this external network to compensate to lack of signal from direct observations of aggression, political and social grooming. The reinforcing and destabilizing interactions between the affiliative and agonistic layers of our model are providing translational models for understanding stabilizing conflicts and destabilizing conflicts and social cohesion, as discussed further in Sec IV.

**III.E. Network Information Theory:** Collective phenomena in dynamical networks arise due to information exchange between their constituent elements. To address their complexity, we developed new mathematical and information-theoretic tools for analyzing temporal behavior and configurational structure. In particular, we made a major advance that clearly identifies the benefits and limitations of modeling networks with only pairwise interactions and, in particular, the advantages and failings of using information measures [PRL2016]. We also developed a major extension of the functional calculus of linear operators that gives a new approach to a spectral graph theory for networks and a major advance in understanding the role of hierarchical organization and its information-theoretic signatures. In addition, we developed a detailed informational analysis of spin lattices and neuronal spike trains [Entropy2017], and have been able to use these tools for analyzing time-series of macaque visual data [SciRep2019b]. We also laid the foundations of optimal transformations between stochastic processes and identified the source of apparent complexity in nonergodic processes. The accompanying analysis tools and formulations have all been released via open source Python code [JOSS2018].

**III.F. Koopman operator theory:** It is typical that a nonlinear system cannot be studied in its full detail, and is typically studied in linear approximations often around fixed-point behaviors. But in recent years, techniques to study the full phase space of a system, beyond just simple fixed points and limit cycles, have gained popularity. Koopman operator theory is one such approach, where one considers the "observables" of the system – in other words, the macroscopic attributes rather than the detailed microscopic state of the system. Such techniques are allowing opportunities to bridge mathematical formulations of dynamical systems with time-series data on the evolution of a real system, promising data driven theory. Our work on Koopman operators has focused on how symmetries of systems aid in reducing the dimension of the problem.

Specifically, we have continued our work on utilizing operator theoretic methods for examining control theoretic properties of nonlinear networks, and in particular their observability properties using Koopman operators. Another facet of our work has revolved around developing a compositional approach for computing noise propagation statistics on large-scale networks using

the theory of inf-convolution for series-parallel networks. In addition, we have examined the role of time-scales on network performance, and in particular, how time-scales associated with node-level dynamics can be used as a control parameter to optimize network-level noise propagation properties and network resilience. Lastly, we have shown how symmetries in system structure and dynamical evolution can be used to simplify data driven approximations of Koopman operators [Chaos 2019].

**III.G. Reliability, quantum circuits, optimization and constraints**: We developed a new quantum circuit to implement Hamiltonian dynamics on Noisy-Intermediate Scale Quantum (NISQ) devices, which unravels combinatorial properties of graphs. The study shows how the Quantum Alternating Operator Ansatz (QAOA)-based algorithm outperforms classical Optimal Monte Carlo bounding network reliability in terms of execution time and reduced variance (Submitted for publication to *Quantum Science and Technology*). We also developed a Best Virtual Solver (BVS) to tackle constrained counting problems relevant in probabilistic inference on networks. The portfolio method adds to existing logic-based tools a tensor contraction approach that requires less memory and solves denser problem instances not handled by other solvers in the BVS (Uploaded onto the arXiv). Additional accomplishments are developing a decentralized optimization method to restore interdependent networks. The team's solutions approach guaranteed-optimality centralized solvers and bound the offered multi-agent choices between optimal pessimistic and optimistic contexts (Submitted for publication to the *Journal of Risk and Uncertainty.*

Finally, we developed a new algorithm to upper-bound the reliability of engineered networked systems via constrained satisfaction formulae and quantum tensor network contractions. The study shows how the quantum tensor networks outperforms advanced Monte Carlo methods and analytical decomposition techniques. team developed new probably approximately correct algorithms to estimate the reliability of complex networks. These methods guarantee a priori the quality of their estimates, which is desirable as networked systems are becoming more automated and interdependent while operating in uncertain environments.

