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Comment on "Catching the Network Science Bug" by David L. Alderson

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This fascinating and provocative essay by Alderson in *OR Forum* is a wakeup call for the Operations Research community. In the essay, Alderson overviews the major developments in what has been termed as the "network science" literature, which focuses on "complex" networks, and argues for greater participation in such research by the operations research community. The primary developments in the complex networks literature according to the citations by the author are less than a decade old. He also argues for optimization-based reverse engineering as a means of addressing some open questions to which operations researchers may be able to contribute.

Although complex networks and network science are not defined in the essay (and the same holds for the related physics literature), the National Research Council (2006) report promulgates this "new" field of study although a survey of researchers from 39 countries showed that nearly 25 percent doubt that network science is an identifiable discipline. Amazingly and shockingly, the NRC report has no OR representation, despite the contributions of those in OR/MS to network modeling, analysis, and computations for over half a century.

Physicists, and, especially, theoretical physicists with backgrounds in statistical mechanics, have been the principal drivers of network science. Physicists tend to search for fundamental laws about the universe and often use experimental data from which to infer theory. The network science and complex network literature from a physicists' perspective is focused on graph theory and the statistical structure of networks and how the network structure evolves over time. Clearly, the World Wide Web has provided an outstanding repository of structures from which to study new links and nodes as webpages sre being created (and destroyed). Indeed, the explosion of literature on such topics has been enabled and has coincided with the World Wide Web and the Internet coupled with the immense volumes of digitized data. Physicists, led by Barabasi, saw an opportunity to which ideas of statistical mechanics and power laws could be applied. Their focus was on the topology of networks and statistical properties of networks as well as on the growth and evolution of complex networks. More or less in parallel, applied mathematicians (working also in sociology) led by Strogatz and Watts were investigating what are known as small-world networks, with interesting experiences dating back to Stanley Milgrom. Many of their results on networks over the past decade have been published in physics journals and in such top scientific journals as *Nature*, the *Proceedings of the National Academy of Science (PNAS)*, and *Science*, with quick refereeing and publication schedules, and well-known powerful publicity machines. At the same time, as Alderson notes, there have been popular books over the past decade written on small-world and scale-free networks, two types of networks that have marked statistical properties, and that are principal topics in the study of complex networks. Interestingly, many of the books on networks cited in the NRC report may be viewed more as popular press publications rather than scientific publications.

Scharnhorst (2003) noted in her bibliometric study based on the Web of Science that only in 2001 did the number of articles with “complex networks” in the title, keywords, or abstract become dominated by physics. She grouped mathematics, engineering, and technology into one group and specifically recognized operations research. Given that “complexity” had been a theme in physics for several decades the fact that “complex” networks as a term was used by physicists is not surprising.

What is Missing and How Can We as a Community Contribute and Share in the Discoveries?

In the Introduction of his essay, Alderson identified three basic scientific questions of interest to network science researchers. He first noted, as a relevant question, whether there exists a network structure that is responsible for large-scale properties on such systems. The second question was whether or not there exist universal laws for complex networks, which has been one of the major themes of this literature.

The third question/topic that Alderson made reference to, but, I suspect that, because of page limitations, could not much amplify upon, is that of vulnerability analysis of networks (and this also leads to critical infrastructure issues and, of course, a topic of great interest in OR/MS – supply chain vulnerabilities and disruptions). He identified the third scientific question of interest to network science researchers as being, specifically: “How can one assess vulnerabilities or fragilities inherent in complex networks in order to avoid ... disasters?” In addition, how can one design and manage complex networks?

It is precisely the vulnerability issue that we have been exploring and publishing on in the physics literature (cf. Nagurney and Qiang (2007a, b)) and in the operations research literature. Our publications in physics cite the OR-based transportation science literature. Indeed, one has to “join” them, I believe, to have work recognized and promulgated accordingly. Towards that end, we have been arguing (a direct point missing from Alderson’s essay) that it is not just the network topology and associated statistical aspects of networks that matter but flows that must be incorporated into network modeling as well as behavior. To quote Barabasi (2003) p. 225, “To achieve that [understanding of complexity] we must move beyond structure and topology and start focusing on the dynamics that take place along the links. Networks are only the skeletons of complexity, the highways for various processes that make our world hum.” Moreover, Barrat et al. (2004, pp. 3747) state... “networks are specific not only by their topology but also by the dynamics of information or traffic flow taking place on the structure. ..., the amount of traffic characterizing the connections in communication systems and large transport infrastructures is fundamental for a full description of these networks.”

