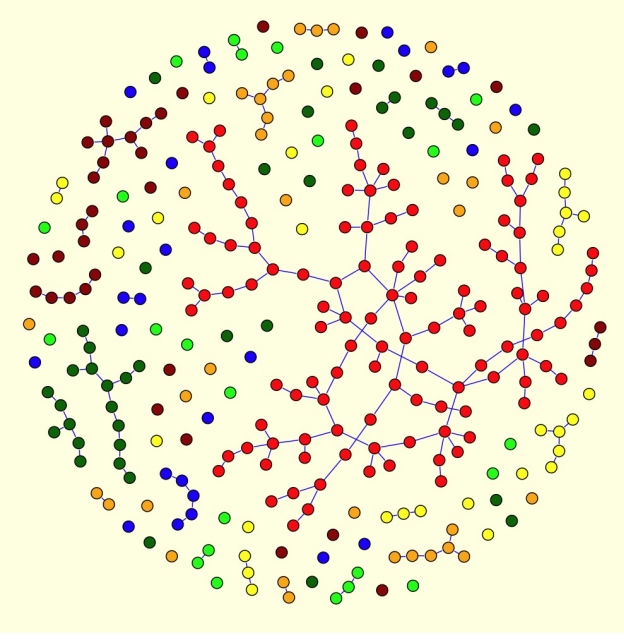
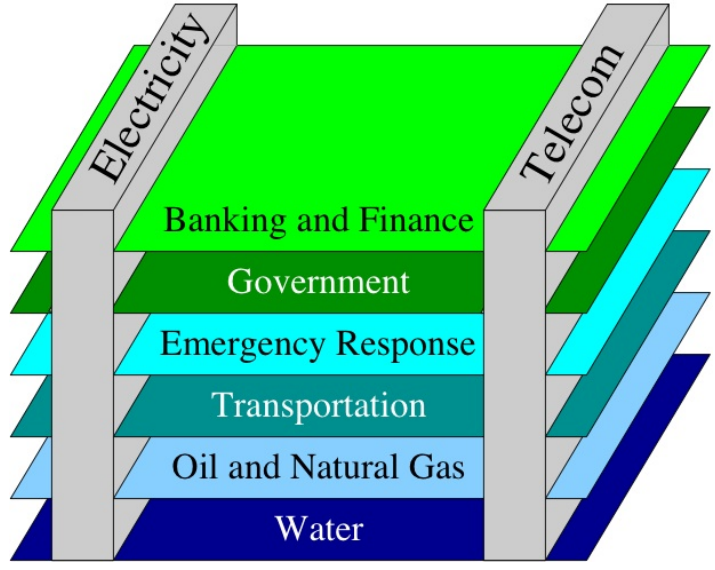
Predicting and controlling systems of interdependent networks: Exploiting interdependence for control





FY2013 Multidisciplinary University Research Initiative (MURI)
Topic: Controlling Collective Phenomena in Complex Networks

U. S. Army Research Laboratory and the U. S. Army Research Office contract/grant number W911NF-13-1-0340

The core team

- Raissa M. D'Souza, UC Davis
- Jim Crutchfield, UC Davis
- Leonardo Duenas-Osorio, Rice University
- Jessica Flack, University of Wisconsin
- David C. Krakauer, University of Wisconsin
- Mehran Mesbahi, University of Washington
- Michael Roukes, California Institute of Technology

A diverse team, spanning an array of fields: Network Science, Information Theory, Control Theory, Critical Infrastructure, Sensitivity Analysis, Statistics, Nonlinear Dynamics, Animal Behavior, Nanoscale device physics...

Three main tasks

State-dependent, dynamic networks

Dynamics of networks coupled to dynamics on networks, especially in noisy, dynamic environments

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- Task 1. Collective Computation
- Task 2. Interdependent and layered networks
- Task 3. Exploiting interdependence for control

Task 1. "Collective Computation"

- Task 1.1: Network Information Theory and Functional Pattern Formation:
  Crutchfield (Lead), Flack & Krakauer, Roukes (pattern formation)

- Task 1.2: Collective Computation (Game theoretic underpinnings: Network function and structure):
  Flack (Lead), Krakauer, Crutchfield, Roukes (node knock-out experiments; subsystems with competing objectives)

- Task 1.3: Control of state-dependent dynamic networks:
  Mesbahi (Lead), Flack, Crutchfield, D'Souza, Roukes (state-dependence)

Task 2. Interdependent and layered networks

- Task 2.1: Structure of interdependent networks:
  D'Souza (Lead) & Dueñas-Osorio

- Task 2.2: Function of interdependent networks:
  D'Souza & Dueñas-Osorio (co-leads), Roukes (synchronization)

- Task 2.3: Beyond the adjacency matrix: New mathematical representations for networks of networks:
  Mesbahi (Lead), D'Souza, Dueñas-Osorio
  - Cartesian products
  - Kroneker graphs
  - hypergraphs

Task 3. Exploiting interdependence for control

- Task 3.1: Multi-modal recovery and distributed control:
  Dueñas-Osorio (Lead), D'Souza, Mesbahi

- Task 3.2: Control theory formulations:
  Mesbahi (Lead), Dueñas-Osorio, D'Souza, Roukes (layered arrays?)

Fundamental objectives stated in proposal

- To understand the mechanisms for the emergence of structure and function and for controlling them.
- To identify feedback, co-evolution and opportunities for control.
- To assess fundamental bounds on effective means of influencing dynamic networks through control- and system-theoretic formalisms.
- To create new mathematical models of interdependent networks.
- To uncover coupling and recovery processes from empirical databases.
- To reveal feasible control strategies for critical infrastructure, coupled systems, and social response.
- To reveal the mechanisms for emergence of synchronization and global clocks in noisy dynamic environments.
- To quantify the effects of node knock-out and compensatory perturbations for multi-system control.
- To build a vibrant community of researchers actively working on control of collective phenomena in complex multi-networks.
- To provide transdisciplinary training to the next generation of scientists and engineers.

