Network Science Undergraduate Minor: Building a Foundation

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1 Introduction

As an interdiscipline, network science (NS) encompasses several intellectual perspectives and subjects, including mathematics, sociology, psychology, information science, and biology. Unlike traditional statistical approaches, which assume data independence, NS assumes dependent interconnection that can then be modeled by a graphical structure. Through its methodology, NS focuses on the impact of the relationships among individual entities. This enables NS students to identify and analyze the essential characteristics and properties of the structures and processes on the network. Many systems rely on both physical connections, such as those supporting communications or shared computing, and sociocultural connections, such as the web of trust-based relationships that exist among people [1, 2]. NS methods provide the tools to study many elements of contemporary information society as described in Easley and Kleinberg [3]. NS is an active, growing discipline in the modern information world, and consequently, undergraduate institutions are beginning to offer academic courses and programs in NS. This paper will discuss and provide information on the NS education minor program at USMA as an example of the type of program that can educate undergraduates in this important area of modern science.

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2 Background

Network science has been enhanced by an entirely new arsenal of methods and models. As an interdiscipline, its methods connect quantitative concepts from several disciplines such as mathematics, biology, physics, computer science, data science, operations research, cognitive science, sociology, and information science, with qualitative approaches from sociology, linguistics, social science, behavioral science, and psychology. By its very nature, NS uses methods and theories that involve emerging areas of science such as complex adaptive systems, cooperative game theory, agent-based modeling, and data analytics. NS is modeling with a structured, entity-linked, framework. Much of the strength of network modeling is in its ability to embrace the complexities of the real world. NS has become an important and empowering form of interdisciplinary analysis and problem solving to confront the important issues of the society. Network science research is still building its underlying framework, inventing new computational tools and techniques, and organizing network relevant data. This makes NS an exciting, relevant, modern field of study at all levels of education.

3 Network and Information Science

As the world becomes more globally connected, it is increasingly defined by networks. Our ability to quantify underlying factors that drive these networks continues to improve [ibid] and [4]. Whether systems are made up of physical, technological, informational, or social networks, they share many common organizing principles and thus can be studied with similar approaches. With this powerful framework, we have discovered how networks form, grow, transform, dissolve, evolve, and behave; how they facilitate the flow and the spread of information, behaviors, resources, and diseases; how knowledge transforms the network and how the networks transform knowledge; what mechanisms drive network formulation and operation; and how we can intervene to disrupt or rehabilitate networks. Undergraduate education is designed for the future success of the students, and reports on the future of network science given by National Research Council Network Science Committee [5] and Coronges et al. [6] provide these application domains with great potential for impact by network science:

- Group decision-making
- Personal and population health
- Biological systems and brain activity
- Socio-technical infrastructure
- Human-machine partnerships

The academic minor program that we have established at USMA seeks to build a foundation in the basic science of networks for our students. These foundational elements include:

- Mathematical computation to measure properties and modeling methods for dynamic processes
- Data analysis and processing methods for data visualization, network inference techniques, and tools to navigate and synthesize network data
- Theory and mechanisms for understanding network processes, such as diffusion, control, and coordination
- Ethics in collecting, storing, sharing, and using information

One way to define a network is to establish its components (nodes, links, data, processes, etc.), its properties (dynamic, functional, layered, etc.), and its applications (logistics, flow, transportation, information transfer, metabolic networks, social networks, organizational networks, etc.). The foundational research management report on network science written by the National Research Council Network Science Committee [5] used a layered approach for the network roles – physical, communicative, informational, biological, and social/cognitive. Modern networks often contain a critical information layer that can be exploited; security is always an issue. Therefore, cybersecurity is a big part of informational network science [7].

Many networks are too complex to rely on visualization to achieve understanding. Defining, computing, and measuring well-defined properties can counter those misguided visual perceptions and improve network modeling and analysis. According to Arney [8], the roles of the discipline include: working with information scientists to build explicative (based on a theory or conjecture) and empirical (based on statistical analysis of data) models, creating appropriate measures for important applications, finding appropriate properties, formalizing measurement systems for properties, and increasing security of the information in the network system.