## IV. Culminating team-wide insights --- Integrating across scales:

To bridge control theory, non-linear dynamics, complex networks, and statistical physics requires understanding the origin of the emergent behavior displayed. In the realm of control theory and non-linear dynamics, one studies a system made of a small number of nodes that are typically connected to one another in a simple structure, like a ring network of oscillators. Here each node exhibits highly non-linear behavior (i.e., the complexity is in the nodal dynamics). In the realm of statistical physics of networks, one studies a large (in fact, asymptotic) collection of nodes with very simple behaviors, with the complexity emerging from the non-trivial patterns of

interconnectivity between the nodes (i.e., the complexity is in the network). This is extremely useful for understanding many network properties like phase transitions in connectivity, epidemic spreading, information cascades, etc., but it does not incorporate nodal dynamics.

Our key insight is that all real systems lie in the realm between these two extremes as shown in Fig 4, with the two axes of nodal complexity and of network complexity depicted. A real system lies at a point in this space and to understand and control it requires bridging the appropriate techniques for the timescales, lengthscales and underlying origin of the complexity of the behaviors. As such, our three empirical MURI testbeds have allowed us to develop detailed understanding of different points along this underlying parameter space that we have integrated into a collective framework. For instance, critical infrastructure networks can be approximated as a product of layered, geometric graphs, whereas social networks are known for their heavy-tailed connectivity patterns. Our theory and data driven approaches exploit the structure and symmetry present in a system and its dynamics to reduce the complexity of the challenge and ultimately assert controllability.

To ensure that we addressed the challenge across the scales of complexity, we studied three distinct empirical platforms that are also representative of three radically different spatial and temporal scales. At the nano-scale, we studied simple networks of NEMs oscillators. This enables studies into intricate synchronization patterns that can arise from complex non-linear elements that are connected in a simple fashion, and also the dynamics of information transfer between nodes and the resulting emergent couplings that can arise. At the mega-scale we studied collections of critical infrastructure to extract the principles of interdependent layered networks and scenarios such as optimal recovery, graph clustering methods, strategic decision making (i.e., games) on networks, and the design of decentralized controllers. At the social scale, we studied the multiplex networks of conflicts and alliances in macaque monkey societies -- a translational model for human systems -- and developed useful quantitative multilayer network methodology for general networks as well as first-principles models of instability and social hierarchies. Results obtained across these differing scales of complexity provide a foundation for a general theory of control of multilayered, multi-scale systems of nonlinear agents interacting via complex interdependent networks. Our work, which cuts across the scales of node and network complexity (see Fig 4), has laid the foundation for this broader theory while also leading to many specific scientific innovations that have met acclaim in the scientific community, creating new knowledge across disciplines (Fig 2 and Fig 3).

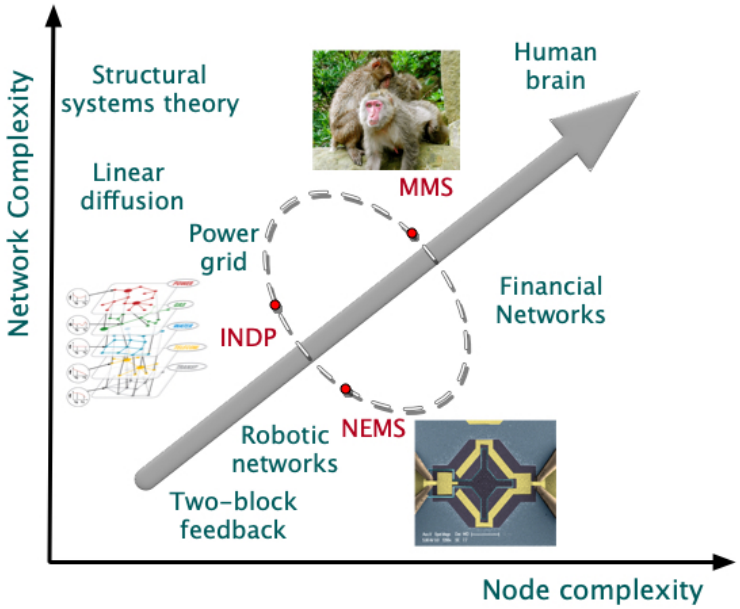


**Figure 4.** Node complexity and network complexity are two fundamental but independent considerations for understanding types of emergent behaviors and principles for network control. Our three testbeds are indicated: the NEMS oscillators, the Macaque Monkey Society, and the Interdependent Network Design Problem applied to critical infrastructure.

