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What are essential concepts about networks?

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Networks have become increasingly relevant to everyday life as human society has become increasingly connected. Attaining a basic understanding of networks has thus become a necessary form of literacy for people (and for youths in particular). At the NetSci 2014 conference, we initiated a year-long process to develop an educational resource that concisely summarizes essential concepts about networks that can be used by anyone of school age or older. The process involved several brainstorming sessions on one key question: 'What should every person living in the 21st century know about networks by the time he/she finishes secondary education?' Different sessions reached diverse participants, which included professional researchers in network science, educators and high-school students. The generated ideas were connected by the students to construct a concept network. We examined community structure in the concept network to group ideas into a set of important themes, which we refined through discussion into seven essential concepts. The students played a major role in this development process by providing insights and perspectives that were often unrecognized by researchers and educators. The final result, 'Network Literacy: Essential Concepts and Core Ideas', is now available as a booklet in several different languages from http://tinyurl.com/networkliteracy.

Keywords: network literacy; essential concepts; core ideas; NetSci High; education; educational outreach; brainstorming; concept network.

1. Introduction

Network science has matured over the past few decades, and its potential importance for improving understanding of complex natural and human-made phenomena is now recognized in an increasingly diverse set of domains [1,2]. Its potential beneficiaries include not only researchers, but also business practitioners, policymakers, educators and virtually all lay people, as they need to understand and deal with complex real-world phenomena. To advance the use of networks as a lens on ourselves and on our world, there needs to be widespread and sophisticated knowledge about how the study of networks—the science of connectivity—can be an important epistemological tool for all people. In other words, we assert that an understanding of networks is a new kind of literacy that is important for everyone living in the 21st century.

We favour the term 'Network Literacy' over 'Network Science Literacy', because we believe that the scope and impact of networks goes beyond what one would typically construe as 'science'. The scope of Network Literacy is also rather different from what is currently being taught as 'Digital Literacy' or 'Internet Literacy' (or sometimes also called 'Network Literacy') about the use of computers, the Internet and other digital media [3–5]. Network Literacy needs to include fundamental concepts about networks, including (1) how an overwhelming abundance of everyday phenomena can be viewed through the lens of connectivity, interactions and interdependence; and (2) how one can analyse, understand, utilize and improve their features.

In response to such emerging societal needs, researchers in the network-science community have started educational outreach efforts to bring network science to secondary education [6–8]. There are also a few other dispersed outreach efforts that have considered, or even focused on, teaching ideas about networks (see, e.g., [9–13]). However, there do not yet exist educational materials about networks that are both systematically structured and easily accessible—such as grade-school-level textbooks, workbooks, curricular modules and lesson plans (e.g., the educational materials [14–16] developed by the 'System Dynamics' community [17,18])—and which can be integrated readily into formal and informal educational programs. As a first step towards meeting this need, we undertook a year-long effort to develop a set of Essential Concepts for Network Literacy.

We started by consulting people who had succeeded in similar educational initiatives. We were particularly inspired by the 'Ocean Literacy' initiative [19–21], which was spearheaded by members of the US NSF Centers for Ocean Science Education Excellence (COSEE). The work on the Ocean Literacy initiative began in 2002 when a grassroots group of scientists and educators, frustrated by the lack of ocean-science content in national education standards, came together to discuss what they felt every person should know about the ocean by the time he/she graduates from high school.[1] After discussing initial ideas for two years, the group organized a two-week online conference in 2004 that included more than 100 participants, a live keynote talk and virtual 'rooms' organized according to scientific disciplines and age groups. Their next step was to hold a charrette, at which 30 people convened for two days and distilled the combined input into seven principles (plus 44 fundamental concepts to more fully explain these principles). The final result was published in 2005 as a pamphlet called 'Ocean Literacy: The Essential Principles and Fundamental Concepts of Ocean Sciences for Learners of All Ages'.[2] To date, more than 30,000 brochures have been distributed in hard copy (in addition to digital dissemination). The success of Ocean Literacy was followed by similar processes in Climate Literacy, Atmospheric Literacy, Earth Science Literacy, Great Lakes Literacy, Energy Literacy and more.[3]

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[1] Their history is discussed at http://oceanliteracy.wp2.coexploration.org/ocean-literacy-network/foundations/history/.
[2] See http://www.oceanliteracy.net/.
[3] See http://nagt.org/nagt/teaching_resources/literacies.html.

Our goal is similar: we wish to provide a simple, concise, high-level guiding document that can facilitate the process of developing resources for disseminating Network Literacy to all people. To initiate this process, we posed one key question to ourselves and to the network-science community: *What should every person living in the 21st century know about networks by the time he/she finishes secondary education?*

In the present paper, we describe the highly collaborative process by which we developed the first version of 'Network Literacy: Essential Concepts and Core Ideas' (which is now available at http://tinyurl.com/networkliteracy). Network-science researchers, educators, high-school students and others collectively explored a wide variety of ideas and developed a network of concepts. We examined community structure [22] in the network of concepts to obtain several concept clusters, which were further discussed and refined to ultimately yield seven essential concepts about networks. We hope that the process and outcomes of this initiative will be useful for people who are interested in network science and in networks more generally, and we also hope that it will have positive effects on teaching, learning, communicating and policy-making about networks.

2. Methods

2.1 *Brainstorming and concept generation*

Our starting point was to hold several brainstorming sessions to explore various concepts and ideas about networks that could be used for developing the list of essential concepts (see the top panel of Fig. 1). Each session followed the same basic procedure:

1. Have each participant introduce him/herself to the rest of the group.
2. Explain the objective of the session and then pose the following key question to the group: 'What should every person living in the 21st century know about networks by the time he/she finishes secondary education?'
3. Hand out sticky notes to the participants.
4. Let each participant write his/her ideas about what 'network literacy' might mean on the sticky notes. Participants work on this phase as individuals without communication. This usually takes about 15 min.
5. Have participants place their sticky notes on a large wall or a blackboard, and then have them cluster the notes into several topical areas based on their similarity and relatedness. This phase usually takes 15 min or often longer, and it involves a lot of physical interaction and conversations among the participants (see Fig. 2).
6. Have a group discussion on the result of brainstorming to refine and distill a final set of essential concepts. This phase also takes about 15 min.
7. Break the group into subgroups and have each subgroup visualize one of the essential concepts that arise from the brainstorming. For educational purposes, we included this phase only at sessions with high-school students. Their visualization results were later compiled into a PowerPoint presentation and presented to the students to summarize and reinforce their learning experience.