It is interesting to look at a topical family tree for network science. While the historical development and the contribution relationships are subjective (based on an aspect of the transition but possibly not all elements) and incomplete (often limited to one primary contributor being listed when there were many), one can see in Fig. 1 the disciplinary web that brings together some of the many elements that have contributed to network science.

4 Undergraduate Curricula

At USMA, we have seen that undergraduate students have considerable interest in network science. Courses and programs that traditionally were offered at the graduate level are attracting undergraduates' interest. As social media and online systems are seen to be parts of NS, student interest in NS has grown in leaps and bounds. NS is a valuable addition to the academic program at USMA for several important reasons.

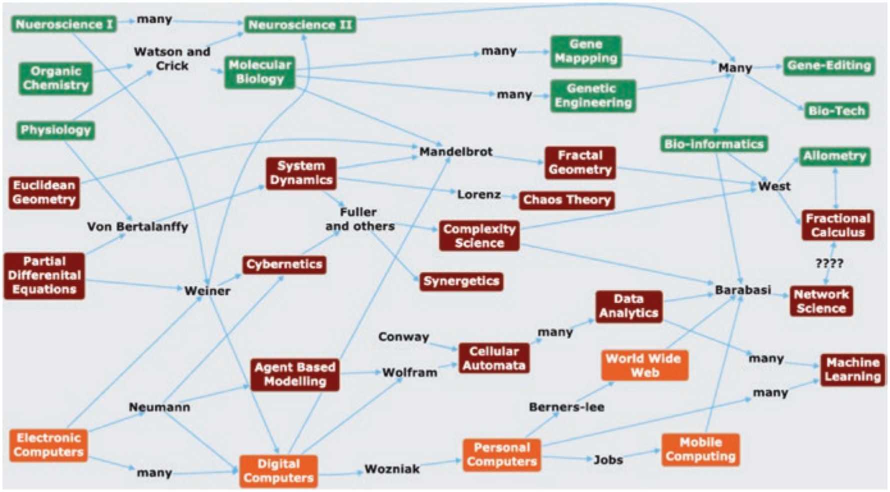

Fig. 1 Disciplinary connection network model showing links between subjects (Green denotes biological subject, maroon denotes mathematics subjects, and orange denotes computing subjects). (Fig. 1 was assembled by network science student John McCormick as part of his senior thesis at USMA)

4.1 Network Science Minor

At USMA, the network science minor consists of five academic courses:

- One required course (Foundations of Network Science). This course provides the basic introductory framework necessary for learning and understanding network science.
- Three electives within the minor. Students are required to select three courses from an extensive, flexible, multidisciplinary list of possibilities, thus designing their program to complement their other coursework and interests. The selected courses must fulfill the required elements of theory, modeling, and application. The theory requirement can be fulfilled by a course such as:
  - Linear Algebra
  - Discrete Mathematics
  - Graph Theory
  - Sociological Theory
  - Design And Analysis Of Algorithms
- The modeling requirement can be fulfilled by:
  - Human Physiology
  - Genetics
  - Data Structures
  - System Simulation

  - Mathematical Modeling
  - Deterministic Models
  - Stochastic Models
  - Systems Dynamics Simulation

- The application elective has many possible courses, some that fulfill this requirement are:

  - Infrastructure Engineering
  - Computer Networks
  - Artificial Intelligence
  - Cyber Security Engineering
  - Comparable Military Systems
  - Supply Chain Engineering
  - Urban Geography
  - Geographic Information Systems
  - Cyber Policy, Strategy, and Operation
  - Leading teams
  - Human-Computer Interaction
  - Econometrics
  - Network Science for Cyber Operations

- One required course in integration of their learning. This final course in the network science minor is a capstone of their learning within the minor. Students select a topic of interest in conjunction with a faculty advisor. This integration experience is an opportunity for cadets to synthesize previous material in tackling a demanding problem. This course provides experiences in presenting technical results both orally and in a technical report. Recent titles of projects that fulfilled this requirement include "Modeling Household Vulnerability in Kampala, Uganda," "Optimizing Intelligent Walks for Dark Network Discovery," "A Heuristic for Approximating a Minimum Dominating Set of an Arbitrary Directed Graph," "Undersea Communication Cables," and "Analyzing a Network of NATO Scientists."