We in the transportation science community of INFORMS have been addressing such issues dating back to the seminal work of the book by Beckmann, McGuire, and Winsten (1956). In fact, the 50th anniversary of the publication of the book was recognized in two special sessions at the INFORMS San Francisco meeting; please see: http://supernet.som.umass.edu/classic.htm for the presentations and links to the online version of the book. Furthermore, researchers in OR have not only contributed to optimization and centralized decision-making but also to decentralized decision-making, and the associated tools of game theory and variational inequalities. Methodologies developed under the umbrella of OR are fundamental and have been well-recognized in other fields for several decades, but, strangely, only recently when it comes to the physicists and their “network science.”

In addition, interestingly, Alderson in Section 5, "On the Role of Design in Complex Networks," of his essay emphasizes that "What appears to the outside observer as emergent self-organization can often be understood in terms of rigorous mathematics and engineering that explain the "design" in many complex systems." He goes on to say that several Internet protocols can now be understood as primal-dual algorithms solving a global resource allocation problem and cites the work of Kelly (2001), who, coincidentally, references the Braess (1968) paradox (see also Braess, Nagurney, and Wakolbinger (2005), Boyce and Nagurney (2005)), and the Beckmann, McGuire, and Winsten (1956) book (as well as the Bertsekas and Gallager (1987) book) so, in a sense, we are coming full circle back to some of the original contributions that have been long referenced and utilized in OR and transportation science and that deal with flows and behavior! Coincidentally, computer scientists have also discovered such and related fundamental contributions/publications.

Alderson, at length, identified a specific topic in which the operations researchers could contribute to network science – that of reverse engineering and optimization, and singled out the work of Ahuja and Orlin (2001). This general topic, and with a focus on networks, could serve as a major research agenda for operations researchers. Would not it be illuminating to be able to determine whether (complex) networks (and, I would also emphasize, with the inclusion of flows) were the result of optimization processes, whether centralized or decentralized? In addition, if the feasible solutions that actually exist in the real-world were far away from optima or equilibria, how fantastic wouldn't it not be for the OR community with its *Science of Better* to show how such systems could be improved? Such discoveries and results would be invaluable to a variety of policy-makers and decision-makers.

Finally, the network scientists are well-aware that dynamics on networks have to be integrated with dynamics of networks over time. Which community can better contribute to dynamic networks than the OR community, given its already extensive publications on both models as well as fundamental methologies for dynamic networks, which, of course, would include flows, constraints, and either single or multiple objective functions associated with the various agents/decision-makers?

This Essay Also Implicitly Raises the Following Philosophical Questions:

• Given the plethora of books and scientific articles with *networks* published in the OR literature, why is it that only fairly recently that such contributions are being cited/acknowledged by those working on networks in physics?

• As Alderson notes, his essay did not directly discuss computer science and that discipline's perspective on network science. As is well-known, computer scientists publish primarily in proceedings, rather than journals, and their representation in terms of refereed journal articles is hard to track (see Alderson's Table 2 footnote). Are we sufficiently communicating with this community?

• Given the recent substantial growth in funding for network science (and engineering), how do we as a community present ourselves as leaders in this area (or because of time delays – followers)?

• More broadly, should we be involved in better popularizing our results and, if so, are we doing everything possible in this dimension as a community?

Personal Reflections / Actions

Personally, I have become increasingly aware (hard to miss with all the media attention to the work of the authors' above) that it is necessary to communicate directly with the leaders in network science, in addition to publishing in "their" journals and making them aware of the network research in OR/MS. Coincidentally, beginning in 2000, I was a Principal Investigator on an NSF grant with "complx networks" in the project title that evolved into a seven project.

