

Europe's First PhD Program in Network Science

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Abstract The new science of networks had reached such maturity by 2010 that the idea of launching a PhD program became natural. We at the Central European University (CEU) had the vision of a truly interdisciplinary, problem driven, and data oriented program for students with diverse backgrounds. The program was launched in September 2015, and is the first of this kind in Europe. In this chapter we discuss the motivation, the scientific environment, and the curriculum for the new program. We argue that a network science PhD program can be successful even with high student diversity, once we place emphasis on a flexible curriculum with opportunities to equalize missing skills, and a strong element of solidarity and mutual learning among the students. We also report about the recruitment process and the first experience with two cohorts.

1 The need for a network science PhD program

During the past decade network science has become a highly fertile interdisciplinary field, integrating natural and social sciences around the coherent agenda of identifying the mechanisms that govern the dynamics of complex interacting systems with a high number of constituents from cell metabolism and brain structure to the emergence of social movements and international trade dynamics.

In fact, a new discipline of network science has emerged and matured remarkably fast: i) Conference series have been organized, the most important being NetSci, an annual international gathering of hundreds of researchers from all over the world with NetSci 2017 in Indianapolis [1]. (These conferences have regular satellite sec-

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tions on Education of network science.) ii) Excellent review articles, monographs and textbooks were canonizing disciplinary knowledge, as shown by this list, without a claim for completeness: [2, 3, 4, 5, 6, 7, 8, 9]. A number of journals have been launched [10, 11, 12, 13] and centers emerged in the US, Europe and Asia. In 2012, at the Budapest NetSci conference the Network Science Society was established, which since then has coordinated the events within the discipline and serves as an information hub as well [14]. Network science university courses are by now regular at all major universities. Modern network science is growing out of its teenage years with no signs of slowing down: Results and their broad applications are accumulating fast as ever. In fact, one of the reasons for the rapid development of network science is the versatile applicability of the results of this new discipline.

We are witnessing an ever increasing job market that is keen to absorb highly qualified network scientists. Experts with a solid background in network science are welcome in social media and telecommunication services. They introduce new, efficient tools in marketing and finance. A whole new branch of business consulting has emerged, building massively on network science. One can be highly confident in predicting that the number of openings will increase in such areas as public policy and government, international and civic activism. The spectacular developments in network science have had a major impact on university programs and policy. The resulting research programs and centers as well as funding for large-scale projects generate attractive job opportunities in academia.

The high level of maturity of network science as a discipline together with the increasing need for well educated experts made launching a new Network Science PhD Program a natural idea. Several centers around the world started simultaneously developing such programs and we at the Center of Network Science of Central European University were one of them.

2 Problem-driven interdisciplinary approach at CEU

Central European University (CEU) [15] is an English language postgraduate training institution of higher education with accreditation both by the Middle-States Network of American Universities, the New York State Board of Education, and the Hungarian government ¹. From its inception in the early 1990s, CEU has implemented a systematical policy of recruiting its staff and students in a multicultural environment. As a consequence, the staff of CEU is decisively international with a number of American, West and East European scholars as well as some coming from the Mediterranean region, Scandinavia, the Near East (Turkey, Israel, Egypt),

¹ CEU has been under attack by the Hungarian government during the last months, which tried to hamstring the university by a new legislation [16]. This move has launched a wave of protests in Hungary and worldwide [17]. The Venice Commission is dealing with the Lex CEU [18] and the European Commission has started an infringement proceedings in this matter [19]. CEU is determined to continue its mission as a center of academic freedom and its programs, including the PhD Program in Network Science, will go on without any disruption [20].

altogether from more than 40 countries. Students from more than 100 countries have earned Masters or PhD degrees at CEU. It is a leading and well-established international academic institution known for the high level of interdisciplinary research. CEU's special strengths are in social sciences and humanities, however, it is increasingly focusing on data aspects and quantitative methods.

The Center for Network Science [21] was established in 2008, with strong support from the president of CEU, Yehuda Elkana, and the provost, Liviu Matei. CNS was formed with the mission of building academic excellence in the field of network science and strengthening quantitative interdisciplinary research. An important feature of this mission is to deal with network aspects of social problems central to the core values of CEU, such as: social inequalities, discrimination and exclusion, abuses of political and economic power, the emergence of civic activism, the origins of collective creativity, gender related issues or the protection of free speech and open communication. The Center aims to fulfill its mission by actively collaborating with (and to some extent integrating into) other departments at CEU, as well as other research centers in Europe and the world. The Center has members from the following Departments of the CEU: Mathematics, Sociology, Political Science, Economics and Environmental Science. Among others, the Center organized NetSci 2011 [22] that brought more than 400 participants to CEU.