5 Network Science Minor Learning Model

Academic curriculum has three principal structural components: breadth, depth, and integration. Network science, as an interdisciplinary minor, provides opportunity for additional study in an area beyond the major, thus reinforcing all three academic components. The network science minor also offers military-related knowledge, which enhances graduates' ability to meet the USMA overarching academic program goal to respond effectively to the uncertainties of a changing technological, social, political, and economic world.

- *Structure of learning experiences*: the structure of the network science minor program is designed to expose cadets to an emerging interdisciplinary field with enough depth to develop their modeling, analysis, and problem-solving skills. The program nurtures creativity, critical thinking, and self-directed learning through activities performed in theory, modeling, and application settings. The minor includes both the acquisition of a body of knowledge and the development of thought processes judged essential to understanding fundamental ideas and principles in network science.
- *Process of learning experiences*: the introductory course provides theoretical and mathematical foundations for further study and experience in applying network concepts to real-world problems. The three elective courses selected by the cadet give depth in the discipline. The integration course is generally taken last and provides an opportunity to work on a more complex problem involving analysis of real-world data or understanding of an important issue. The goal of the integration course is to enhance conceptual understanding of key concepts and to unify concepts through their application to a real-world problem. Learning takes place through various means such as reading, discussion, laboratory discovery, research projects, and leveraging the various emerging technologies in network science.

6 Fundamentals in Network Science Course[1]

This required course starts the educational minor by exposing students to the basic concepts of networks and gives them an opportunity to apply techniques learned in the course to real-world problems. Students develop skills and problem-solving strategies for modeling complex networks associated with physical, informational, and social phenomena. The Organizational Risk Analysis (ORA) software package (http://www.casos.cs.cmu.edu/projects/ora/) is used to investigate application problems and augment understanding of the course material. The course seeks to build the students' ability to understand and learn and solve problems through these following goals:

- *Acquire a base of knowledge*. Learn basic graph theory terms and acquire the fundamental skills and concepts required to conduct network analysis. These skills include representing networks of nodes and links with graphs and matrices, calculating network level and node level measures, identifying group structures, analyzing the distribution of centrality measures, and evaluating the underlying causes for link formation. Students learn to calculate and measure centralities (degree, closeness, betweenness, eigenvector), PageRank, homophily, transitivity, reciprocity, and balance.
- *Apply technology*. Use software to build and analyze models using network analysis software.

[1] Much of the new content for the Fundamentals of Network Science course was developed by Donald Koban in 2016 and 2017.

- *Communicate effectively*. The students improve their communication skills, both verbally and in writing by presenting article summaries throughout the course, writing a technical paper and creating a research poster.
- *Solve problems confidently and competently*. The students analyze problems by formulating models, discussing critical assumptions, analyzing networks, and interpreting the results.
- *Develop habits of mind*. Students practice several important intellectual elements such as creativity, critical thinking, curiosity, and teamwork.
- *Think with an interdisciplinary perspective*. This course embraces the complexity of modeling the structures and processes of organizations, systems, and networks [9].