Towards that end, we invited Barabasi to speak in the UMass Amherst Speaker Series in Operations Research / Management Science, which is hosted by the UMass Amherst

INFORMS Student Chapter, and he delivered a presentation in Spring 2006; please see: http://student.som.umass.edu/informs/ for a full listing of all the seminars to-date. Interestingly, that same Spring, we also had such luminaries and popularizers of OR and its contributions speak as Ed Kaplan, Georgia Perakis, and Irv Lustig. In addition, that same spring, we were also privileged to be able to host Dietrich Braess of the Braess (1968) paradox fame; see: http://supernet.som.umass.edu/cfoto/braess-visit/braessvisit.html

In the Fall 2006 semester, together with David Parkes of Harvard University, I organized an Exploratory Seminar, entitled: "Dynamic Networks: Behavior, Optimization and Design" at the Radcliffe Institute for Advanced Studies at Harvard. Mark Newman and David Alderson spoke at this seminar, along with a variety of economists, operations researchers, applied mathematicians, and computer scientists. The presentations and additional papers can be found at: http://www.ecs.harvard.edu/%7Eparkes/RadcliffeSeminar.htm

In 2007, Springer published the volume, *Network Science, Nonlinear Science and Infrastructure Systems*, which was edited by Terry L. Friesz and was based on an NSF-funded workshop of the same name held at Penn State, which took place in the Spring of 2005. I had the pleasure of taking part in this workshop.

Finally, in order to bring the operations research and physics communities together in March 2008 I co-organized with Professor Patrizia Daniele of the University of Catania a workshop on complex networks as part of my Fulbright Senior Specialist Award entitled: "Complex Networks and Vulnerability Analysis: From Innovations in Theory to Education and Practice." More information as well as the talks can be found at: http://supernet.som.umass.edu/fulbright-catania/FulbrightCataniaNagurney.htm

The "rewards," some, direct, whereas others, indirect, and others completely surprising include that our work on supply chains in the European Journal of Operational Research is being cited in physics journals as is our translation in Transportation Science of the Braess (1968) paper.

Coming Back Full Circle

As Alderson notes in the last paragraph of his essay, "For more than half a century, the OR community has been quietly solving some of the most challenging problems related to the practical design, operation, and management of networks exhibiting 'organizational complexity'." I take this as the highest compliment; however, can we remain quiet for much longer and lose our identification with these problems?

In a sense, we are coming "full circle." Philip M. Morse, who is widely considered to be the founder of Operations Research in the US had all his degrees in physics, yet was a principal mover behind the creation of ORSA in 1952 and launched the OR Center at MIT in 1956. He co-authored books in both physics and in operations research and received the 1968 Lanchester Prize. He served as President of the American Physical Society. His autobiography, *In at the Beginnings*, provides a perspective on the origins and evolution of Operations Research and its relationships with Physics. Coincidentally, Robert Herman, after whom the Lifetime Achievement Prize in Transportation Science of the TS&L Society of INFORMS is named, also had all his degrees in physics! I am married to a physicist, but that is another story.

References

Ahuja, R. K., Orlin, J. B., 2001. Inverse optimization. Operations Research 49, 771-783.

Barabasi, A. L., 2003. *Linked: How Everything if Connected to Everything Else and What it Means.* Plume, New York.

Barrat, A., Barthelemy, M., Pastor-Satorras, R., Vespignani, A., 2004. The architecture of complex weighted networks. Proceedings of the National Academy of Sciences USA 101, 3747-3752.

Beckmann, M. J., McGuire, C. B., Winsten, C. B., 1956. *Studies in the Economics of Transportation.* Yale University Press, New Haven, Connecticut.

Bertsekas, D. P., Gallager, R., 1987. *Data Networks.* Prentice-Hall, Englewood Cliffs, New Jersey.

Boyce, D. E., Nagurney, A., 2005. Preface to "On a paradox of traffic planning." Transportation Science 39, 443-445.

Braess, D., 1968. Uber ein paradoxon aus der verkehrsplanung. Unternehmenforschung 12, 258-268.

Braess, D., Nagurney, A., and Wakolbinger, T., 2005. On a paradox of traffic planning, translation of the 1968 article by Braess. Transportation Science 39, 446-450.

Friesz, T. L. editor, 2007. *Network Science, Nonlinear Science and Infrastructure Systems*, Springer.

Morse, P. M., 1977. *In at the Beginnings*, MIT Press, Cambridge, Massachusetts.

Nagurney, A., and Qiang, Q. (2007a). A network efficiency measure for congested networks. Europhysics Letters 79, 38005, p1-p5.

Nagurney, A., and Qiang, Q. (2007b). Robustness of transportation networks subject to degradable links. Europhysics Letters 80, 68001, p1-p6.

National Research Council, Committee on Network Science for Future Army Applications (2006). *Network Science.* The National Academies Press, Washington, DC.

Scharnhorst, A. (2003). Complex networks and the web: Insights from nonlinear physics. Journal of Computer-Mediated Communication 8, July.