Each brainstorming session produced two primary sets of outcome data: (a) handwritten data on sticky notes; and (b) a final compiled list of essential concepts that the group produced (inspired by

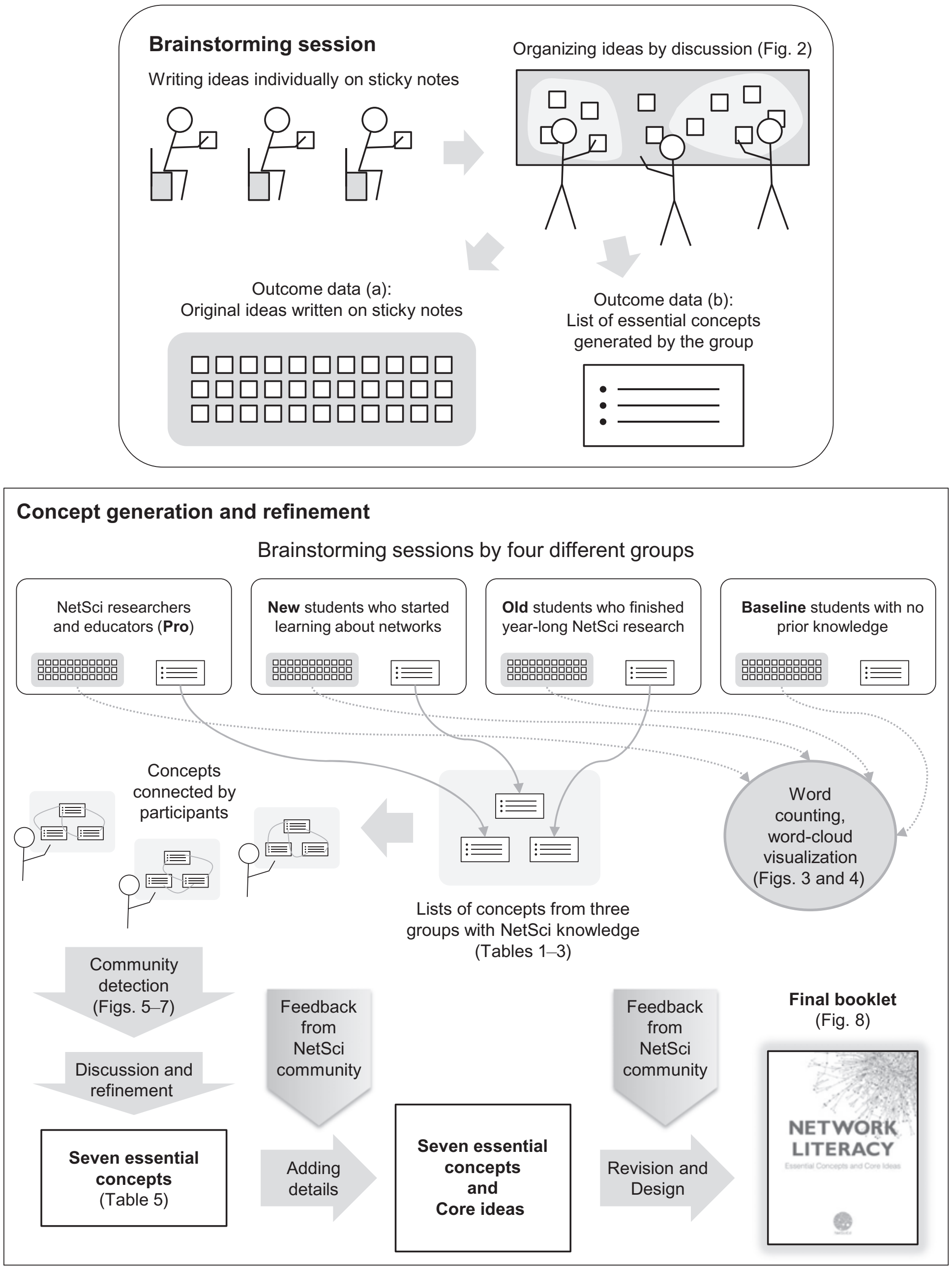

FIG. 1. Overview of the work flow of the process by which the 'Network Literacy' booklet was developed. Top: Procedure of each initial brainstorming session. Bottom: Process of concept generation and refinement.

FIG. 2. Initial brainstorming session by network-science researchers and educators at the NetSci 2014 pre-conference event held at University of California at Berkeley on 1 June 2014. No high-school students were present at this session. Participants posted their ideas of essential concepts about networks using sticky notes, and they then organized them into several concept clusters through discussion. The same format was used for the other brainstorming sessions with high-school students. (Photo credit: Hiroki Sayama).

the sticky notes) through brainstorming. We used the former to qualitatively compare the outputs of different participant groups, and we used the latter to develop a final version of the essential concept list.

We ran brainstorming sessions with the following four participant groups (see the bottom panel of Fig. 1):

- Network-science researchers and educators who participated in NetSci 2014 ('professionals' or 'pro'). The session was run at a NetSci 2014 pre-conference event at University of California at Berkeley on 1 June 2014. Unlike the other three sessions, this group also had a follow-up discussion during the next day at the NetSciEd3 satellite symposium[4] to revise the list of essential concepts (and to get input from people who could not attend the previous day).
- The 2014–2015 cohort of NetSci High [8] high-school students who just finished an initial training workshop on network science ('new students' or 'new'). The session was run at the NetSci High Summer Workshop at Boston University on 22 July 2014.
- The 2013–2014 cohort of NetSci High high-school students who had completed a year-long research experience in network science ('old students' or 'old'). The session was run at the NetSci High Summer Workshop at Boston University on 23 July 2014.

[4] See https://sites.google.com/a/nyscience.org/netscied3/.

- Explainers at the New York Hall of Science (mostly high-school students, but also some university students) who did not have any learning or training experience about networks (‘baseline group’). The session was run at the New York Hall of Science on 13 August 2014.

2.2 *Comparison between participant groups*

To compile raw text data from each group, the original ideas written on the sticky notes by the participants were collected and typed up. We conducted simple content analysis of this data set based on word-frequency counting [23,24]. Specifically, we broke the text data into words, and we then removed trivial words (e.g., articles and simple prepositions). We converted the remaining words into a canonical form by converting plural nouns to singular ones and by removing aspects and tenses from verbs. We also removed words that appeared only once in the data for each group.

For initial visual inspection, we used Mathematica 10.2’s `WordCloud` function (in its default settings) to construct a word cloud for the words generated by each group. We then compared the word frequencies across the four groups to detect semantic differences between them. We generated word rankings based on their frequencies and visualized them in Mathematica 10.2 using a custom script. Because of the small number of samples, we did not conduct statistical tests.

2.3 *Development of final list of essential concepts*

We used the lists of essential concepts produced by the three participant groups with some experience in network science (‘professionals’, ‘old students’ and ‘new students’) to help develop a final list of essential concepts about networks (see the bottom panel of Fig. 1). To facilitate this process, we presented the participants (researchers, educators and high-school students) at the NetSci High Summer Workshop with a sheet of paper on which *all* of the concepts from the three groups were presented together, and we asked them to draw connections among those concepts.

