Modeling and Analysis of Complex Urban Infrastructure Systems

CEVE 492/592 – Fall 2010
TR 10:50 AM – 12:05 PM, Mechanical Laboratory, Room 254

by

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Course objectives and Scope:

To introduce concepts of graph theory, complexity and optimization for characterizing engineered infrastructure systems; to explore models of networks and evaluate their ability to predict infrastructure system properties and performance; and to study and implement computer algorithms to efficiently measure processes taking place on networked systems including percolation, resilience, and dynamics. Complex systems concepts apply to the structure and dynamics of civil, mechanical, electrical and bioengineering systems and networks. The graduate level course includes advanced exercises in homework and exams as well as a research-oriented final project. *The instructor expects students to read in advance relevant required reading material and search for additional archival papers to maximize learning and interactions.*

Course outcomes:

Students completing the course should be able to:

1. Identify the topological structure of complex engineered systems, model their behavior, and synthesize predictive response metrics.
2. Compute topological and functional properties of networks at the local and global scales.
3. Adapt existing network models to account for infrastructure spatial constraints and commodity flow requirements.
4. Implement efficient computer algorithms to study infrastructure systems and validate their codes with numerical experiments.
5. Classify real networks according to their structure and function and predict their behavior with theoretical and empirical models.
6. Quantify the vulnerability and robustness of networked systems to attacks, hazards, and cascading failures.
7. Communicate complex technical concepts on network science and infrastructure engineering to expert and non-expert audiences.

Definition of *complex systems*:

From an engineering point of view, complex systems are large man-made collections of structures and utility networks that interact with each other, evolve in time due to aging and demographic growth processes, and are prone to catastrophic cascading failures from natural hazards, deliberate attacks, and in rare cases from benign disruptions as well. Cascading failures are difficult to prevent in complex systems. They exemplify the disproportionate damage of engineered infrastructure systems resulting from external disruptive events, including seemingly harmless triggering events, such as trees creating short circuits on a single high voltage transmission line that leads to a regional blackout. The response intractability, uncertainty, and vulnerability of engineering systems to perturbations are a result of emergent behavior that is typical of complex systems, but that is difficult to anticipate from the sole knowledge of the performance of individual system components. Complex systems are also resilient and sustainable when their design and growth is optimized to ensure long term structural and environmental performance.

Examples of engineering-based complex system challenges include the deployment of intelligent lifeline systems, integration of wind turbines with existing power grids, reliability of bridge-road networks, growth of water distribution networks, and the rigorous study of interacting social and technical systems. These complex system challenges are expected to be explored within normal and abnormal operation regimens, and during their entire life cycle.

Course calendar:

Week	Date	Lecture Topic	Reading
Introduction to Complex Infrastructure Systems			
1	Aug. 24	Course overview and sample infrastructure studies.	
The Empirical Study of Networks			
	Aug. 26	Bridge networks and other technological systems.	[6] Ch.2; [1] S.1, 2.3
2	Aug. 31	Social, informational, and biological networks.	[6] Ch.3-5; [1] S.2
Fundamentals of Network Theory			
	Sep. 2	Mathematics of networks – Network representations, network types.	[6] Ch. 6; [1] S.3; [2] S.2.1, S.2.4
3	Sep. 7	Mathematics of networks – Spatial networks, vertex and edge degrees.	[6] Ch. 6; [1] S.3; [2] S.2.1, S.2.2, S.2.5
	Sep. 9	Mathematics of networks – Paths, connectivity.	[6] Ch. 6; [1] S.3; [2] S.2.1
4	Sep. 14	Mathematics of networks – Advanced concepts, graph Laplacian, and spectral properties.	[6] Ch. 6; [1] S.3; [2] S.2.1
	Sep. 16	Network metrics – Topological centrality. Course project search.	[6] Ch. 7; [1] S.3; [2] S.2.1
5	Sep. 21	Network metrics – Eigenvector centrality and PageRank.	[6] Ch. 7
	Sep. 23	Examination No. I	
6	Sep. 28	Network metrics – Functional centrality.	[6] Ch. 7; [1] S.3; [2] S.2.1

