A First Course in Network Science

Networks are present in all aspects of our lives: networks of friends, communication and transportation networks, and the Web are all examples that we experience outwardly, while the neurons in our brain and the proteins within our body form networks that determine our intelligence and survival. This modern and accessible textbook introduces the basics of network science required across a wide range of job sectors from management to marketing, from biology to engineering, and from neuroscience to the social sciences. Students will develop important, practical skills and the ability to write code for using networks in their areas of interest — even as they are just learning to program with Python. Extensive sets of tutorials and homework problems provide plenty of hands-on practice and longer programming tutorials online further enhance students' programming skills. This intuitive and direct approach makes the book ideal for a first course, aimed at a wide audience without a strong background in mathematics or computing but with a desire to learn the fundamentals and applications of network science.

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Colleen, Massimiliano, Iris: thank you.
—Filippo Menczer

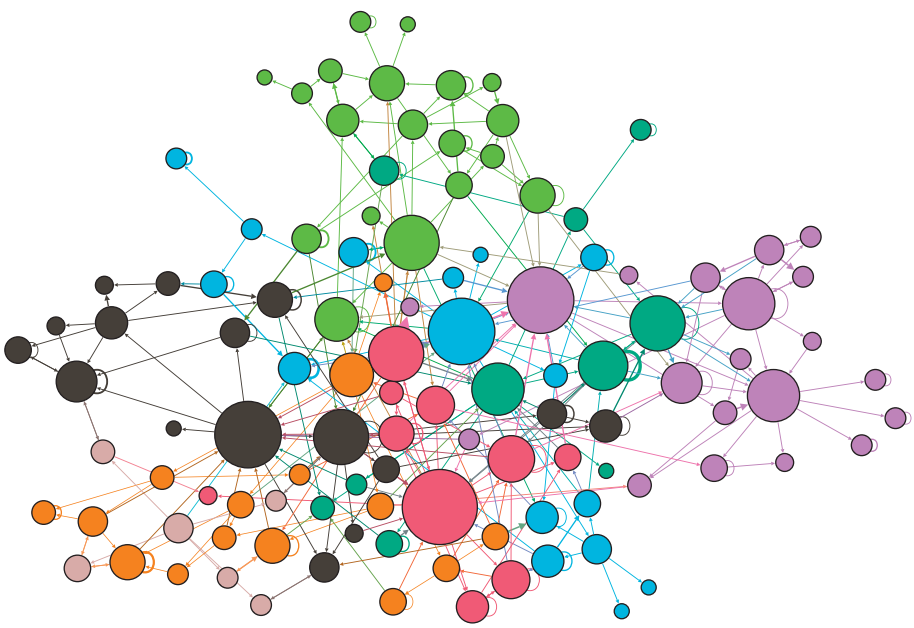
To my parents and my brother.
—Santo Fortunato

Liz, Gina, Mary Jo and Jay: your love and support mean everything to me.
—Clayton Davis

Contents

Preface

Networks are present in all aspects of our lives: networks of friends, communications, computers, the Web, and transportation are examples that we experience outwardly, while our brain cells and the proteins within our body form networks that determine our survival and intelligence. When people communicate through Facebook or Twitter, buy stuff on Amazon, search on Google, or buy an air ticket to visit family, they use networks without knowing it. Today, a basic understanding of network processes is required in job sectors from technology to marketing, from management to design, and from biology to the arts and humanities. This textbook explores the study of networks and how they help us understand the complex patterns of relationships that shape our lives.



This book is also a network! The relationships between chapters, sections, and subsections are depicted in the above image. Links represent both the hierarchical structure of the book (as seen in the Contents) and cross-references among chapters, sections, figures, tables, equations, and boxes. Node colors represent chapters and node size is proportional to the number of neighbors.

Why a "First Course" in Network Science?

This is not the first book on network science — in fact there are several excellent ones to choose from, and we list a few in Chapter 1. We have been teaching these topics for several years at Indiana University, to a broad audience of undergraduate students in informatics, computer science, data science, information science, business, and the natural and social sciences. This experience has taught us that students are eager to "get their hands dirty" and write code to both understand and use networks in their application domains of interest — even as they are just learning to program and lack math and computing background beyond high school and entry-level college courses. So we developed a wide set of tutorials and problems, both theoretical and computational, providing students with an abundance of hands-on practice in network science. Using such an approach, the book introduces networks to a wide audience of learners with no technical prerequisites other than some introductory programming, and a willingness to learn by doing. This makes the textbook appropriate for a "first course" in network science.