From the results of this activity, we produced a single multigraph, in which each essential concept produced by the three groups is represented by a node and in which an edge represents a connection that a participant made between a pair of concepts. We detected communities of concepts on this multigraph using Mathematica 10.2’s `FindGraphCommunities` function in its default settings (which uses a method based on maximizing the modularity objective function). This produced several distinct communities with clear topical themes, as well as a patchwork community (i.e., a community whose topical theme was not clear) that consisted of the remaining concepts. We applied the same community-detection technique to the patchwork community (extracted as an induced subgraph) repeatedly to attempt to discern more subtle concept clusters within it. This procedure was repeated twice (i.e., considering patchwork communities as networks and detecting communities in them), after which we were able to obtain a set of concept clusters that were thematically meaningful.

Once we detected several meaningful concept clusters, we further discussed and refined them. We then used the resulting clusters to draft seven essential concepts for Network Literacy, and we announced this list (which we posted on Google Drive) to the network-science community via e-mail to collect feedback. We incorporated the community’s feedback and used it to help develop in-depth descriptions of each essential concept (called ‘core ideas’) to provide more details about each concept (including examples and implications). We then announced this version, now furnished with both essential concepts and core ideas, to the network-science community to receive additional feedback. We incorporated this feedback, which we also discussed and refined further among ourselves, and placed the final content into a booklet for public distribution.

TABLE 1 *List of essential concepts that were created by network-science researchers and educators who participated in the NetSci* 2014 *pre-conference event and the NetSciEd3 satellite symposium* (*'professionals'*)

No.	Concept
1.	Networks describe how things connect & interact.
2.	The world around us can be represented as networks of interconnecting parts.
3.	Representing networks allows them to be used as a tool.
4.	Modeling systems as networks can help reveal and explain patterns and general principles.
5.	Network structure can influence behaviour and vice versa.
6.	Networks help us understand similarities among systems found in our everyday life.
7.	Networks can be represented and studied in many different ways.

TABLE 2 *List of essential concepts that were created by the* 2014–2015 *cohort of NetSci High high-school students* (*'new students'*) *who just finished a short training workshop at the* 2014 *NetSci High Summer Workshop at Boston University*

No.	Concept
1.	Networks are connections and interactions.
2.	Networks are present in every aspect of life.
3.	Examples include economics/social/political sciences.
4.	Networks consist of nodes and links.
5.	Computers are often used to study networks.
6.	Networks can be used for making predictions.
7.	Visualization of networks helps understanding.
8.	Networks allows us to analyze human interactions.
9.	Network science should be incorporated into schools.
10.	Future of network science can include preinstalled programs and networks in media.
11.	Networks connects various aspects of the world.

3. Results

3.1 *Comparison between participant groups*

In Tables 1–4, we show the lists of essential concepts that were created by the four participant groups. There is a large difference between the concepts created by the baseline group (i.e., high-school or university students without any formal training with networks), whose concepts we present in Table 4, and the other groups. The concepts generated by the baseline group tended to be vague and general, and they were likely derived from everyday uses of the word 'network' in English (e.g., social networking and computer networks). In contrast, the concepts that were created by the other three groups (see Tables 1–3), who had learning and training experiences about networks, included much more concrete notions about networks that likely also encapsulated a better understanding of salient ideas. This demonstrates emphatically that education can and does have an impact on people's understanding of networks.

There are also some interesting differences between the concepts that were created by professionals and those that were created by students. The former (see Table 1) generally used abstract language and also had a clear focus on what could be done using network models (which they also described in abstract ways). In contrast, the concepts that were created by students (see Tables 2 and 3) consisted

Table 3 *List of essential concepts that were created by the* 2013–2014 *cohort of NetSci High high-school students* (*'old students'*) *who had completed a year-long research experience*

No.	Concept
1.	Networks are everywhere.
2.	A connection between more than one person can form a link.
3.	People should understand basic terminology in a network such as nodes, edges and hubs.
4.	Visualizations are the key to understanding the network.
5.	Networks can be applied to various fields, whether through entertainment, disease spread, finding quality furniture, etc.
6.	Life is hard. . . then you die.

Table 4 *List of essential concepts that were created by high-school students* (*explainers at the New York Hall of Science*) *who had not had any learning or training experience about networks* (*i.e.*, *the 'baseline group'*)

No.	Concept
1.	People and connections
2.	Act of network
3.	Technology + networking

predominantly of definitions of networks and concrete examples, together with research methodologies that they had learned (e.g., visualization and use of computer software). These differences convey a clear gap between professionals and lay people regarding what is perceived as most essential to the study of networks, and they suggest that it is crucial to actively involve non-professionals (in addition to practising network scientists) in the development of a guiding booklet of essential concepts about networks.

The Powerpoint presentations of concept visualizations that the NetSci High students constructed (see our description above) are available online.[5]

Our aforementioned observations are supported further by word-cloud visualizations (see Fig. 3) and word-ranking visualizations (see Fig. 4), which we constructed using the methods described in Section 2. The word 'network' was the most frequently used word in all four groups, and we thus removed it from the analysis. The other most common words give identifiable characterizations for each of the groups. For example, the baseline group was the only one to include career-related words (such as 'job', 'work' and 'opportunity'), which came from the participants' recognition of the importance of 'networking' for their future career development. Additionally, the total number of words produced by the baseline group was the smallest, suggesting that they were not aware of the broad applicability of network-related concepts to a wide variety of phenomena. The words from the old students included more technical terms (e.g., 'node', 'link' and 'edge') than any other group, indicating that they had become familiar with those technical words from their year of research experience in network science.

[5] Presentation by old students:
http://www.bu.edu/networks/files/2012/08/Networks-by-NetSciHigh2013-2014-student-team.pptx
Presentation by new students:
http://www.bu.edu/networks/files/2012/08/Networks-by-NetSciHigh2014-2015-student-team.pptx.

FIG. 3. Word clouds generated (using Mathematica 10.2) to visualize the frequencies of words used by each of the four participant groups (excluding ‘network’, which was the most frequently used word). We scaled the word sizes logarithmically based on their number of appearances.