The Center for Network Science started to offer a certificate in network science in 2010. This was an added-on specialization to other PhD programs. The idea for a proper PhD program in network science was first raised in 2012, with strong support from CEU president John Shattuck, and provost Katalin Farkas.

We at CEU see network science as intrinsically multidisciplinary. It has grown out of the mathematical theory of graphs, it uses computer science tools as well as concepts and methods of statistical physics. Besides natural sciences, its development was substantially influenced by sociology, economics, environmental science and political science. The excellence of the faculty in these disciplines, together with the expertise at the Center of Network Science at CEU and the multi-departmental character of the program ensures a high quality PhD degree in network science. To better grasp the particular ways in which we translate multidisciplinary ambitions into action, we outline some of our integrated activities below:

We collaborate closely with colleagues in Mathematics. Due to the data deluge provided by information communication technology network science deals with huge databases and often with very large networks (typical size: order of 10^6 nodes). One of the focus problems in graph theory is the problem of graph limits, which is closely related to the large networks. A further mathematical problem is related to the dynamics of and on networks, which involve stochastic processes. The Department of Mathematics and Its Applications together with the Rényi Institute as well as the members of the CNS have the required experience to provide top quality teaching and guidance in these fields.

Economics is one of our key areas for interdisciplinary integration. Economy is a complex system and the network approach can be fruitful at many levels, representing diverse points of view. Trade networks, ownership networks, membership and affiliation networks or networks of market players following similar strategies

are some examples. The recent global crisis has shed light to the importance of the topology of financial networks as cascading failures of the interbank loan system depend heavily on it. Analysis and modeling of data from network point of view will be crucial in understanding financial interactions, systemic risk and in developing efficient regulation. The availability of some detailed data on individual strategies of investors offers an unprecedented depth in the analysis of individual behavior and their clustering. To this end the methods of statistical validation combined with advanced network theoretical tools have proved to be extremely efficient and generally applicable. The faculty staff of the CNS and the members of the Department of Economics have top-level expertise to provide the necessary teaching and research guidance.

We pursue several projects together with colleagues from political science. Networks play undoubtedly important role in political interactions. The formation of opinions, its relation to the social structure and finally to the articulation of political will require a multi-level dynamic network theoretical approach. Network science finds applications in numerous areas: Spreading of information and its relation to manipulative techniques, the analysis of bottom up and top down organizations and strategies, discourse analysis and its relation to social networks, voting behavior, party structure and development, etc. The study of these phenomena will rely on existing techniques, but will also require new tool development. Hence the collaboration between CNS and the Department of Political Science has a synergic effect.

Environmental science is another key area of interdisciplinary interest for network science at CEU. A main issue in environmental science is sustainability, in other words, environmental stability. This is closely related to one of the focal questions in network science, the robustness and vulnerability of complex networks. The stability of food webs, biodiversity, energy security and sustainable development strategies under transitions are all questions with direct network relations. Collaboration between the staff of the Department of Environmental Science and CNS ensures a high-level education and timely PhD work in this field.

Sociology is an obvious area where network science can contribute to the solution of crucial research problems. Network science has been significantly influenced by social network analysis. On the other hand, the information-communication revolution has opened unprecedented opportunities to approach classical questions of social sciences like identifying the driving forces behind violence or the factors influencing how ideas, attitudes and prejudices spread through human populations. A new interdisciplinary branch called Computational Social Science [23] emerged with strong emphasis on the network aspects. Researchers of CNS have been at the forefront of this scientific endeavor.

Network science is linked to many further activities at CEU. In the study international relations the network aspect seems unavoidable. Cognitive science is related to network science in at least two ways: Analysis of the neural network is one of the biggest challenges in this field. Furthermore, the analysis of large amount of temporal data uses massively recent results of network science. Even in the field of history network science can be helpful, e.g., in the analysis of narrative networks.

The Network Science program plans to build up links to these programs as well through joint research programs.

This interdisciplinary environment, together with the great Hungarian traditions in graph theory and network science made CEU a unique and ideal place for a new PhD Program in network science. After a successful Advanced Certificate Program [24], within which 8 credits in network science could be earned in several PhD programs, we decided to launch a full PhD Program hosted by the Center for Network Science.

3 The program

3.1 Aims

The purpose of the program is to offer doctoral-level education matching the highest international standards, to train researchers, who would advance the nascent discipline of network science, and would take advantage of the opportunities created by high demand for network analysis expertise.