	Sep. 30	Network metrics – Topological balance and mixing patterns. Course project assignments.	[6] Ch. 7; [1] S.3
7	Oct. 5	Large network structure – Degree probability distributions.	[6] Ch. 8; [1] S.3
	Oct. 7	Large network structure – Network types by vertex degree distributions.	[6] Ch. 8; [1] S.3; [2] S.2.2
8	Oct. 12	Large network structure – Probability distributions of centrality and coefficient metrics.	[6] Ch. 8; [2] S.2.2
Computer Algorithms			
	Oct. 14	Basic algorithm concepts – computational complexity and data structures.	[6] Ch. 9; [9] Ch. 3
9	Oct. 19	Fundamental algorithms – Degrees, clustering, shortest paths.	[6] Ch. 10; [9] Ch. 4
	Oct. 21	Fundamental algorithms – Network flows.	[6] Ch. 10; [9] Ch. 6
10	Oct. 26	Fundamental algorithms – Maximum flow and minimum cuts.	[6] Ch. 10; [9] Ch. 6
	Oct. 28	Examination No. II	
11	Nov. 2	Matrix algorithms – Graph partitioning.	[6] Ch. 11; [2] S.7.1
	Nov. 4	Matrix algorithms – Modularity and clustering.	[6] Ch. 11; [2] S.7.1
Theoretical and Computational Network Models			
12	Nov. 9	Network models – Random graphs	[6] Ch. 12-13; [1] S.4; [2] S.2.3; [3] S. V
	Nov. 11	Network models – Evolving networks	[6] Ch. 14; [1] S.7; [2] S.2.3; [3] S. VIII
13	Nov. 16	Network models – Other networked system models, interdependencies	[6] Ch. 15; [1] S.6; [2] S.2.3; [3] S. VII
Processes on Networked Systems			
	Nov. 18	Percolation – One-dimensional models	[6] Ch. 16; [1] S.8; [3] S. IV
14	Nov. 23	Percolation – Two-dimensional models	[6] Ch. 16; [1] S.8; [3] S. IV
	Nov. 25	No class – Thanksgiving holiday	
15	Nov. 30	Vulnerability and resilience – Performance of ideal and real infrastructure systems.	[6] Ch. 16; [1] S.8; [2] S.3.1; [3] S. IX
	Dec. 2	Network dynamics	[6] Ch. 17; [1] S.8; [2] S.3.2; [3] S. X
16	Dec.8 – Dec.15	Course project presentations.	

Required reading:

[1] Newman, M. E. J., (2003). “The structure and function of complex networks.” *SIAM Review*, 45(2): 167-256.
[2] Boccaletti, S., V. Latora, Y. Moreno, M. Chavez, and D.-U. Hwang (2006). “Complex networks: structure and dynamics.” *Physics Reports*, 424: 175-308.
[3] Albert, R., and A.-L. Barabási, (2002). “Statistical mechanics of complex networks.” *Review of Modern Physics*, 74(1): 47-97.
[4] Dorogovtsev, S. N., and J. F. F. Mendes, (2002). “Evolution of networks”. *Advances in Physics*, 51(4): 1079-1187.

Additional reading:

[5] Barrat, A., M. Barthelemy, and A. Vespignani, (2008). *Dynamical processes on complex networks*. Cambridge: Cambridge University Press.
[6] Newman, M. E. J., (2010). *Networks: an introduction*. Oxford: Oxford University Press.
[7] Newman, Mark E.J., Albert-László Barabási, Duncan J. Watts, (2006). *The structure and dynamics of networks*. Princeton, NJ: Princeton University Press.
[8] Christensen, K., and N. R. Moloney, (2005). *Complexity and criticality*. Vol. 1. London: Imperial College Press.
[9] Ahuja, R., T. Magnati, and J. Orlin, (1993). *Network flows - theory, algorithms, and applications*. Upper Saddle River, NJ: Prentice Hall, Inc.

On-line resources:

Complex systems:

- http://www.santafe.edu/
- http://cse.ucdavis.edu/
- http://www.ccsr.uiuc.edu/
- http://www.cscs.umich.edu/
- http://www.mpipks-dresden.mpg.de/
- http://necsi.org/
- http://complex.upf.es/
- http://css.csregistry.org/tiki-index.php/
- http://www.barabasilab.com/

Course grading:

Homework	25%
Examination I	25%
Examination II	25%
Final Project	25%

Academic honor code:

The Honor System embodies the concept of personal honor in a framework of law and practice. To quote the Constitution, Rice students are placed on their honor by the group "not to violate the trust placed in them in any way."

The result is a system of conducting examinations, writing papers, and performing other academic endeavors with regard for individual honor and without faculty proctoring. Thus, the responsibility for maintaining the validity of academic work is placed on all students.
Website: http://honor.rice.edu/

Disabilities:

Any student with a documented disability needing academic adjustments or accommodations is requested to speak with me during the first two weeks of class. All discussions will remain confidential. Students with disabilities will need to also contact Disability Support Services in the Ley Student Center.

Office hours:

Tuesdays 1:00 PM – 3:00 PM