## IV. Grand challenges that we can now address include:

- **Theory of multilayered social systems**: Social systems are comprised of layers of both agonistic and affiliative behaviors. Yet, data obtained from our digital footprints capture primarily the affiliative interactions (e.g. Facebook friendships, phone calls, texts, Twitter flows, proximity data). Likewise, data on co-authorship networks, paper citation networks, joint board memberships, professional networks, etc., capture cooperative interactions. Conflict, and likewise conflict resolution, are essential for the resilience and adaptation of social systems including at the level of building functional teams. Macaque societies provide the unique opportunity to understand these principles, especially given our existing longitudinal data. Longer term directions include using the macaque model (in both captive and free-ranging conditions) to better understand the basic biological and social processes underlying teamwork and trust. We will do so by focusing on the multimodal and multilayered nature of macaque communication networks. We will examine keystone communication networks of subordination and affiliation that signal trust in macaque relationships and the process by which these signaling systems lead to the emergence of teamwork in alliance and policing networks. Understanding of these systems as well as systematic perturbations of such systems will give us greater causal insight into how basic systems of trust and teamwork not only develop and operate, but also can be engineered and controlled. These generative processes that underlie the more complex

emergent structures observed in effective human teamwork, whose architecture requires multiple layers of mutual trust, can then be further evaluated in more complex social circumstances.

- **Information transfer in higher-order network interactions:** Our network information advances open a new avenue for dynamical network analysis pushing us to move beyond dyadic interactions, as will be necessary for developing a true understanding of our experimental systems. Information flows through higher-order motifs, particular in multilayer systems, will be a key challenge for future research. This has implications and for all three of our testbeds, where understanding and controlling emergent higher-order behaviors are of tantamount importance.

## V. Summary & Conclusions:

Bringing together theory from multiple disciplines, and testbeds across scales of nodal and network complexity, we have developed overarching control principles as well as principled methods for control at each of the different levels of complexity. When the behavior of nodes is linear, complex collective behaviors can arise due to non-trivial patterns of network connectivity. We have shown that such systems are easily amenable to the tools of structural control theory, linear diffusion, and graph products, leading to the development of decentralized control protocols and successful random graph approximations of optimization problems. When the behavior of nodes is non-linear, simple linear connections between nodes can give rise to an array of emergent behaviors that break the physical symmetries in the system leading to intricate patterns of synchronized behaviors. The implications are staggering, as the modern systems we need to control require massive scale-up in network complexity, beyond the simple ring connectivity we studied. Yet, intricate patterns of sub-network synchronization may provide a key to distributed control across scales.

Modern society depends on a collection of interdependent networks, from electric grids, to transportation networks, to the internet. Likewise, society is a multi-layered network of human interactions, where many types of interactions are affiliative, and many others are agonistic or competitive. Our detailed data on such multilayered macaque monkey societies has allowed us to develop first-principle models of social resilience and adaptation, develop methodology for consensus ranking in general multilayered networks, and develop optimal intervention strategies for preserving affiliative interactions while disrupting aggressive interactions.

We have also developed fundamental measures of information transfer that reveal the inadequacy of current measures of causality and the applicability for measuring emergent couplings and information flows in networks.

We leave a legacy in terms of publications, students and postdoctoral scholars trained, and scientific impact with many research groups around the world now citing and working on follow

on work to the publications achieved via this MURI funding. We have also left impact across all of the many domains of the PI's of this project. The PI's institution created an institutional legacy with UC Davis awarding 2 faculty positions to the PI's proposed network science initiative, one in social sciences and one in computer science, showing long term institutional commitment to network science and the work of this MURI.

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