Complex Systems 535/Physics 508: Network Theory

Instructor: Mark Newman

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Web site:

Everything on this information sheet, and more, can be found on the course web site:

`http://www.umich.edu/~mejn/courses/2009/cscs535/`

Course text:

There is no set book for the course, but there are two required course packs. The first is now available, from Dollar Bill Copying Church St. Ask for CmplxSys 535/Physics 508, Prof. Newman, Bin 6064. The cost is $19 plus tax. Together the two course packs contain of a draft copy of the as-yet unpublished book *Networks*, by Mark Newman (your instructor!), Oxford University Press (2010).

Review articles: There are no other comprehensive books on this subject that I'm aware of, but there are a number of review articles that you might wish to look at if you want a second opinion on anything:

- S. H. Strogatz, Exploring complex networks. *Nature* **410**, 268–276 (2001)
- R. Albert and A.-L. Barabási, Statistical mechanics of complex networks. *Rev. Mod. Phys.* **74**, 47–97 (2002)
- S. N. Dorogovtsev and J. F. F. Mendes, Evolution of networks. *Advances in Physics* **51**, 1079–1187 (2002)
- M. E. J. Newman, The structure and function of complex networks. *SIAM Review* **45**, 167–256 (2003)
- S. Boccaletti, V. Latora, Y. Moreno, M. Chavez, and D.-U. Hwang, Complex networks: Structure and dynamics. *Physics Reports* **424**, 175–308 (2006)

Books: There are also a number of specialized books that cover parts of the syllabus in greater depth. **None of these books is required.** If you want to look at them, however, then I'd recommend for graph theory either West or Wilson, and for social network analysis probably Scott. The Ahuja book is excellent if you're interested in the computer programming/algorithms side of things.

- R. K. Ahuja, T. L. Magnanti, and J. B. Orlin, *Network Flows: Theory, Algorithms, and Applications*. Prentice Hall, Upper Saddle River, NJ (1993)
- A.-L. Barabási, *Linked: The New Science of Networks*. Perseus, Cambridge, MA (2002)
- B. Bollobás, *Modern Graph Theory*. Springer, New York (1998)
- S. Bornholdt and H. G. Schuster (eds.), *Handbook of Graphs and Networks*. Wiley-VCH, Berlin (2003)
- A. Degenne and M. Forsé, *Introducing Social Networks*. Sage, London (1999)
- S. N. Dorogovtsev and J. F. F. Mendes, *Evolution of Networks: From Biological Nets to the Internet and WWW*. Oxford University Press, Oxford (2003)
- F. Harary, *Graph Theory*. Perseus, Cambridge, MA (1995)
- R. Pastor-Satorras and A. Vespignani, *Evolution and Structure of the Internet*. Cambridge University Press, Cambridge (2004)
- J. Scott, *Social Network Analysis: A Handbook*. Sage, London, 2nd edition (2000)
- S. Wasserman and K. Faust, *Social Network Analysis*. Cambridge University Press, Cambridge (1994)
- D. J. Watts, *Small Worlds*. Princeton University Press, Princeton (1999)
- D. J. Watts, *Six Degrees: The Science of a Connected Age*. Norton, New York (2003)
- D. B. West, *Introduction to Graph Theory*. Prentice Hall, Upper Saddle River, NJ (1996)
- R. J. Wilson, *Introduction to Graph Theory*. Addison-Wesley, Reading, MA, 4th edition (1997)

Syllabus

Introduction

Empirical studies of networks

- Technological networks
- Social networks
- Information networks
- Biological networks

Graph theory

- Vertices, edges, adjacency matrix
- Directed/undirected graphs, hyperedges
- Bipartite graphs and types of vertices
- Cyclic/acyclic graphs, upper triangular adjacency matrices
- Trees, planar graphs, proof of planarity
- Degree, in-degree, out-degree, mean degree and density, degree distributions
- Paths, powers of the adjacency matrix, geodesics, diameter
- Eulerian/Hamiltonian paths, Königsberg problem
- Components, strongly-connected components
- Independent paths, connectivity, Menger's theorem
- Weighted networks, maximum flows and minimum cuts
- Graph Laplacian, diffusion, spectra
- Random walks, resistor networks

Social network analysis

- Degree centrality
- Eigenvector centrality, PageRank, Katz centrality, HITS algorithm, co-citation and bibliographic coupling
- Closeness, betweenness
- k-components, k-cliques, k-cores, k-plexes
- Transitivity, clustering coefficients, Watts–Strogatz clustering, Burt's redundancy, structural holes, reciprocity
- Valued networks, weak ties, signed networks, structural balance, clusterability
- Structural equivalence, cosine similarity, Euclidean distance, Pearson correlations, regular equivalence
- Assortative mixing, degree correlations

Algorithms

- Summary of available standard software: Pajek, UCInet, JUNG, NetworkX, Netminer, NetDraw, GraphViz, MAGE, Krackplot, R, Combinatorica, AGD, LEDA, Visone
- Computational complexity
- Data structures and representations of networks: adjacency matrices, adjacency lists, trees, heaps, hybrid representations
- Trivial algorithms: calculation of degree, clustering coefficient, degree distributions, rank/frequency plots (cumulative histograms)
- Shortest path algorithms: breadth-first search, finding components, depth-first search, closeness centrality, Freeman betweenness, edge betweenness, Dijkstra's algorithm
- Maximum flows, the augmenting path algorithm
- Eigenmodes, eigenvector centrality, algebraic connectivity, matrix diagonalization, the multiplication method and the Lanczos algorithm
- Graph partitioning: Kernighan–Lin algorithm, spectral partitioning
- Community detection: modularity maximization, vertex moving algorithms, spectral community detection, betweenness-based methods, hierarchical clustering

Models of networks

- The Erdős–Rényi random graph: definition of $G(n,m)$ and $G(n,p)$, heuristic derivation of the phase transition
- Generalized random graphs and the configuration model: degree and excess degree distributions; the generating function method, component sizes, the phase transition, the giant component; directed graphs
- Growing graphs: preferential attachment, Price's model, and the rate-equation method; simulations; the Barabási–Albert model; nonlinear kernels, fitness models, models that include removal of edges or vertices; vertex copying models
- Optimization models: shortest path models, travel-time models
- Other network models: exponential random graphs; the small-world model

Processes taking place on networks

- Percolation, network resilience, vaccination and herd immunity
- Epidemic processes on networks: SIR, SIS, SIRS models; compartmental models and moment closure, percolation theory, mean-field theory; dynamics of epidemics on networks
- Dynamical systems on networks: nonlinear dynamics, fixed points and linearization, stability conditions, special cases, synchronization
- Network navigation and search on networks