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Game Theoretic Problems in Network Economics and Mechanism Design Solutions

Springer

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Dedicated to

Our Beloved Parents

for giving us this wonderful life,
for teaching us the fundamentals of the game of life,
and for continuously inspiring us in this life
through their exemplary mechanisms

Yadati Narahari
Dinesh Garg
Ramasuri Narayanam
Hastagiri Prakash

Preface

The project of writing this monograph was conceived in August 2006. It is a matter of delight and satisfaction that this monograph would be published during the centenary year (May 27, 2008 – May 26, 2009) of our dear alma mater, the Indian Institute of Science, which is truly a magnificent temple and an eternal source of inspiration, with a splendid ambiance for research.

Studying the rational behavior of entities interacting with each other in organized or ad-hoc marketplaces has been the bread and butter of our research group here at the Electronic Commerce Laboratory, Department of Computer Science and Automation, Indian Institute of Science. Specifically, the application of game theoretic modeling and mechanism design principles to the area of network economics was an area of special interest to the authors. In fact, the dissertations of the second, third, and fourth authors (Dinesh Garg, Ramasuri Narayanam, and Hastagiri Prakash) were all in this area. Dinesh Garg's Doctoral Thesis, which later won the Best Dissertation Award at the Department of Computer Science and Automation, Indian Institute of Science for the academic year 2006-07, included an interesting chapter on applying the brilliant work of Roger Myerson (Nobel laureate in Economic Sciences in 2007) to the topical problem of sponsored search auctions on the web. Ramasuri's Master's work applied mechanism design to develop robust broadcast protocols in wireless ad hoc networks while Hastagiri's Master's work developed resource allocation mechanisms for computational grids. The moment we realized, in these three strands of work, the common thread of applying mechanism design to solve important current problems in network economics, the monograph suggested itself, and we immediately embarked on this journey of putting together this monograph.

The last decade (1999-2008), as ingeniously observed by Christos Papadimitriou in his sparkling foreword to the edited volume *Algorithmic Game Theory* (Cambridge University Press, 2007), has seen the convergence of two intellectual currents, *Game Theory* and *Computer Science*, created more than six decades ago by the legendary John von Neumann. In particular, during this decade, the application of game theory and mechanism design to problem solving in electronic commerce, supply chain management, protocol design in networks, etc., has seen a

dramatic rise. This phenomenon certainly inspired our foray into this area in the year 2000. Concurrently, there were other developments that helped us to get locked into this area during the past eight years. Intel India, Bangalore, funded a collaborative project in 2000 that required the development of a multi-attribute combinatorial procurement auction for their indirect materials procurement. General Motors R & D, Warren, Michigan, next collaborated with our group to develop procurement auction mechanisms for their direct materials procurement during 2002-2004. Following this, General Motors R & D again funded us to design game theory and mechanism design based algorithms for procurement network formation during 2005-2007. Meanwhile, Infosys Technologies, Bangalore, collaborated with us in 2006-07 on applying game theory and mechanism design to the web services composition problem. More recently, the Office of Naval Research, Arlington, Virginia, USA, has funded an ongoing project on applying game theory to problem solving in complex networks. These projects helped us to investigate deep practical problems, providing an ideal complement to our theoretical work in the area. We have also been very fortunate to be working in this area during an eventful period when game theorists and mechanism designers have been awarded the Nobel Prize in Economic Sciences. We were excited when Professors Robert Aumann and Thomas Schelling were awarded the Nobel Prize 2005. In fact, we had an illuminating visit by Robert Aumann in January 2007 to the Indian Institute of Science. Our excitement reached a crescendo when, just two years later, Professors Leonid Hurwicz, Eric Maskin, and Roger Myerson were awarded the Nobel Prize in Economic Sciences in 2007 for their fundamental contributions to mechanism design theory.