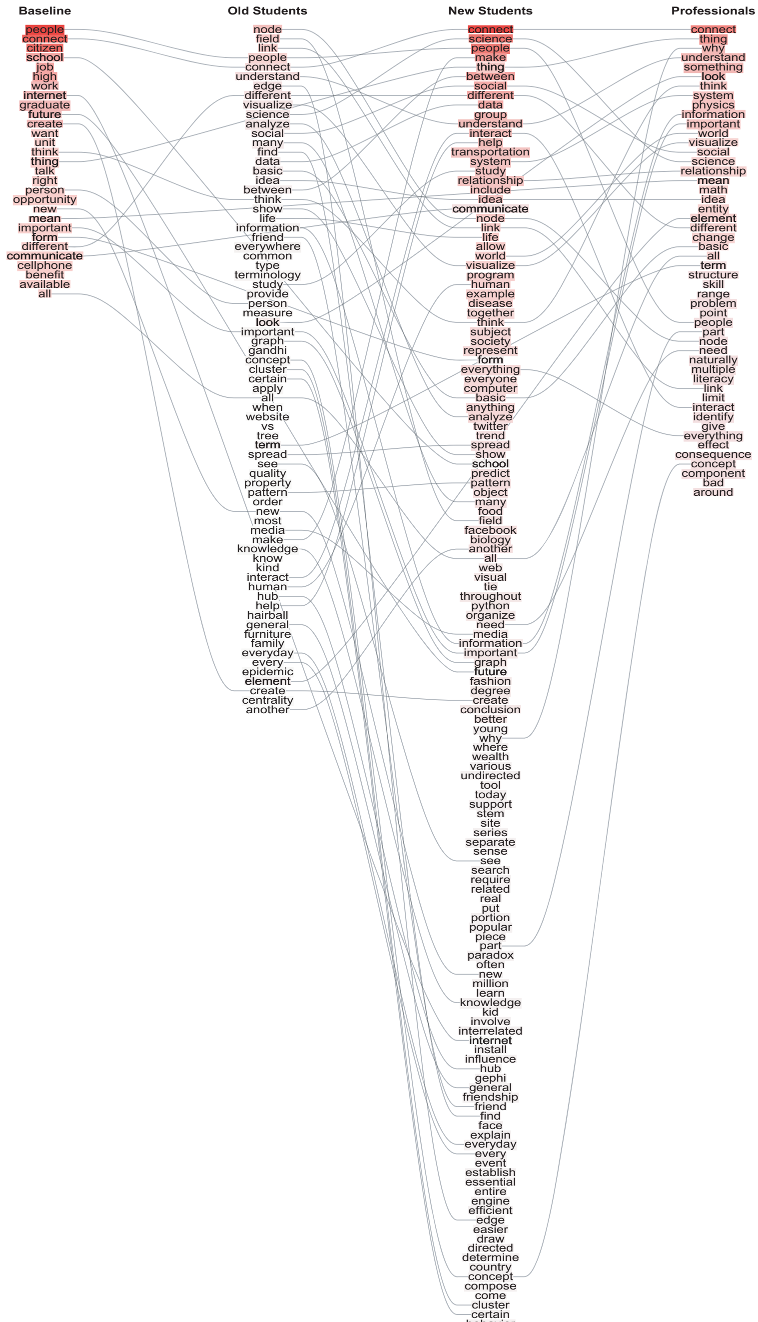

FIG. 4. Visualization of words from the raw text data written on sticky notes during each of the brainstorming sessions (generated by Mathematica 10.2 using a custom script). In each case, we rank the words (again excluding the word 'network') from highest frequency at the top to lowest frequency at the bottom. The background colour intensity (which is not scaled linearly) represents the relative frequencies of the words. When the same word appears in multiple groups, we use a curve to connect the word in the different groups.

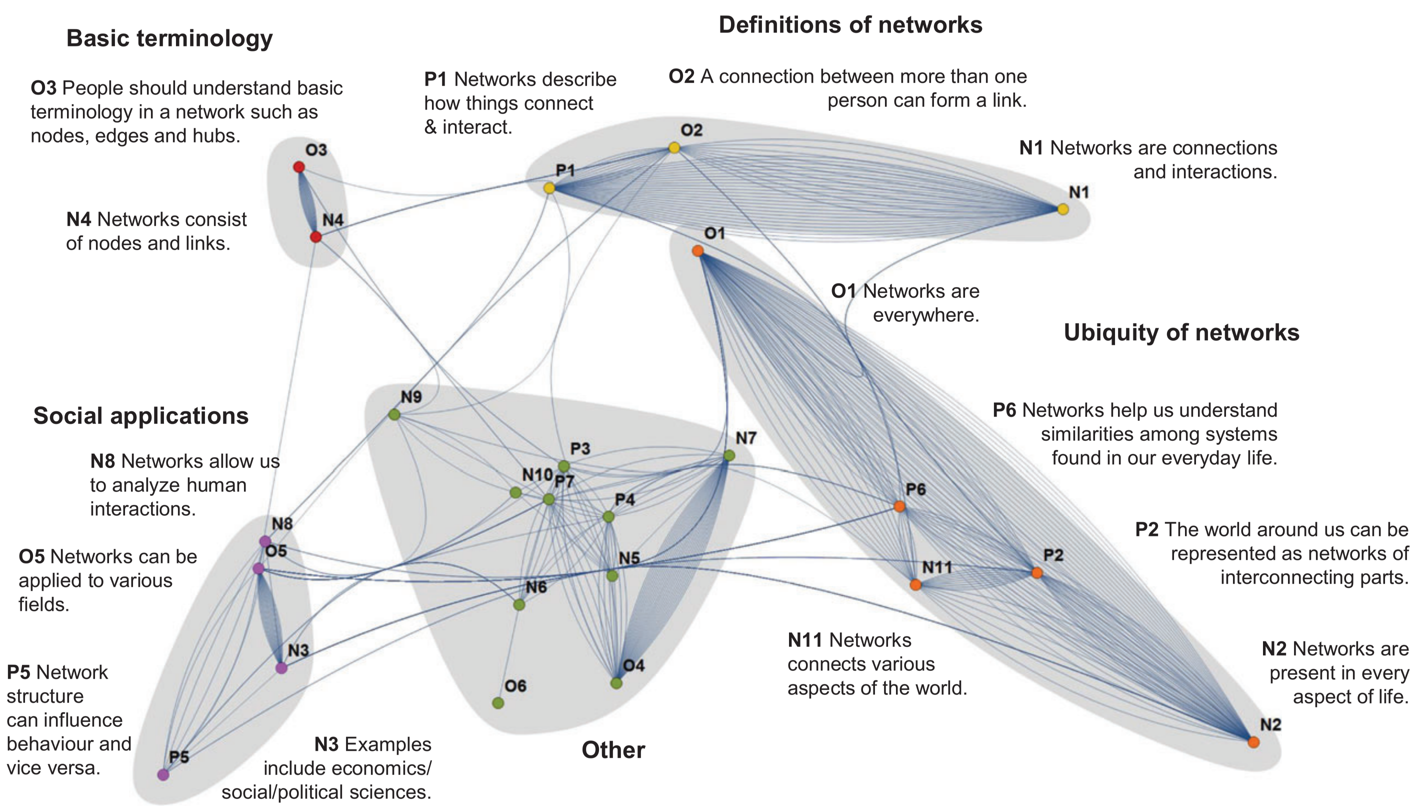

FIG. 5. Concept network generated by connecting concepts made by three groups: ‘old students’ (‘O’), ‘new students’ (‘N’) and ‘professionals’ (‘P’). The grey clouds indicate the communities that we detected using Mathematica 10.2’s `FindGraphCommunities` function. They represent ‘Basic terminology’ (top left, old + new), ‘Definitions of networks’ (top right, old + new + pro), ‘Ubiquity of networks’ (bottom right, old + new + pro), ‘Social applications’ (bottom left, old + new + pro), and ‘Other’. We partition the community labelled ‘Other’ in Figs. 6 and 7.

