NetSciEd: Network Science and Education for the Interconnected World

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Abstract

This short article presents a summary of the NetSciEd (Network Science and Education) initiative that aims to address the need for curricula, resources, accessible materials, and tools for teaching K-12 students and the general public the concept of *networks*, a crucial framework in understanding complexity. NetSciEd activities include (1) NetSci High educational outreach program (since 2010) that connects high school students and their teachers with regional university research labs and provides them with the opportunity to work on network science research projects, (2) NetSciEd symposium series (since 2012) that brings network science researchers and educators together to discuss how network science can help and be integrated into formal and informal education, and (3) Network Literacy: Essential Concepts and Core Ideas booklet (since 2014) that was created collaboratively and subsequently translated into 18 languages by a large number of network science researchers and educators worldwide.

Introduction

Since its boom in the late 20th century (Watts & Strogatz 1998; Barabási & Albert 1999), the concept of *networks*, a crucial framework in understanding complexity, has become ever-more relevant to people's everyday life (Buchanan 2003; Newman 2010; Caldarelli & Catanzaro 2012; Barabási 2014). Nearly every system that surrounds us, or exists among or inside us, can be understood as a network, i.e., a discrete structure that consists of nodes (vertices, entities, actors, items) and edges (links, relationships, ties, connections) that connect the nodes. Examples of networks are ubiquitous, including the Internet, social media, financial systems, transportation networks, ecosystems, organizations, friendships, schools, classrooms, learning materials, brains, immune systems, and even genes/proteins within a single cell. Knowledge about networks can help us to make sense of those systems, making it a useful literacy for people to be effective and successful in this increasingly complex, interconnected world of the 21st century (Sheetz, Dunham, & Cooper 2015; Sayama et al. 2016). Network science (Barabási 2013), an interdisciplinary field of scientific research on networks, offers a powerful approach for conceptualizing, developing, and understanding solutions to complex social, health, technological, and environmental problems. It also provides opportunities to develop many of the skills, habits of mind, and core ideas that are not currently addressed in extant elementary/secondary education curricula and teaching practice (Harrington et al. 2013; Sánchez & Brändle 2014). There is a need for curricula, resources, accessible materials, and tools for teaching network science to K-12 students (and their teachers) and the general public.

In this short article, we present a summary of the NetSciEd (Network Science and Education; http://tinyurl.com/netscied) initiative that we have been running over the last several years to address the educational need described above. NetSciEd activities include (1) NetSci High educational outreach program (Cramer et al. 2015b; http://bit.ly/2qwS3oh) that connects high school students and their teachers with regional university research labs and provides them with the opportunity to work on network science research projects, (2) NetSciEd symposium series (http://bit.ly/2cNd7RV) that brings network science researchers and educators together to discuss how network science can help and be integrated into school education, and (3) Network Literacy: Essential Concepts and Core Ideas booklet (Cramer et al. 2015a; http://tinyurl.com/networkliteracy), which was created collaboratively and subsequently translated into 18 languages by a large number of network science researchers and educators worldwide.

NetSci High

NetSci High (Cramer et al. 2015b; http://bit.ly/2qwS3oh) is a high school educational outreach program that brings network science to high schools through workshops and year-long, open-ended research projects supervised by graduate students, postdocs, and faculty at regional

university research labs. One of the objectives of NetSci High is to provide high school students and teachers an interdisciplinary learning experience that transcends the boundaries among traditional academic subjects (e.g., languages, mathematics, science, social studies, art, music, etc.). The concept of networks can be easily understood and applied to various subjects, which is ideal for achieving such an interdisciplinary educational objective.

Since its inception as a small pilot project created by the New York Hall of Science and Binghamton University in 2010, NetSci High has been taking several different formats with various funding sources (see Table 1 for an overview). Its first year (2010-2011) was run as a poster competition among seven high school teams in the New York City, Boston, and Binghamton areas. In the second year (2011-2012), it took the form of travel scholarships for two high school teams in the Binghamton area. Supplemental funding from the U.S. National Science Foundation (NSF) and a corporate donation from BAE Systems supported these first two years of activities.