Set in the above backdrop, the monograph is organized into two logical parts. The first part comprises a long chapter (Chapter 2) that contains an overview of foundational concepts and key results in mechanism design. This chapter is intended as a self-sufficient introduction to mechanism design theory with the help of carefully crafted, stylized network economics examples. The chapter also includes interesting biographical notes on legendary researchers who have made key contributions to game theory and mechanism design. The second part of the monograph contains an exposition of representative game theoretic problems in three different network economics situations and a systematic exploration of mechanism design solutions to these problems. This part has three chapters: Chapter 3 deals with the sponsored search auction problem, Chapter 4 with the resource allocation problem in computational grids, and Chapter 5 with robust broadcast protocol design problem in ad hoc networks. We conclude the monograph with Chapter 6 where we provide several pointers to the relevant literature to facilitate a deeper and broader investigation of problem solving with mechanism design.

The monograph has been structured with the objective of providing a sound foundation of relevant concepts and theory to help apply mechanism design to problem solving in a rigorous way. At the end of a serious reading of this monograph, the readers should be able to model real-world situations using game theory, analyze the situations using game theoretic concepts, and design correct and robust solutions (mechanisms, algorithms, protocols) that would work for agents that are rational and intelligent.

All the authors of this monograph have learned game theory by reading their favorite book *Game Theory: Analysis of Conflict* by Roger Myerson, and they have learned mechanism design by reading the amazingly comprehensive book *Microeconomic Theory* by Mas-Colell, Whinston, and Green. Therefore the readers would find many discussions in this monograph inspired in a quite striking way by these two classics. This is an involuntary response to the indelible impact and awesome influence these two books have had on all of us.

We wish to draw the attention of our readers regarding the use of certain words and phrases. We use the words *players* and *agents* interchangeably throughout the text. The words *bidders*, *buyers*, and *sellers* are often used to refer to players in an auction or a market. The words *he* and *his* are used symbolically to refer to both the genders. This has been done to avoid frequent usage of phrases such as *he/she* or *his/her*. Also, we have occasionally used the words *it* and *its* while referring to players or agents.

The monograph is targeted at several categories of audience. The first target includes first year graduate students and final year Master's students in the departments of computer science, electrical engineering, communications, systems engineering, industrial engineering and operations research, management science, and economics, and business schools. The next target includes researchers from both academic institutions and industries working in the areas of Network and Internet Economics, Internet Analytics, Electronic Commerce, Supply Chain Management, Wireless Networks, Communication Networks, Social Networks, etc. The monograph would serve as a suitable supplementary reference for courses such as Game Theory, Mechanism Design, Microeconomic Theory, Electronic Commerce, Network Economics, and Supply Chain management. The first author has successfully used the material from this monograph in two courses: Game Theory and Electronic Commerce. It is our sincere hope that the monograph will whet the appetite of the intended audience and create an intense interest in this exciting subject.

Acknowledgments

It is our pleasant duty to recall the exemplary support we have received from numerous individuals and organizations. First, we thank General Motors R & D, Warren, Michigan, and the General Motors India Science Lab, Bangalore for their wonderful support during the past eight years. We also thank, for their splendid support, Intel India, Bangalore, during 2000-2003; Infosys Technologies, Bangalore, during 2006-07; and the Office of Naval Research, Arlington, Virgina, during 2007-08. The first author would like to thank the Homi Bhabha Fellowships Council, Mumbai, for awarding him a fellowship during 2006-07 to undertake this work.

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It is a true privilege and pleasure to be associated with the Indian Institute of Science. As already stated, this pleasure is made even more intense by the fact that the institute is currently celebrating its Centenary Year. We would like to thank our Director Professor P. Balaram and our Associate Director Professor N. Balakrishnan for their wonderful support and encouragement. Similarly the Department of Computer Science and Automation is like a paradise for researchers. We would like to remember the support and encouragement of Professor M. Narasimha Murty, chairman, and other colleagues at the Department of Computer Science and Automation.