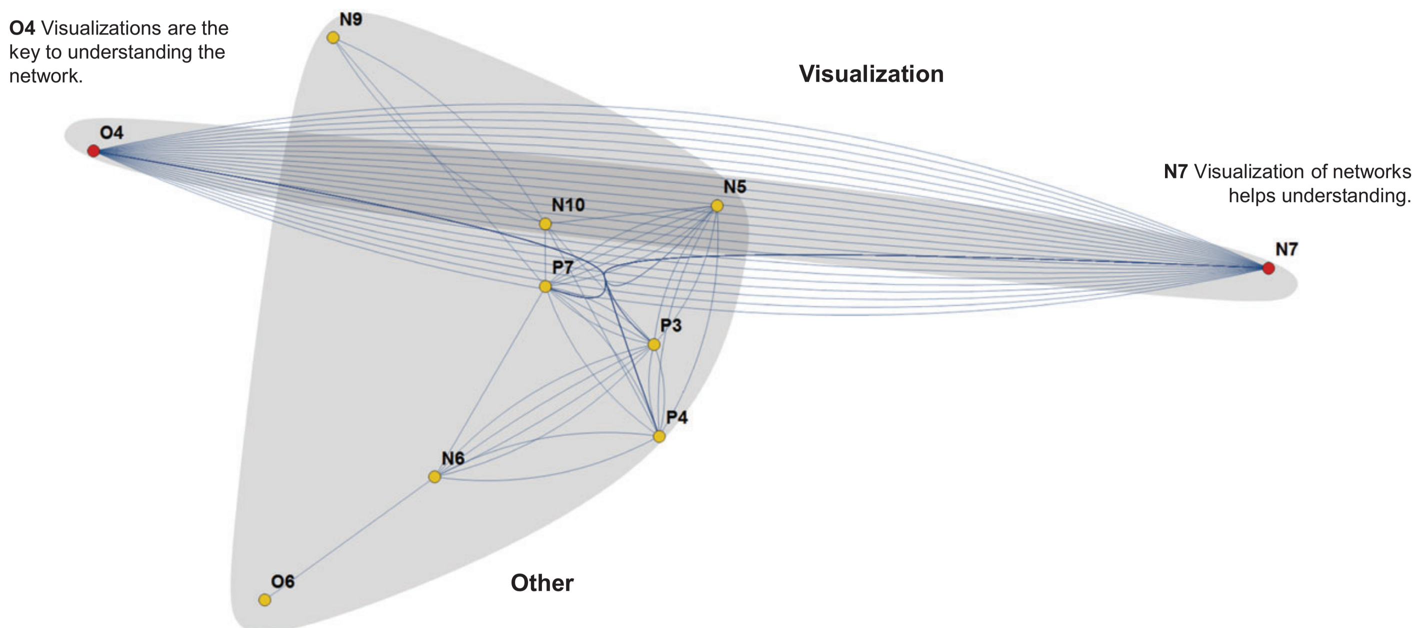

Fig. 6. Decomposition of the 'Other' community in Fig. 5. We find another community about 'Visualization' (old + new). We further partition the remaining 'Other' community in Fig. 7.

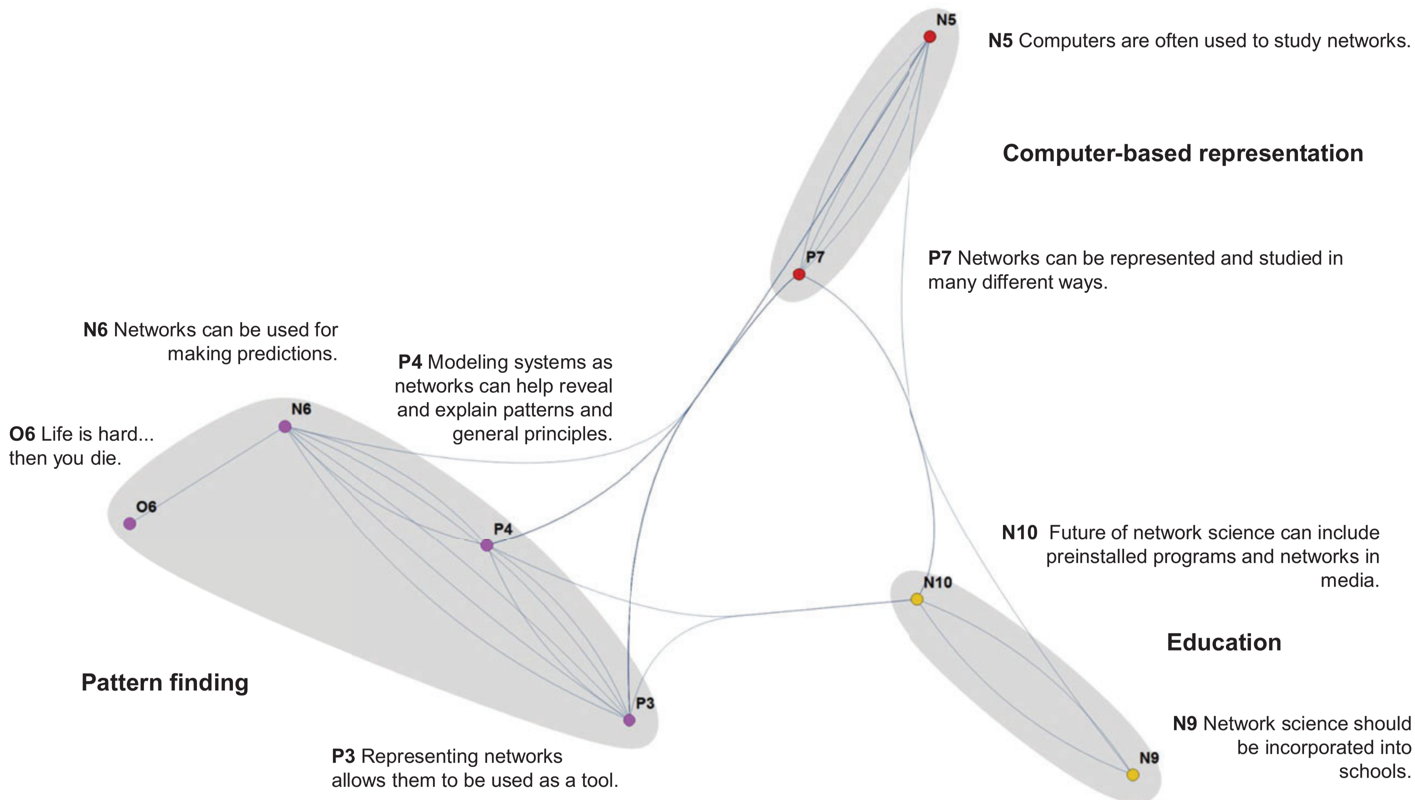

FIG. 7. Final breakdown of the remaining 'Other' community in Fig. 6. We find three communities: 'Computer-based representation' (top, new + pro), 'Education' (bottom right, new), and 'Pattern finding' (bottom left, new+ pro + old).