In the subsequent three years (2012-2015), NetSci High was further developed as an NSF ITEST (Innovative Technology Experiences for Students and Teachers) project "Network Science for the Next Generation," with Boston University and the United States Military Academy at West Point as official partner institutions, and Newburgh, NY, was included as another target geographical region. Two-week summer workshops were developed as an initial kick-off event for the students' year-long research experience (Figure 1). Several educational modules and activities were developed for these summer workshops (for teachers as well as for the students) (http://bit.ly/2rfGWB3), which were highly effective in motivating and fully preparing students and teachers for network science research projects.
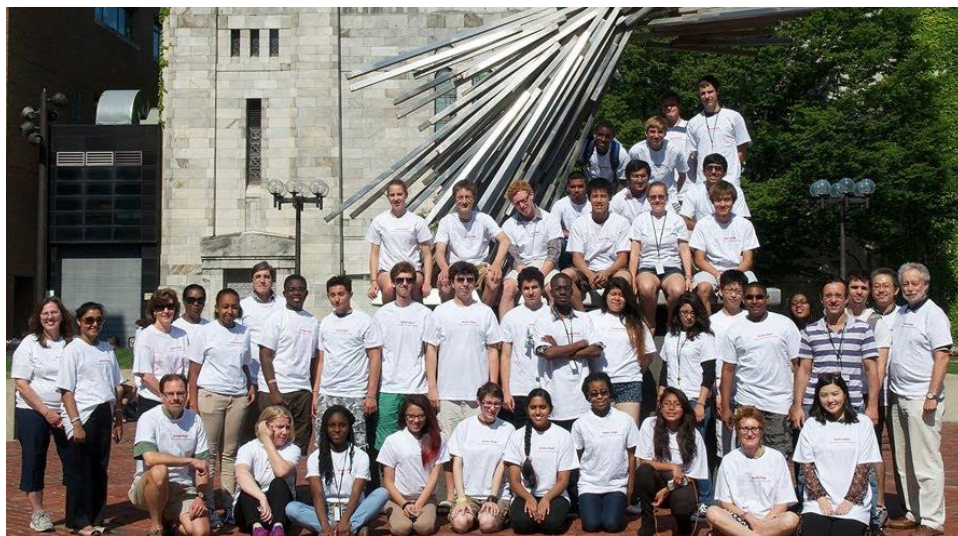

Figure 1: Participants at the NetSci High summer workshop at Boston University in July 2013.

At the end of each academic year, NetSci High student teams had an opportunity to attend academic conferences and present their work themselves as the final output of their research, depending on the availability of appropriate conferences and travel funding. Several student teams also published their work outside the NetSci High program on their own (Blansky et al. 2013; Onwuka, Pineda, & Stepakoff 2015; Shah et al. 2015; Asante, McMillan, & Peticco 2016; Chen & Mendoza 2016; Mariano 2016).

Table 1: Overview of NetSci High educational outreach program.

Year	Format	Participating schools and # of students participated	Participating universities	Final conference(s)
2010-2011	Poster competition	Flushing International High School (Flushing, NY) – 2 Elmont Memorial High School (Elmont, NY) – 1 Thomas A. Edison CTE High School (Jamaica, NY) – 1 Jericho High School (Jericho, NY) – 1 Maine-Endwell High School (Endwell, NY) – 7 Windsor School (Boston, MA) – 2	City College of New York Columbia University St. John's University Binghamton University Harvard Medical School	NetSci 2011, ICCS 2011
2011-2012	Travel scholarship	Maine-Endwell High School (Endwell, NY) – 4 Vestal High School (Vestal, NY) – 2	Binghamton University	NetSci 2012
2012-2013	Workshop + supervised research	Boston University Academy (Boston, MA) – 7 Newburgh Free Academy (Newburgh, NY) – 7 Vestal High School (Vestal, NY) – 2	Boston University Harvard Medical School US Military Academy Binghamton University	NetSci High Conference at Boston University
2013-2014	Workshop + supervised research	Boston University Academy (Boston, MA) – 4 Chelsea High School (Chelsea, NY) – 4 Elmont Memorial High School (Elmont, NY) – 6 Newburgh Free Academy (Newburgh, NY) – 7 Vestal High School (Vestal, NY) – 8	Boston University Harvard Medical School Stevens Institute of Technology Columbia University US Military Academy Binghamton University	NetSci 2014, NetSci High Conference at Boston University
2014-2015	Workshop + supervised research	CATS Academy (Braintree, MA) – 3 Chelsea High School (Chelsea, NY) – 4 Newburgh Free Academy (Newburgh, NY) – 12 Vestal High School (Vestal, NY) – 8	Harvard Medical School Stevens Institute of Technology US Military Academy Binghamton University	CompleNet 2015

The summative assessments of NetSci High (Faux 2015) have shown that the program had a significant impact on students' understanding of networks and their importance, and on the development of students' basic literacy of data driven science (e.g., data collection, manipulation, analysis; mathematical/computational skills; visualization), academic and scientific skills (e.g., creative/critical thinking; hypothesis forming; technical writing and presentation; interdisciplinary interest), and professional skills (e.g., time management; collaborative skills; self-confidence; leadership). These constitute an excellent preparation for high school students for higher education and STEM-related career paths.