The course textbooks are Newman [1] (2010), which provides an overview and introduction to network science, and Easley, Kleinberg [3] (2010), which provides more exposure to diverse applications. The videos watched in class include:

- http://www.wimp.com/wolvesrivers/
- https://www.youtube.com/watch?v=nJmGrNdJ5Gw
- http://www.opte.org/the-internet/
- http://www.ted.com/talks/nicholas_christakis_the_hidden_influence_of_social_networks

The data sets used include:

- Stanford Large Network Dataset Collection: http://snap.stanford.edu/data/
- Clauset et al. Collection [10]: http://tuvalu.santafe.edu/~aaronc/powerlaws/data.htm
- UC Irvine Network Data Repository: http://networkdata.ics.uci.edu/
- Mark Newman Collection: http://www-personal.umich.edu/~mejn/netdata/
- Sean Everton Noordin Top Terrorist Network: https://sites.google.com/site/sfeverton18/research/appendix-1
- Visualization of A Day in the Life of Americans: http://flowingdata.com/2015/12/15/a-day-in-the-life-of-americans/

The articles used for readings are an important component of the course. Getting the students into the network science literature early in the sequence of the program helps them in their courses later in the program. In addition to the two textbooks, the students also read articles [11–24].

7 Network Science for Cyber Operations[2]

This course fulfills the application component of the minor. The course goal is to enable students to confront cyberspace issues by modeling, solving, analyzing, and understanding problems involving cybersecurity on networks. Students learn about

[2]The content of the Network Science for Cyber Operation was developed by Professors Chris Arney and Natalie Vanatta, who have team-taught this course several times.

networks, perform complex modeling, work on a project of their choosing, write and present a book review, produce a poster on their project, and give presentations on their project. Much of the material is learned through individual reading, class discussions, and lectures by cyber professionals. The course material is supplemented by the many examples in the news related to cybersecurity. The course embraces the complexity of determining human-based security measures (utility functions) for the structures and processes of cyber systems and information networks. From a cyber perspective, this course explores the role of cyber policies and practices on networked systems, communities, and all of society.

Defensive cyber operations seek to maintain network performance and reliability while protecting and securing information and communication validity. Offensive cyber operations seek to disrupt network performance or damage the information and communications of an adversary. Cyber concerns are critical to the functionality of the Internet and the World Wide Web. The layers of the various networks within the dark or deep web can affect critical infrastructure and information used for national and global commerce and communications. Disruptions in the Internet or World Wide Web or lapses in their security put the infrastructure and economic health of the United States at risk. The sheer volume and heterogeneity of the data, the dynamics of evolving threats, and the sensitivity of normal and malicious behavior all pose major challenges. The course content includes:

- *Cryptography*: This material traces the history of cryptography from Caesar to modern elliptic curves. Students will explore the innovation of encryption through the mathematical foundations that they are built on. Emphasis will be placed on the military applications of encryption and how they have changed the face of the battlefield.
- *Cyber Mission Forces*: The Cyber Mission Forces are a new addition to the US military to concentrate on cyber-related military operations.
- *Internet of Things*: The Internet of Things is quickly becoming our new reality–or perhaps the greatest threat to our way of life. Students explore the complex issues (both technical and non-technical) that create the foundation for the Internet of Things.
- *Social Sciences*: There are many important aspects to cyber operations that are nontechnical in nature. Students study cyber policy, regulation, and law as it pertains to both military and nonmilitary operations. Special emphasis is placed on cyber ethics and the tug-of-war between privacy and security.
- *Data Analytics and Science*: Visualization and how to do data analytics for the security of large-scale networks.

The course uses *Network Science* by Albert-László Barabási [25] for its network science textbook along with each student selecting one of these three books as a second textbook:

1. *Cyber War* [26] (policy, regulation, and nation state actors)
2. *Code Book* [27] (historical to modern ciphers and a brief chapter on the future)
3. *Cybersecurity and Cyberwar* [28] (how the Internet and basic tenants in cyberspace work)

The students are asked to consider the course material in the context of the cyber book they select and these questions:

- What kind of public policy should be in place to regulate/manage access to information technology?
- Should we establish a list of laws and rules that carry severe penalties for violators, or should we use incentives, and build an infrastructure that guides usage?
- How can we identify trends found in social media to understand how changes in networks can signal shifts in beliefs and behaviors?
- How can social media be used to sway public opinion and create consensus to vote or protest?
- Who has knowledge about the security of the Internet (including the resource providers and resource consumers)?
- What is the complexity or interconnectedness of public systems networks?
- What kinds of policies or controls would help regulate security in such a complex system?
- What are the roles of the public and private sector in these public needs?