The new students produced the most diverse set of words (which is apparent in both word clouds and word rankings), which nicely conveys their intellectual excitement immediately after learning about networks. Finally, the words produced by professionals often tended to be about high-level, abstract concepts. Interestingly, the word 'people' was not used as often by the professionals as by other groups.

3.2 *Development of final list of essential concepts*

Detecting communities in our final concept multigraph yielded several distinct concept clusters. These include basic terminology, definitions of networks, ubiquity of networks and social applications (see Fig. 5). Detecting communities in networks consisting of the remaining patchwork communities revealed concept clusters about visualization, computer-based representation, education and pattern identification (see Figs. 6 and 7). Three of those clusters (basic terminology, visualization and education) arose only in the student groups. This again illustrates the limitation of brainstorming without active student participation.

The algorithmically detected concept clusters served as the basis for additional discussion and refinement of the essential concepts. Through iterative discussion sessions among the authors, we decided (to reduce potential redundancy) to include social applications in the cluster about the ubiquity of networks and to combine basic terminology with definitions of networks. We also decided not to include education explicitly as a separate concept, because the importance of education was the main motivation of the Network Literacy initiative. This yielded the following five major concepts:

1. Ubiquity of networks, including social applications
2. Definitions of networks and basic terminology
3. Pattern identification
4. Visualization
5. Computer-based representation

Through further discussion about the above five concepts, we recognized that some of the contemporary (and actively researched) concepts about network science were missing. Specifically, this includes the power of networks for interdisciplinary comparison of systems and the interactions between structures and temporal dynamics of networks. These concepts were present in the list of concepts produced by the professionals, but they were misunderstood and misrepresented in the concept network when the students connected concepts together. This is possibly because these concepts are among the most

TABLE 5 *Final version of the Network Literacy: Essential Concepts*

No.	Concept
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.

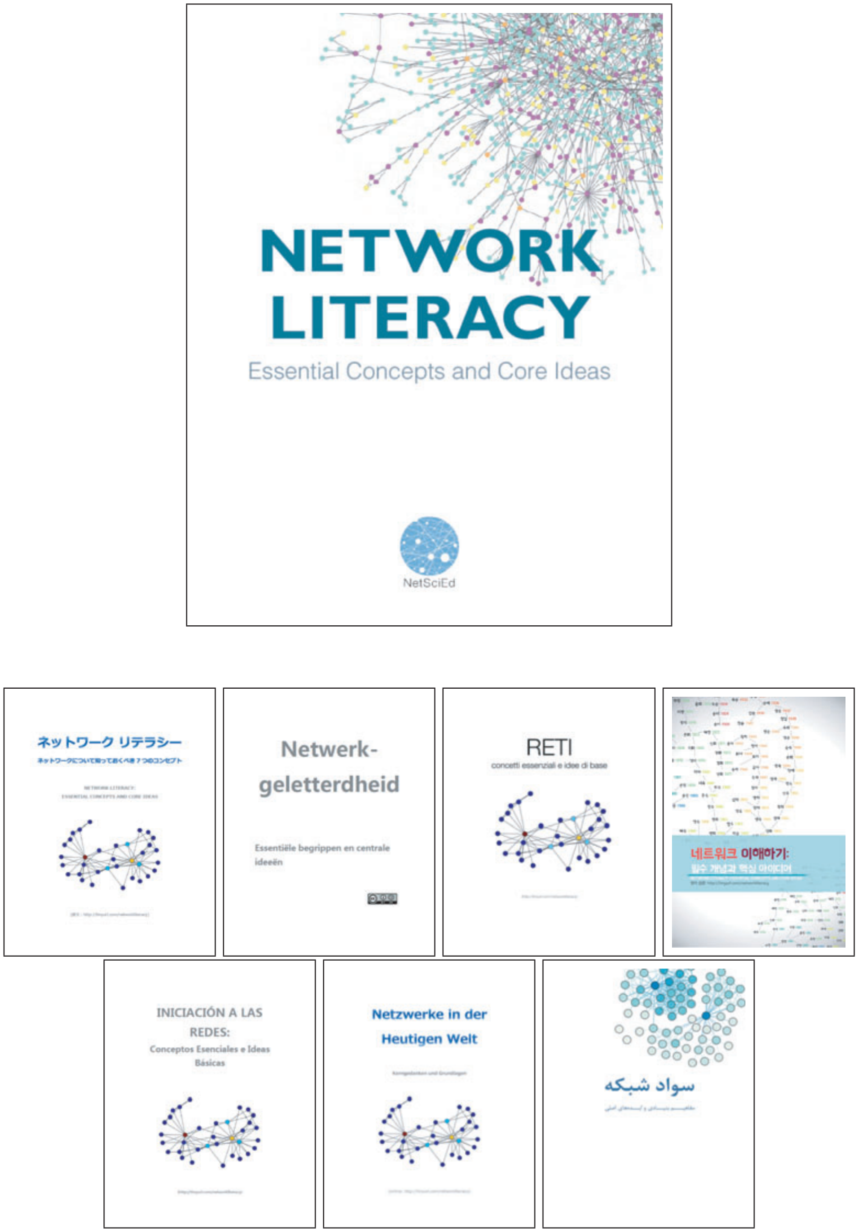

FIG. 8. ‘Network Literacy: Essential Concepts and Core Ideas’ booklets. Top: Original (English) version. Bottom: Non-English versions translated by volunteers. (The Japanese version was produced by Yoshi Fujiwara, Toshihiro Tanizawa and Hiroki Sayama; the Dutch version was produced by Paul van der Cingel; the Italian version was produced by Paolo Tieri; the Korean version was produced by Sang Hoon Lee and Mi Jin Lee; the Spanish version was produced by Rosa Benito; the German version was produced by Andreas Joseph and Florian Klimm; and the Persian version was produced by Taha Yasseri.) The graphical design of the original English version was created by Eri Yamamoto; the design of the Korean version was created by Mi Jin Lee; the design of the Japanese version was created by Hiroki Sayama; the design of the Persian version was created by Taha Yasseri based on the English and Japanese versions; and the other four versions adopted the design template of the Japanese one. All of these versions are available at http://tinyurl.com/networkliteracy. Translations into other languages are in progress.

difficult ones about networks for non-professionals to grasp. We decided to add these concepts to the final list because of their importance.