Another important accomplishment of NetSci High is that it educated not just high school students and teachers but also the scientific community in return. Continuous participation of high school student teams at network science conferences has increased the awareness of educational values of network science, as well as the academic potential of students in secondary education, among the researchers in the network science community. As a result, education is now being recognized as one of the key themes in network science and other related fields. While federal financial support officially ended in 2015, the NetSci High model of educational outreach has made a lasting impact and has been adopted at several other outreach programs (e.g., Cramer 2015; Trunfio 2016; Mangal et al. 2016; USMA CLD STEM 2017). The resources of the summer workshops are made publicly available for others to replicate the program (http://bit.ly/2rfGWB3).

NetSciEd Symposium Series

Concurrently with the NetSci High program described above, we have been organizing the NetSciEd symposium series at NetSci conferences every year since 2012 (http://bit.ly/2cNd7RV; Figure 2). These symposia aim to bring network science researchers and educators together to discuss any issues that arise at the intersection between network science and education. Symposium programs typically include oral presentations, posters, and roundtable discussions. NetSci High student teams' posters have also been displayed at the symposium venues.

Figure 2: Participants at the First NetSciEd symposium in Evanston, IL, in June 2012.

Table 2 shows basic statistics of the NetSciEd symposium series. While the symposium programs were typically made of solicited talks in the first few years, the number of unsolicited abstract submissions has been rapidly increasing over the last few years, indicating the growing interest in education as a research topic among network science researchers.

Table 2: Basic statistics of NetSciEd symposia.

Name	Year	Location	Total # of presentations	# of unsolicited submissions	Format
NetSciEd	2012	Evanston, IL	9	0	Half-day
NetSciEd2	2013	Copenhagen, Denmark	11	0	Half-day
NetSciEd3	2014	Berkeley, CA	10	0	Half-day
NetSciEd4	2015	Zaragoza, Spain	12	1	Full-day
NetSciEd5	2016	Seoul, Korea	8	2	Half-day
NetSciEd6	2017	Indianapolis, IN	15	6	Half-day

Topics discussed at NetSciEd symposia include: (1) educational outreach activities, tools, and materials about network science; (2) curricular development and practices for teaching network science at schools/colleges; (3) teacher education and informal education about networks; (4) network modeling and analysis of educational systems, curricular materials, or classroom/school dynamics; (5) network modeling and analysis of learning processes; and (6) applications of network science for the improvement of education. Table 3 shows an informal breakdown of topics presented at the NetSciEd symposium each year. While the first two topics consistently attract the largest attention of the presenters, there has been a considerable diversity of topics being discussed.

Table 3: Informal breakdown of topics presented at NetSciEd symposia.

Topic	2012	2013	2014	2015	2016	2017
Outreach, tools, materials	4	4	3	8	2	4
Curricular development and practice	1	2	2	3	5	4
Teacher education/informal education		1	1			1
Modeling/analysis of educational systems	2	3	2		1	3
Modeling/analysis of learning processes		1	1			2
Application for improving education	1		1	1		1
Other	1					

Given these statistical trends, it is anticipated that network science and education will continue to be a steadily growing area of research with diversifying topics. One tangible outcome of the NetSciEd symposium series is the forthcoming Springer book "Network Science in Education – Tools and Techniques for Transforming Teaching and Learning" (Cramer et al. 2017). This volume will be a collection of selected contributions presented at the past NetSciEd symposia,

summarizing the current state of research and practice in this area and illustrating its potential future directions.

Network Literacy: Essential Concepts and Core Ideas

One critical missing piece that was repeatedly recognized throughout the NetSci High program and the NetSciEd symposia was the lack of systematic, accessible, easy-to-understand educational materials about networks and their implications for our everyday life, similar to grade-school-level textbooks and workbooks. Some academic communities have successfully produced such educational materials, such as textbooks produced by the System Dynamics community (Quaden, Ticotsky, & Lyneis 2005; Potash & Heinbokel 2011; Anderson & LaVigne 2014) and the "Ocean Literacy" and other science literacy booklets produced by several geoscience communities (http://bit.ly/2qvsw2B). Following the "Ocean Literacy" case (Cava et al. 2005; Schoedinger, Cava, & Jewell 2006; Strang, DeCharon, & Schoedinger 2007) as an example, a year-long collaborative process was launched in June 2014 to produce "Network Literacy: Essential Concepts and Core Ideas," (Cramer et al. 2015a; http://tinyurl.com/networkliteracy) a free online booklet that summarizes in layman's terms what every person who lives in the 21st century should know about networks by the time he/she graduates from high school.