Our aim is to train researchers with theoretical, mathematical and computational skills as well as hands-on experience with large datasets and participation in international research projects. Our focus is mostly on research in applications of network science to tasks in a diversity of fields including social sciences, economics, finance, environmental science and political science but fundamental contributions to the theory of complex networks are also welcome. We designed a program that is at the forefront of network research, and at the same time engages existing resources, research directions, and interdisciplinary interests at CEU.

The program is unique and novel in many ways: It is the second such program in the world (after Northeastern University in Boston [25]). It is a program that is offered by the Center for Network Science (CNS), in close collaboration with the departments of Mathematics, Economics, Political Science, and Environmental Sciences. Students completing the program are learning the fundamental ideas of network science, possess deep statistical, big data management and modeling skills, and are equipped to undertake independent research in a wide variety of network science areas, both in academia and industry.

The PhD Program in Network Science is primarily research-oriented, and includes substantive training in data analysis methods. It is inter-disciplinary, with substantial coursework and research collaboration from other departments. The doctoral theses generated within the framework of the proposed Network Science PhD program should be typically based on closely supervised intensive empirical research studies that requires often (though not exclusively) the application of large dataset-based computationally sophisticated methodologies. The special requirements to efficiently realize such a research-oriented doctoral program is reflected in the organizational structure of the PhD degree courses.

3.2 *The Curriculum*

Students are "probationary PhD candidates" before they pass the Comprehensive Exam. The PhD studies are planned altogether for up to four years, with three years covered by a regular CEU fellowship, and one year (in between) spent abroad at one of our partner institutions.

First year coursework. By the end of the first academic year, probationary PhD candidates have to complete 24 course credits by attending courses offered by the Network Science PhD Program and such courses which are cross-listed with this program.

Research Workshop and Colloquium. Probationary PhD candidates have to attend regularly the Research Workshop, where faculty and students present and discuss their work in progress. Students are also expected to participate in the Colloquium a series of invited lectures by network scientists visiting the Center.

First year work with a research advisor. Every probationary PhD candidate is assigned a research advisor (or early supervisor) by the Doctoral Committee of the Network Science PhD Program during the second term (Winter Term). Students have to meet advisors regularly (typically once a week) according to a prearranged schedule. The task of the research advisor is to help the student to identify their research topic, to draw up a structured plan for data collection and research methodology to be used, and to organize and start the empirical research leading to the preparation of the thesis. The advisor should also be regularly consulted during the preparation of the Detailed Research Proposal.

Comprehensive Exam. During the Spring Term of the first academic year students should take the Comprehensive Exam for which an Examination Committee is appointed by the Doctoral Committee. The Comprehensive Exam comprises the topics of the mandatory courses.

Detailed Research Proposal. In the first year 6 credits are given for the preparation of the Detailed Research Proposal. The Network Science PhD Program is markedly research oriented, where the PhD Thesis is expected in most cases to be based on the results of data collection, analysis and modeling. Therefore, by the end of their first year, probationary PhD candidates are required to write a Detailed Research Proposal of 10-15 pages. The Research Proposal should specify the central question(s) to be investigated in the Thesis Research and the aim of the research; it should provide a brief review of previous relevant work and methodologies used to investigate the research topic, it should include a theoretical rationale for the line of research proposed, it should specify the data to be analyzed and the novelty of the planned work. The Detailed Research Proposal has to represent a realistic and specific plan of the thesis research that should be tailored to be realizable within the framework of the PhD studies.

Courses. In the first year students are expected to do mainly course work, prepare their Detailed Research Proposal and pass the Comprehensive Exam. Table 1 gives a list of courses. In the Fall Term they have to collect 8 credits from mandatory and a minimum of 4 from elective courses, in the Winter term another 8 credit from

mandatory and at least 2 credits from elected courses. In the second year they have to provide teaching assistance to one of the courses of CNS.

Table 1 First year course and related work

Courses	Category	Credits
Fall Term		
Fundamental Ideas in Network Science	mandatory	4
Social Networks	mandatory	4
Research workshop	mandatory	no credits
Scientific Programing in Python	elective	3
Data and Network Visualization	elective	2
Agent Based Models	elective	2
Graph Theory (Math Dept.)	elective	3
Large Graphs and Groups (Math Dept.)	elective	3
Other courses with agreement of the Doctoral Committee	elective	
Winter Term		
Structure and Dynamics of Complex Networks	mandatory	2
Data mining and Big Data analytics	mandatory	2
Statistical Methods in Network Science and Data Analysis	mandatory	4
Research workshop	mandatory	no credits
Economic Networks	elective	2
Stochastic Processes in Nature and Society	elective	2
Other courses with agreement of the Doctoral Committee	elective	
Spring Term		
Writing of Detailed Research Proposal	mandatory	6
Network Science	elective	2
Other courses with agreement of the Doctoral Committee	elective	