The Latexing of Chapter 2 of this document was done flawlessly by Mrs. Ashalata, who also created many of the pictures appearing in the monograph. Doctoral candidate Sujit Gujar should take a major credit for contributing in an invisible way to several sections and several pictures in this monograph. Sujit also has gone through carefully several draft versions of this monograph. In fact, the students at the Electronic Commerce Laboratory have provided excellent input on the various drafts.

All members of the Electronic Commerce Laboratory have been directly or indirectly involved with this monograph project over the years. We wish to thank all of them: Shantanu Biswas, Venkatapathi Raju, S. Kameshwaran, T.S. Chandrashekar, Sujit Gujar, Pankaj Dayama, A. Rajagopal, K. Rajanikanth, Sourav Sen, Karthik Subbian, Ramakrishnan Kannan, Sunil Shelke, Nagaraj, Ashwin, Sriram, Prashanth, Raghav Gautam, Megha, Santosh Srinivas, Nikesh Srivastava, Kalyan Chakravarty, Radhanikanth, Siva Sankar, Soujanya, Durgesh, Mukti Jain, M.D. Srinivasulu, Kalyan, Madhuri, Chetan, Ravi Shankar, Maria Praveen Kumar, Sharvani, Devansh, Chaitanya, Vadlamani Sastry, Sharat, and N. Hemanth.

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For the first author, behind any effort of this kind, there are two immortal personalities whose blessings form the inspirational force. They are his divine parents, Brahmasri Y. Simhadri Sastry and Matrusri Y. Nagavenamma. They are not here anymore in physical form but their magnificent personalities continue to be a beacon and a driving force. This work is dedicated with great humility at their lotus feet. He would like to lovingly thank his better half, Padmashri, who has made numerous sacrifices during the past decade because of her husband's continuous struggle with his research. The same applies to his son Naganand, who put up with his father during very crucial and formative years. The first author also cannot forget the love and affection of his brothers, sisters-in-law, sister, and brother-in-law.

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support and encouragement. He strongly believes that all the efforts involved in successfully completing this monograph are due to the divine blessings of Lord Sri Venkateswara.

The fourth author wishes to dedicate this and everything in his life to his beloved parents, Srimathi Chitra and Shri Vanchi, without whom his very existence would not have come to be. He wishes to thank his fiancee, Manjari, and his sister, Haripriya, for being understanding and loving all the time. The four of them have motivated, counseled, loved, and cared the right amount. He owes a debt of gratitude to his mentor, guide, and teacher, Professor Narahari, for his keen insight, inspiring guidance, and kind nature. Professor Narahari has made the fourth author a better researcher and more importantly, a better person. The fourth author also thanks his friends and colleagues who have been wonderful supporters right through his life. He has journeyed from the motto: "Life is a Game: Play it" to the motto "Life is a Game: find its equilibrium and stay in it." He wishes to thank everyone who was and will be part of his game.

Contents

Acronyms

NE	Nash Equilibrium
PSNE	Pure Strategy Nash Equilibrium
MSNE	Mixed Strategy Nash Equilibrium
SCF	Social Choice Function
IC	Incentive Compatible
DSIC	Dominant Strategy Incentive Compatible
BIC	Bayesian (Nash) Incentive Compatible
G-DSIC	Grid - Dominant Strategy Incentive Compatible Mechanism
DSIC-B	Dominant Strategy Incentive Compatible Broadcast
G-BIC	Grid - Bayesian Incentive Compatible Mechanism
BIC-B	Bayesian Incentive Compatible Broadcast
AE	Allocative Efficiency (Allocatively Efficient)
BB	(Strictly) Budget Balanced
WBB	Weakly Budget Balanced
EPE	Ex-Post Efficient
IR	Individually Rational
IIR	Interim Individually Rational
VCG	Vickrey-Clarke-Groves Mechanisms
GVA	Generalized Vickrey Auction
dAGVA	d'Aspremont and Gérard-Varet mechanisms
SSA	Sponsored Search Auction
GFP	Generalized First Price
GSP	Generalized Second Price
OPT	Optimal Mechanism
G-OPT	Grid - Optimal Mechanism
SRBT	Source Rooted Broadcast Tree