The production process of the Network Literacy booklet started with a one-day preconference event held before the NetSci 2014 conference in Berkeley, CA in June 2014, in which several network science researchers and educators held a brainstorming and discussion session to create a list of essential concepts and their clusters (Sayama et al. 2016). Similar brainstorming sessions were also held with NetSci High students and teachers to receive their inputs, which later turned out to be extremely helpful and important. Network science was actively utilized in this process, not only as the subject of the booklet, but also as the technical toolbox for analyzing and organizing the generated concepts. Specifically, the generated concepts were connected to each other by the NetSci High students and teachers according to their perceived relatedness, forming a "multigraph" of the concepts (i.e., a network graph in which a pair of concepts can be connected by more than one edges). Then, a modularity-maximizing community detection algorithm that is frequently used in network science (Blondel et al. 2008) was applied hierarchically to this multigraph of concepts to detect important concept clusters. Those clusters were further reviewed and refined by network science researchers. This eventually resulted in the following seven essential concepts:

1. *Networks are everywhere.*
2. *Networks describe how things connect and interact.*
3. *Networks can help reveal patterns.*
4. *Visualizations can help provide an understanding of networks.*

5. *Today's computer technology allows you to study real-world networks.*
6. *Networks help you to compare a wide variety of systems.*
7. *The structure of a network can influence its state and vice versa.*

For each of these seven essential concepts, a more detailed description with several related core ideas were collaboratively written, and were then revised again collaboratively by the community of network science researchers worldwide through several iterations. After being illustrated with professionally designed visuals and layout (Figure 3), the booklet was published online in March 2015 (http://tinyurl.com/networkliteracy), and hard copies were disseminated at the CompleNet 2015 conference, at which the final cohort of NetSci High students were also presenting their research work. Sayama et al. (2016) provide more details of the complete production process of the Network Literacy booklet.
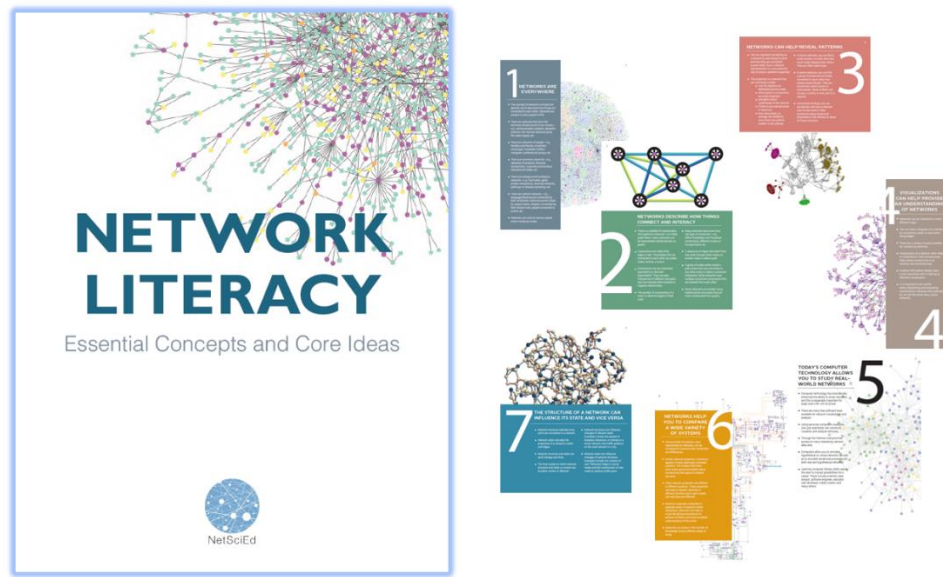
Figure 3: Network Literacy: Essential Concepts and Core Ideas booklet (original English version). Left: cover, right: content page design (design by Eri Yamamoto).