Synopsis

After surveying networks in many areas, we talk about social networks, which are the most familiar to students. This allows the introduction of concepts like the small-world property (short paths) and clustering (triangles and transitivity). These topics are explained through fun learning activities such as the *Six Degrees of Kevin Bacon* game. Then we delve into the role of hubs by using the Friendship Paradox and discuss network robustness. Next, we introduce directed and weighted networks, respectively. The Web, Wikipedia, citations, traffic, and Twitter are used to illustrate the role of direction and weights. The final three chapters cover more advanced topics, namely models for the emergence of networks, community detection methods, and dynamic processes that take place on networks.

Each chapter brings into focus the basic concepts necessary to understand a fundamental aspect of networks; advanced topics and formalism are avoided. When a bit of math is helpful, we include it in boxes. This slightly more technical content can be skipped without loss of basic understanding of a topic. But students who can follow these extra notes will be able to gain a deeper comprehension of the material. Each chapter includes programming tutorials and exercises, allowing readers to apply and test their knowledge through hands-on activities for building and analyzing networks. These tutorials work on examples of real-world networks that are used to illustrate concepts throughout the book. Both tutorial code and network data are available on the book's GitHub repository.[1]

[1] github.com/CambridgeUniversityPress/FirstCourseNetworkScience

Target Audience

With the explosion of popularity and commercial success of online social media, many students are interested in learning a bit about what is "under the hood" of networks. This textbook is aimed at all of those students, mainly at the undergraduate level, although the book may be useful for introductory graduate courses in non-technical fields as well. Students in programs such as data science, informatics, business, computer science, engineering, information science, biology, physics, statistics, and social sciences will benefit from courses based on this textbook. Their interest will be piqued enough to study network science in greater depth, and perhaps they will choose a career that might land them a job at Google, Facebook, Twitter, or a network start-up of their own.

Pedagogy

No technical mathematical or programming background is required, making the book feasible for introductory courses at any level, including network literacy and programming literacy courses. Such courses may skip the math boxes. By working through the programming tutorials in a collaborative computing lab and assigning the coding exercises, instructors will enable students to acquire sufficient technical skills to perform data-analytic tasks involving networks. This is our approach at Indiana University, where we teach the material in the book over two courses: a first introductory class aimed at sophomore/junior students who have taken or are taking concurrent programming courses in Python; and a second class aimed at junior/senior students. The first course roughly covers the material in Chapters 0–4. The second focuses on Chapters 5–7 after an extended review and some more advanced tutorials on the earlier material.

The extensive programming tutorials and exercises will allow instructors to easily lead and assign hands-on activities, and empower students to reinforce and test their understanding of network concepts. The activities include tutorials on *NetworkX*, a widely adopted library for network analytics; and on all topics covered in the book, from basic exercises to advanced techniques. For example, one tutorial guides students through the steps of extracting social network data from the Web. Using the Twitter application programming interface (API), students will be able to analyze popular topics, identify influential users, and reconstruct information diffusion networks showing how hashtags spread online. Students who carry out the programming tutorials and exercises will become proficient in building, importing/exporting, analyzing, manipulating, and visualizing networks of any type.

The tutorials are in Python, which is the most popular scripting/programming language. A primer that reviews the basic concepts of programming in Python is included in Appendix A. All tutorials are available online as Ipython Notebooks. Over time, NetworkX (and even Python) may evolve and some of the code in the book may need to be updated. We will note such updates in the book's GitHub repository.

There are, of course, other libraries for programming networks, for example *igraph*, *SNAP*, and *graph-tool*. Our selection of NetworkX is based on the fact that it is written in pure Python, which makes it easy to debug for students who are familiar with Python. Many alternatives have Python interfaces but are written in C, making them more efficient but also harder to debug.

Finally, some chapters leverage interactive models to demonstrate network phenomena such as giant components, small worlds, PageRank, preferential attachment, and epidemics. These models run in NetLogo, a popular simulation platform. A tutorial on NetLogo and some of the most relevant models is presented in Appendix B.

About the Cover

The network on the cover, generated by Onur Varol (Ferrara *et al.*, 2016), depicts the diffusion of the `#SB277` hashtag on Twitter. This hashtag refers to a 2015 California law on vaccination requirements and exemptions, and the network represents the discussion that was taking place online among supporters and opponents of the bill. Nodes represent Twitter users, and links show information spreading among users via retweets. Node size represents account influence (how many times a user is retweeted) and node colors represent bot scores: red nodes are likely to be bot accounts, blue nodes are likely to be humans.

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The initial idea for this book originated from conversations with our former colleague Alex Vespignani. Over the years, our colleagues Sandro Flammini, YY Ahn, and Filippo Radicchi have provided precious advice. Several students have assisted in the teaching of our network science courses at Indiana University. Among them, we want to acknowledge Mike Conover, who first conceived some of the exercises found in these pages. We are also grateful to colleagues who provided feedback on early drafts of the book, especially Claudio Castellano, Chato Castillo, and several anonymous reviewers.

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