This yielded a list of seven essential concepts. Incorporating feedback from the network-science community then resulted in the final version of the seven essential concepts about networks (see Table 5).

Naturally, each of the seven concepts subsumes several more detailed ideas. We thus developed in-depth descriptions of each concept as a list of 'core ideas'. We also circulated these core ideas to the network-science community and incorporated their feedback. After numerous iterations of online and offline edits and reviews of the contents, the current version of 'Network Literacy: Essential Concepts and Core Ideas' was finalized on 4 December 2014, approximately six months after the initial pre-conference event at NetSci 2014. We include the text of the final version in the Supplementary material.

The final text of 'Network Literacy: Essential Concepts and Core Ideas' was developed into a professionally designed, printable booklet for use by teachers, students and other learners (see the top panel of Fig. 8). It was first published online for free download at http://tinyurl.com/networkliteracy on 12 March 2015. Hard copies of the booklet were also disseminated at CompleNet 2015 on 25 March 2015 and at NetSci 2015 on 1 June 2015. Several very positive responses followed these initial disseminations. An important development, facilitated through social media and personal contacts, has been the translation of the booklet into non-English languages by volunteers. As of 22 September 2015, seven translated versions (Dutch, German, Italian, Japanese, Korean, Persian and Spanish) are available (see the bottom panel of Fig. 8), and several other translations are in progress.

4. Conclusions

In this paper, we reported our recent initiative of developing an educational resource that concisely summarizes essential concepts about networks in an easily accessible format. The result, 'Network Literacy: Essential Concepts and Core Ideas', is the product of a collaborative effort that involved a large number of network-science researchers, educators, school teachers and students. Since its initial release, we have received many very positive responses from across the globe. We hope that this initiative will help inspire the network-science community to make a large societal impact by launching more educational outreach activities that spread the concepts and ideas about networks into various formal and informal learning settings—with a particular emphasis on the next generation, who will live their whole lives in a networked world.

An important lesson from this process is that the deep involvement of students is crucial. The outcomes of the brainstorming sessions revealed that network-science researchers and educators tended to consider abstract concepts as 'essential' but placed less emphasis on specific examples or research methods (e.g., visualization and computational tools). However, the students who were exposed to network science through the NetSci High program frequently mentioned that concrete examples of networks and the specific research methods that they learned were among the most essential components of their experience. We believe that such a down-to-earth, hands-on viewpoint is extremely important when communicating the value of network science (i.e., 'the study of connectivity') to the public. Although theoretical abstraction of systems is crucial for the modelling and analysis of networks, the general public needs—and wants!—to know *what networks are* and *how to use them*. We are confident that our final booklet will play a large role in successfully addressing this issue, and the booklet has benefited greatly from the significant contributions made by high-school students.

The above successes notwithstanding, our 'Network Literacy' initiative is limited in some important respects. First, the booklet that we produced introduces concepts and ideas only. It does not provide lesson plans (for teachers) or further study guides (for learners). Developing lesson plans in particular will require substantially more effort and resources, as it will need to include details of class instructions, which needs to sufficiently match local school curricular structures, contents and instruction methods (and these are rather heterogeneous) to facilitate adoption in classrooms. Second, the current list of essential concepts may not accurately reflect the scientific importance of various aspects of network science. For example, a major portion of recent discoveries in the study of networks have focused on the dynamical nature of networks and/or on various structural intricacies (e.g., synchronization, diffusion and contagion [25,26], adaptive networks [27], temporal networks [28], and multiplex and other multilayer networks [29,30]), but this topical area was represented only briefly in concept 7 (and it was not present in the students' input). How to accessibly convey the richness of complex network dynamics to the general public remains an important problem to address. We are currently seeking additional resources to make further progress on these frontiers of network science and education, and we invite the entire network-science community to join this challenging yet highly meaningful and societally important endeavour.

Supplementary material

Supplementary material is available at *Journal of Complex Networks* online.

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References

1. Newman, M. E. J. (2010) *Networks: An Introduction*. Oxford: Oxford University Press.
2. Barabási, A.-L. (2014) *Linked: How Everything is Connected to Everything Else and What it Means for Business, Science, and Everyday Life (new edition)*. New York: Basic Books.
3. Wikipedia. Digital Literacy. https://en.wikipedia.org/wiki/Digital_literacy (accessed on 9 July 2015).

4. Council of Europe. Internet Literacy Handbook. http://www.coe.int/t/dghl/StandardSetting/InternetLiteracy/hbk_en.asp (accessed on 9 July 2015).
5. Pegrum, M. (2010) 'I link, therefore I am': Network literacy as a core digital literacy. *E-Learning and Digital Media*, **7**, 346–354.
6. Harrington, H. A., Beguerisse-Díaz, M., Rombach, M., Keating, L. M. & Porter, M. A. (2013) Commentary: teach network science to teenagers. *Netw. Sci.*, **1**, 226–247.
7. Sánchez, A. & Brändle, C. (2014) More network science for teenagers. (2014): preprint arXiv:1403.3618.
8. Cramer, C., Sheetz, L., Sayama, H., Trunfio, P., Stanley, H. E. & Uzzo, S. (2015) NetSci High: bringing network science research to high schools. *Complex Networks VI: Proceedings of the Sixth Workshop on Complex Networks* (*CompleNet 2015*), Studies in Computational Intelligence, vol. 597. Berlin: Springer, pp. 209–218.
9. Budd, C. J. Chris Budd's Home Page. http://people.bath.ac.uk/mascjb/ (accessed on 9 July 2015).
10. Meeks, E. & Krishnan, M. An Interactive Introduction to Network Analysis and Representation. http://dhs.stanford.edu/dh/networks/ (accessed on 9 July 2015).
11. Jenkinson, G., Goutsias, J., Jenkinson, D. & Frennesson, S. Teach Engineering: Curricular Unit 'It's a Connected World: The Beauty of Network Science' (accessed on 9 July 2015).
12. Tangible Networks. http://www.tangiblenetworks.net/ (accessed on 9 July 2015).
13. Virginia Tech Virginia Bioinformatics Institute. Virus Tracker. https://virustracker.vbi.vt.edu/ (accessed on 9 July 2015).
14. Quaden, R., Ticotsky, A. & Lyneis, D. (2005) *The Shape of Change*. Acton, MA: Creative Learning Exchange.
15. Potash, J. & Heinbokel, J. (2011) *Dollars and Sense—Stay in the Black: Saving and Spending*. Acton, MA: Creative Learning Exchange.
16. Anderson, J. & LaVigne, A. (2014) *Systems in Motion: Exploring Complexity through an Interdisciplinary Lens*. Acton, MA: Creative Learning Exchange.
17. Forrester, J. W. (1997) Industrial dynamics. *J. Oper. Res. Soc.*, **48**, 1037–1041.
18. Sterman, J. D. (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World*. New York: Irwin/McGraw-Hill.
19. Cava, F., Schoedinger, S., Strang, C. & Tuddenham, P. (2005) *Science Content and Standards for Ocean Literacy: A Report on Ocean Literacy*. http://www.cosee.net/files/coseeca/OLit04-05FinalReport.pdf.
20. Schoedinger, S., Cava, F. & Jewell, B. (2006) The need for ocean literacy in the classroom: Part I. *The Science Teacher*, p. 44.
21. Strang, C., DeCharon, A. & Schoedinger, S. (2007) Can you be science literate without being ocean literate? *Current: J. Mar. Educ.*, **23**, 7–9.
22. Porter, M. A., Onnela, J. & Mucha, P. J. (2009) Communities in networks. *Not. Am. Math. Soc.*, **56**, 1082–1097. 1164–1166.
23. Weber, R. P. (1990) *Basic Content Analysis*. Beverley Hills, CA: Sage.
24. Stemler, S. (2001) An overview of content analysis. *Pract. Assess., Res. Eval.*, **7**, 137–146.
25. Porter, M. A. & Gleeson, J. P. (2015) Dynamical systems on networks: a tutorial. *Front. Appl. Dyn. Syst.: Rev. Tutorials*, in press (arXiv:1403.7663v2).
26. Pastor-Satorras, R., Castellano, C., Van Mieghem, P. & Vespignani, A. (2015) Epidemic processes in complex networks. *Rev. Modern Phys.*, **87**, 925–979.
27. Gross, T. & Sayama, H. (2009) *Adaptive Networks*. Berlin: Springer.
28. Holme, P. & Saramäki, J. (2012) Temporal networks. *Phys. Rep.*, **519**, 97–125.
29. Kivelä, M., Arenas, A., Barthelemy, M., Gleeson, J. P., Moreno, Y. & Porter, M. A. (2014) Multilayer networks. *J. Complex Netw.*, **2**, 203–271.
30. Boccaletti, S., Bianconi, G., Criado, R., Del Genio, C. I., Gómez-Gardeñes, J., Romance, M., Sendiña-Nadal, I., Wang, Z. & Zanin, M. (2014) The structure and dynamics of multilayer networks. *Phys. Rep.*, **544**, 1–122.