3.3 Student recruitment and the first cohorts

It is of paramount importance to reflect on the criteria of admission and the recruiting process for a new PhD program. According to the policy of CEU we "welcome applications from excellent candidates all over the world," and we provide them with a fellowship sufficient to cover living expenses [26]. We take students with an MSc or MA in a wide variety of fields, including math, physics, computer science, sociology, economy and finance. The electronic application procedure is run by the Admission Office [26]. Applicants have to present full transcripts of their previous studies and diplomas with an official English translation, at least two letters of recommendation with availabilities of the writers of the letters, a CV, a motivation

letter with a conception about planned research and a proof of English proficiency (usually 100+ scores in TOEFL).

The call is announced on the CEU web-page and in various media outlets, like specialized sites for higher education, bulletin boards relevant for network science, Facebook pages and via Twitter. In addition, we spread the news through personal channels via direct email.

Thus far we have had three recruiting rounds (2015, 2016 and 2017). There has been a rapid increase in the number of people interested in our Program. Applicants come with very diverse backgrounds from a large number of countries. The procedure is as follows: An ordered short list is selected by the Doctoral Committee based on the motivation letter, the recommendations, previous studies and interviews. Applicants that are selected then for admission are notified.

Presently we have 15 students from 10 countries (China, Germany, Hungary, Iran, Italy, Mexico, Palestine, Romania, Serbia, US). They have masters degrees in physics, mathematics, sociology, finance, economics, biology, psychology, architecture. Gender balance is good: we have 6 female and 9 male students. The result is a colorful and vibrant community and an inspiring atmosphere, where one of the most important learning mechanisms is the interaction among the students. We place a strong emphasis on the importance of community, and we encourage exchanges among students by providing a desk in two open offices at the Center, where students can, and do, interact intensely.

After admitting our students, we guide them through a process of selecting a supervisor and a research theme. Students are assigned a "preliminary supervisor" during the Winter Term of the first year, who help the students in the preparation of the Detailed Research Plan. Preliminary supervisors are from faculty members of the CNS or from other units of CEU, associated with CNS; in the latter case there is a co-supervisor from CNS involved. In an ideal case the preliminary supervisor will become the thesis supervisor after the student passes the Comprehensive Exam.

Students enjoy much freedom in choosing their thesis topic. The range is extremely broad: Presently students work on spreading of financial innovations, gender equality in creative teams, corruption networks, or network representations of probabilistic learning, to name a few themes. In most cases data collection and handling is a pivotal part of the studies. Such data are collected, for example, from army recruiting files of the US Civil War, from public procurements, and from the online software project hosting site GitHub.

Students are encouraged to choose network related topics from the interest fields of various departments of CEU. Our iexperience in such co-supervising cases is positive with the Department of Cognitive Science and with the Department of Economics.

4 First Experiences and Outlook

By now we have collected our first experiences with the new Program. While our enthusiasm has not abated, nevertheless, some problems have become clear. First of all: while it is very stimulating to have such a diverse collection of students, their differing backgrounds pose a real challenge to the instructor. On the one hand, students with a more modest level of mathematical knowledge have difficulties to catch up with the more quantitative courses. On the other hand, mathematically adept students - like those with physics degrees - are challenged by the task of verbally analyzing complex circumstances, or working through 60 pages of sociological theory from one week to the next. The lesson is that at the beginning we have to pay more attention to equalizing the levels of knowledge of our students. We offer a pre-session course in math, which is compulsory for new students without sufficient matching coursework on their record. The Center for Academic Writing provides excellent assistance in improving the students' skills in structuring academic publications. The main tool of harmonization is, however, a strong interaction among the students. We have achieved a sense of community, where students assist each other relying on their complementary backgrounds.

While it is too early to draw definitive conclusions about this new Program, we strongly believe that we are on a good track with it. The increasing interest by our applicants, and the emergence of similar programs worldwide reaffirm our impetus. Besides PhD level programs [25, 29] new initiatives at the masters level were started recently at Queen Mary College, London [27] and at ENS Lyon [28]. We have already established close collaboration with some of these centers and in the future we plan to make the connections even more intense by possible joint training programs and exchange of students. The discipline of network science will ultimately solidify by the work and collegial solidarity of those who have obtained a PhD degree in it.

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