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Foundations and Trends® in Networking

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
USA
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is R. A. Berry and R. Johari, Economic Modeling in Networking: A Primer, Foundation and Trends® in Networking, vol 6, no 3, pp 165–286, 2011

ISBN: 978-1-60198-654-2

Foundations and Trends® in Networking

Volume 6 Issue 3, 2011

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Foundations and Trends® in Networking, 2011, Volume 6, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in
Networking
Vol. 6, No. 3 (2011) 165–286

DOI: 10.1561/1300000011

Economic Modeling in Networking: A Primer

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Abstract

In recent years, engineers have been increasingly called upon to have basic skills in economic modeling and game theory at their disposal for two related reasons. First, the economics of networks has a significant effect on the adoption and creation of network innovations, and second, and perhaps more importantly, engineered networks serve as the platform for many of our basic economic interactions today. This monograph aims to provide engineering students who have a basic training in economic modeling and game theory an understanding of where and when game theoretic models are employed, the assumptions underpinning key models, and conceptual insights that are broadly applicable.

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1

Introduction

In recent years, network engineers have been increasingly called upon to have basic skills in economic modeling and game theory at their disposal. Economics chiefly concerns itself with the "production, distribution, and consumption of goods and services" (per Merriam–Webster's Dictionary); game theory provides the theoretical foundations on which many economic models are built. Recent history has cast economics at the forefront of network engineering in particular in two ways. First, the economics of networks has a significant effect on the adoption and creation of network innovations (e.g., regulation of wireless spectrum — or the lack thereof — was a significant catalyst for the development of WiFi technologies). Second, and perhaps more importantly, engineered networks serve as the *platform* for many of our most basic economic interactions today. Despite this collision of economics and engineering, our own observation is that the typical networking student does not garner economic training until later in their graduate career — if at all.

Given the two facts in the previous paragraph, our position is that basic economic understanding is a critical tool in the arsenal of the modern student studying networks. Accordingly, this text is targeted at providing a primer in economic modeling and game theory for such students in engineering, operations research, or computer science. Our focus is on providing a grounding for the basics, and particularly an understanding of where and when economic models are employed; the assumptions underpinning key models; and conceptual insights that are broadly applicable. We designed this monograph to be less of a mathematical or computational "how-to" guide to economic theory — there are innumerable textbooks available on the subject that address that requirement much more effectively. Rather, we felt a significant need to answer the following types of questions:

(1) What is the difference between efficiency and fairness?
(2) What assumptions lead to the result that markets are efficient?
(3) When is a game theoretic model appropriate?
(4) When is Nash equilibrium a reasonable solution concept?
(5) Why is one auction format preferable to another?

More than just working with economic models, it is important for engineering students to be able to take a critical eye to such models as well. Our monograph is intended to help students develop that critical eye. In this sense, we view this monograph as a *complement* to a good introductory textbook or course on microeconomics or game theory; some references are provided in the endnotes to the introduction.

As a more specific example of the type of conceptual grounding we are after, we begin by noting that one can identify two distinct but interrelated approaches to the use of economic methods in the engineering sciences. First, we observe that in many instances economic models are used as a *semantic* device to aid in modeling an engineering problem. In this setting, the system under consideration is typically designed and implemented holistically; however, decentralized implementation requires that we understand the output of many interacting subcomponents. In some instances, viewing this interaction as a game can yield useful insight. In the second approach, game theoretic models are used as an *economic* device to explicitly capture incentives of a range of rational, self-interested parties. Here game theoretic models are used to predict the outcome of their interaction, and in some cases design mechanisms to control that interaction. In contrast to the semantic approach, in the economic approach many aspects of the game are dictated by practical realities of the economic problem considered.

In the semantic approach, the usual goal is to leverage game theoretic techniques to design an optimal decentralized system. Congestion control is commonly cited as an example of this approach in networking. Here end-system controllers determine sending rates in response to congestion signals from the network; these signals can range from simple (packet loss due to buffer overflow) to complex (active queue management, or AQM, algorithms to determine explicit congestion notification, or ECN, marks). These algorithms can be naturally viewed in terms of a market, where the "buyers" are the end systems, and the "sellers" are the capacitated links of the network. Prices mediate supply and demand, and under certain conditions a market equilibrium exists and is efficient. Of course, the notion of "buying" and "selling" is purely semantic; however, it serves as a valuable (and powerful) guide that allows us to bring economic tools to bear on an engineering problem.

In the economic approach, by contrast, many features of the game are dictated by practical realities of the economic problem considered. A timely example is provided in recent studies of peer-to-peer (P2P) filesharing. Here there is a fundamental tension between the fact that a well-functioning filesharing system needs users to contribute content; but in the absence of any other incentive, users generally derive maximum benefit from downloading content, rather than contributing it. Note that in this setting the incentives are real: they are the incentives of the users contributing to the system, and any game theoretic model must start from this basic observation. At the same time, we emphasize that this approach can still involve an element of design: often we are interested in designing protocols or mechanisms that can provide the right incentives to self-interested agents. In that case, the economic approach shares much in common with the semantic approach to game theoretic modeling.

This kind of distinction may not be immediately evident to the network engineering student taking an economic modeling class for the first time. However, we believe it is a first order concern in formulating any economic model in a networking setting. As we will see in the remainder of the text, it is a distinction that informs many of the concepts we present.

The remainder of the monograph is organized as follows. In Chapter 2, we introduce the basics of *welfare analysis* — the economic analysis of efficient allocation of resources among competing uses. In Chapter 3, we discuss game theoretic foundations, including a range of equilibrium concepts. In Chapter 4, we discuss *externalities* — the (positive or negative) impact of one individual's actions on others. In Chapter 5, we discuss *mechanism design* — the design of economic environments (such as markets) that yield desirable outcomes.

A note on organization. Every section of every chapter is organized in an identical manner. Each section begins with a preamble setting the stage without technical details. The subsections then progress through *Methodology* (describing the technical approach); *Examples* (illustrating the methodology); and *Discussion* (describing key conceptual issues related to the section topic). The discussion subsections in particular play a significant role in our book: they delve beyond the "how" of economic modeling and game theory, and deal largely with the "why." Each chapter concludes with a section of *Endnotes* that lists several references for the material discussed in the chapter. The literature on economics and game theory is vast. We have not tried to provide a comprehensive bibliography, but rather focus on a few key references to provide interested readers with a starting point for exploring the material in greater depth.

A note on terminology. Throughout the monograph, we refer to individuals as "players," "agents," or "users"; we use the terms interchangeably.

1.1 Endnotes

For more background on game theory we refer the readers to one of many books available on this subject such as Gibbons [12], Fudenberg and Tirole [11], Osborne and Rubinstein [32], Myerson [28], and Owen [33]. Also, Mas–Colell et al. [24] provides a good introduction to game theory as well many other aspects of microeconomics.

In theoretical computer science, algorithmic questions related to game theory have been increasingly studied; Nisan et al. [31] provides an excellent overview of this work. In communication networking, Walrand [42] is a good tutorial on economic issues relevant to communication networks, including situations where game theoretic modeling is used.

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