Anticipated Outcomes

- Network interventions that prevent cascades of failure in critical infrastructures
- Novel control schemes relying on control actions and local interventions
- Rigorous principles for multi-modal recovery of heterogenous systems
- Designing incentives that align human behavior with the capabilities of technological networks
- Design of networks of nonlinear NEMs oscillators that exploit coupling and nonlinearity to create coherent motion
- New mathematical structures for representing and analyzing networks-of-networks, especially with respect to control theory
- Fundamental bounds on controllability of interdependent networks and rigorous techniques to identify which network layers are easiest to steer.

Summary of deliverables (details on pg 19-20)

	Schedule of Major Project Activities
Year 1	– Proposal for semester program in Year 3 sent to IPAM board for approval* (In progress) – Team meeting at UCD; intro to KeckCAVES (Nov 12, and today) – Mini-conference on control of interdependent networks at UC Davis (Leverages NSF funded "Shocks cascading through coupled networks" conference) (NetSci 2014: Tutorials & Satellite meeting) – First postdoc and student rotations (continue throughout project) – First student and faculty visits to ARL (cont throughout project)
Year 2	– Students attend SFI Summer School (1-2 students now and in each subsequent year) – Team meeting at Santa Fe Institute (or partner inst) – Sessions on control of interdependent networks organized at intl. conferences – New graduate courses developed in support of this MURI (materials released online)

*(Simmons Inst might also work as well as IPAM)

Summary of deliverables (details on pg 19-20)

	Schedule of Major Project Activities, cont.
Year 3	– Semester program at IPAM – Team meeting at Caltech, University of Wisconsin or SFI – Special volume of *J. Complex Networks* on control of interdependent networks – First batch of postdocs move onto positions in Academia, Industry or National Labs
Year 4	– Team meeting and mini-conference at UC Davis showcasing Keck-CAVES tools – Sessions on control of interdependent networks organized at intl. conferences – First PhD students trained under this MURI graduate
Year 5	– Team meeting (at Wisc, SFI, Rice or Wash.) – Postdocs move onto positions in Academia, Industry or National Labs – Final PhD students trained under this MURI graduate – Culminating international conference at Santa Fe Institute

Some accomplishments to date

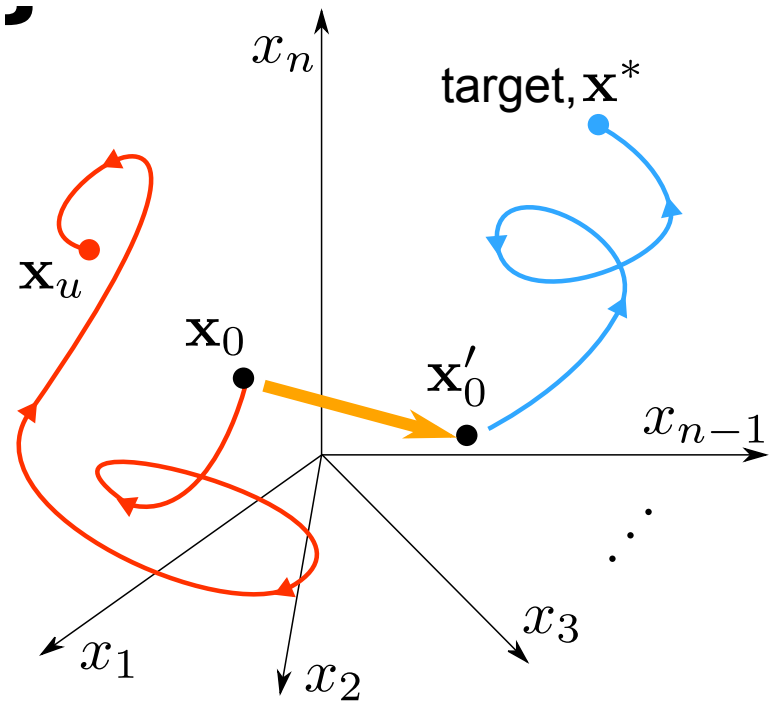
- Team-wide, in-person meeting at UCD on Nov 12th.
  - Cross-cutting threads articulated (e.g., synchronization; spectral statistics; systems of multiple components with only partially aligned interests)
  - Concrete research projects (e.g., Cartesian products for critical infrastructure; NEMs systems to model collective computation; spillover in layered networks)
- Airlie Chapman joins team as postdoctoral scholar and rotation to UCD.
- Flack, D'Souza and Spencer (Google, letter of support for MURI) co-editors of a special volume of *IEEE Spectrum*.
- Crutchfield visit to UWisconsin, Nov 2013.
- NetSci 2014 events organized: Tutorials (Airlie Chapman); Satellite meeting on control of networks (Mesbahi, D'Souza)

Goals for today

- Make more crisp the concrete research projects and collaboration plans
- Guidance from Sam Stanton — vision for success
- Deeper understanding of the experimental systems and real-world data sets
  - NEMs Oscillators – today and planning 2-3 years out
  - Macaque monkey societies
  - Critical infrastructure

Controlling networks

A network with n nodes
an n-dimensional phase space:



S.P. Cornelius, W.L. Kath, and A.E. Motter, arXiv:1105.3726 (2011), Nature Communications (2013).

- Strong Control: want to control the state of each node.
- Weak/Partial Control: want to steer the system.
- Controlling self-organizing systems especially challenging: the system responds to the controller.
- State dependence: of system, including the environment