8 Network Science Problems in the Interdisciplinary Modeling Contest

The Interdisciplinary Contest in Modeling (ICM) http://www.comap.com/undergraduate/contests/index.html is a large international modeling contest conducted annually involving over 24,000 undergraduates from over ten different countries. For 4 days, teams of up to three undergraduates research, model, analyze, solve, write, and submit 20-page solutions to an open-ended problem. The solution papers are judged and categorized as described in the contest's history and overview [29]. The problems are chosen from three areas (network science, environmental science, or policy). Some of the popular network science problems from the contest are as follows:

2012 This problem required teams to investigate the relationships of the members of a criminal conspiracy network within a business organization through social network analysis of their message traffic. It required teams to understand concepts from the informational and social sciences to build effective network and statistical models to analyze the message data between 83 people involving over 400 messages that were categorized into 15 topics. In order to accomplish their tasks, the students had to consider many difficult and complex disciplinary and interdisciplinary issues. An Outstanding-category solution paper by Guo et al. [30] can be found in the *UMAP Journal*.

2013 This problem required teams to investigate the relationships of local and regional ecosystems to the global health of the planet. It required teams to understand concepts from the informational, environmental, and social sciences to build network and statistical models to track the potential changes in Earth's global health. In order to accomplish their tasks, the students had to consider many difficult and complex disciplinary and interdisciplinary issues. An Outstanding-category solution paper by Moitinho de Almeida [31] can be found in the *UMAP Journal*.

2014 The NS requirement investigated the relationships involved in network models for determining influence in a large coauthor network (Mathematician Paul Erdös' 511 coauthors) and measuring impact within a set of foundational papers within the discipline of network science. This problem required teams to mine a large data set and understand concepts from the informational sciences to build effective models for these complex phenomena. The problem contained many multifaceted issues to be analyzed and had several challenging requirements for innovative scientific and network modeling and analysis. In addition to network modeling, informational analysis, and data collection, the teams had to explain the nature of influence and impact in an academic social network and show how their models could be used to help make informed decisions. An Outstanding-category solution paper by Wang et al. [32] can be found in the *UMAP Journal*.

2015 The network problem for 2015 involved modeling human capital issues (especially employee churn) in a hypothetical organization of 370 employees with the intent of aiding managers and decision-makers to build successful systems for recruiting, hiring, training, and evaluating employees. Having teams analyze the network-related issues of human capital is a relevant issue in improving performance and profits of many modern organizations. An Outstanding-category solution paper by Blanc et al. [33] can be found in the *UMAP Journal*.

2016 The network problem was set in a historical context where society's information networks of five time periods (1870s, 1920s, 1970s, 1990s, and 2010s) were compared. By using the news and media networks of each period, measures for the flow of information relative to the value of information were established and compared. Teams used historical data and developed measures and models to determine what qualifies as news and to track the evolution of news throughout the ages. An Outstanding-category solution paper by Norman et al. [34] can be found in the *UMAP Journal*.

The ICM offers an opportunity each year for teams of undergraduate and high school students to tackle challenging, real-world problems that require skills in network science. ICM problems are open-ended, challenging problems. The complex nature of the ICM problems and the short time limit require effective communication and coordination of effort among team members. One of the most challenging issues for the team is how to best organize and collaborate to use each team member's skills and talents. Teams that solve this organizational challenge often submit excellent solutions. We have included information on the network science problems of the ICM because it can be a significant motivator for students to study more NS in their undergraduate programs.

9 Conclusion

The discipline of network science in the undergraduate curriculum has followed similar paths as operations research and computer science in the later part of the twentieth century [7, 35, 36]. If that trend continues, many colleges will have undergraduate network science programs similar to the one at the USMA described here. This the way that science and its curricula evolve and impact our society and education system.

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