Supplemental Material: Final Text of Network Literacy: Essential Concepts and Core Ideas

1: Networks are everywhere.

- The concept of networks is broad and general, and it describes how things are connected to each other. Networks are present in every aspect of life.
- There are networks that form the technical infrastructure of our society—e.g., communication systems, semantic systems, the Internet, electrical grids, the water supply, etc.
- There are networks of people—e.g., families and friends, e-mail/text exchanges, Facebook/Twitter/Instagram, professional groups, etc.
- There are economic networks—e.g., networks of products, financial transactions, corporate partnerships, international trades, etc.
- There are biological and ecological networks—e.g., food webs, gene/protein interactions, neuronal networks, pathways of disease spreading, etc.
- There are cultural networks—e.g., language/literature/art connected by their similarities, historical events linked by causal chains, religions connected by their shared roots, people connected to events, etc.
- Networks can exist at various spatial and/or temporal scales.

2: Networks describe how things connect and interact.

- There is a subfield of mathematics that applies to networks. It is called *graph theory*. Many networks can be represented mathematically as *graphs*.
- Connections are called *links, edges, or ties*. The entities that are connected to each other are called *nodes, vertices, or actors*.
- Connections can be undirected (*symmetric*) or directed (*asymmetric*). They can also indicate ties of different strengths, and can indicate either positive or negative relationships.
- The number of connections of a node is called the *degree* of that node.
- Many networks have more than one type of connection—e.g., offline friendships and Facebook connections, different modes of transportation, etc.
- A sequence of edges that leads from one node, through other nodes, to another node is called a *path*.
- A group of nodes within which a path exists from any one entity to any other entity is called a *connected component*. Some networks have multiple connected components that are isolated from each other.
- Some networks are studied using mathematical structures that are more complicated than graphs.

3: Networks can help reveal patterns.

- You can represent something as a network by describing its parts and how they are connected to each other. Such a network representation is a very powerful way to study a system's properties.
- The properties in a network that you can study include:
  - how the degrees are distributed across nodes
  - which parts or connections are most important
  - strengths and/or weaknesses of the network
  - if there is any sub-structure or hierarchy
  - how many steps, on average, are needed to move from one node to another in the network
- In some networks, you can find a small number of nodes that have much larger degrees than others. They are often called *hubs*.
- In some networks, you can find a group of nodes that are better connected to each other than chance would dictate. They are sometimes called *clusters* or *communities*. Some of them can occupy a central, or *core*, part of a network.
- Using these findings, you can sometimes infer how a network was formed and/or make predictions about dynamical processes on the network or about its future structure.

4: Visualizations can help provide an understanding of networks.

- Networks can be visualized in many different ways.
- You can draw a diagram of a network by connecting nodes to each other using edges.
- There are a variety of tools available for visualizing networks.
- Visualization of a network often helps to understand it and communicate ideas about connectivity in an intuitive, non-technical way.
- Creative information design plays a very important role in making an effective visualization.
- It is important to be careful when interpreting and evaluating visualizations, because they typically do not tell the whole story about networks.

5: Today's computer technology allows you to study real-world networks.

- Computer technology has dramatically enhanced the ability to study networks, and this is especially important for large ones with rich structure.
- There are many free software tools available for network visualization and analysis.
- Using personal computers, everyone (not just scientists) can construct, visualize, and analyze networks.
- Through the Internet, everyone has access to many interesting network data sets.

- Computers allow you to simulate hypothetical or virtual networks, as well as to simulate dynamical processes on both real and hypothetical networks.
- Learning computer literacy skills opens the door to myriad possibilities for a career. These include scientist, data analyst, software engineer, educator, web developer, media creator, and many others.

6: Networks help you to compare a wide variety of systems.

- Various kinds of systems, once represented as networks, can be compared to examine their similarities and differences.
- Certain network properties commonly appear in many seemingly unrelated systems. This implies that there exist some general principles about connectivity that apply to multiple domains.
- Other network properties are different in different systems. These properties can help to classify networks in different families and to gain insight into why they are different.
- Science is typically conducted in separate areas of research called disciplines. Networks can help to cross disciplinary boundaries to achieve a holistic and more complete understanding of the world.
- Networks can assist in the transfer of knowledge across different areas of study.

7: The structure of a network can influence its state and vice versa.

- Network structure indicates how parts are connected in a network.
- Network state indicates the properties of a network's nodes and edges.
- Network structure and state can each change over time.
- The time scales on which network structure and state co-evolve can be either similar or different.
- Network structure can influence changes of network state. Examples include the spread of diseases, behaviors, or memes in a social network, and traffic patterns on the road network in a city.
- Network state can influence changes of network structure. Examples include the creation of new "following" edges in social media and the construction of new roads to address traffic jams.