The online release of the Network Literacy booklet was received with overwhelmingly positive responses from researchers and educators worldwide. One notable reaction to this booklet was the coordinated effort to translate its contents to various non-English languages. Translations have been done entirely by volunteer network science researchers, students, and practitioners who appreciated the importance of learning and understanding networks for the general public at global scales. As of May 2017, the Network Literacy booklet has been translated into the following 18 languages: Arabic, Brazilian Portuguese, Catalan, Chinese (Mandarin), Chinese (traditional Mandarin), French, Dutch, German, Hebrew, Hungarian, Italian, Japanese, Korean, Persian, Polish, Russian, Spanish, and Ukrainian (see Figure 4 for geographical coverage).
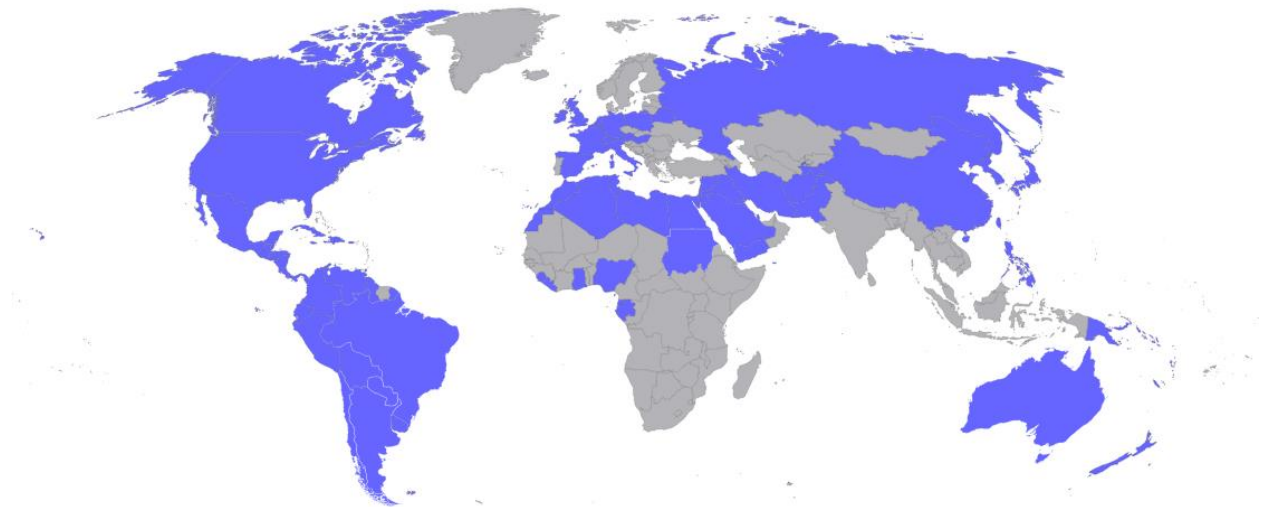
Figure 4: World map of language coverage of the Network Literacy booklet. Network Literacy has been translated into the majority languages of the countries/regions in blue. Chart created using http://www.amcharts.com/visited_countries/.

Conclusions

In this article, we presented brief summaries of three different, yet interrelated, activities that promote fruitful integration of network science and education. Conducted under the moniker of NetSciEd, these activities are based on our strong belief that learning and understanding networks has a direct benefit as the basic literacy for everyone who lives in today's highly interconnected world. In the meantime, network science can also offer more immediate, practical benefits, particularly in educational settings. First, network science can offer an accessible conceptual framework that naturally crosses academic subjects and thus helps students develop interdisciplinary academic/scientific/professional skills early on. Second, network science can also offer theoretical/technical tools to model, analyze, and understand the structure and dynamics of various education-related systems, such as organizational linkages among teachers and administrators, interrelationships among curricular modules, and psychological/cognitive processes of learning, to name a few. The three NetSciEd activities described above all aimed at producing all of those benefits, each to different degrees.

It goes without saying that the NetSciEd initiative is still far from completion, and there are many more goals that need to be accomplished in order to make major societal impacts. Urgently needed for teachers and students to adopt network science in their daily teaching and learning are resources such as: (1) detailed, modular, ready-to-use lesson plans that teachers can easily incorporate into existing curricula; (2) accessible, interactive online self-study guides for students; and (3) intuitive, interactive computer software tools for network drawing, visualization, analysis, and simulation. We are organizing a workshop for K-12 teachers to facilitate the development of lesson plans (to produce (1) above; http://bit.ly/2s9GlRH), and we are in the

process of exploring options for (2) and (3). Another major challenge in NetSciEd is how to better reflect the state-of-the-art of network science in K-12 educational materials, such as dynamical, temporal, adaptive nature of networks (Gross & Sayama 2009; Holme & Saramäki 2012; Porter & Gleeson 2016) and multiplex/multilayer/multiscale topologies of networks (Mucha et al. 2010; Kivelä et al. 2014; Boccaletti et al. 2014). While these concepts are highly applicable to many real-world networks, students and teachers typically find it quite difficult to understand dynamical behaviors or non-trivial topologies of networks. How to make these cutting-edge network science topics accessible and relevant to K-12 education remains an open challenge.

Acknowledgments

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