Research Statement

Swaprava Nath
Fulbright-Nehru Postdoctoral Fellow
Computer Science Department, Carnegie Mellon University

My research is motivated by the strategic interactions between decision making agents. The goal of *artificial intelligence* (AI) is to build systems or automated agents that take efficient decisions in a similar way humans take decisions. With the evolution and proliferation of this kind of intelligent agents, it is important to understand the implications when multiple such agents interact with each other. The decentralized goals of the individual agents often conflict with the goal of taking a globally *efficient* decision by the central decision maker (planner). Many applications on the Internet serve as examples of this phenomena: in online advertisements, allocating (spectrum) resources to users, matching websites to viewers or students to universities, *rationality* and *intelligence* are indistinguishable parts of a multi-agent AI system, and therefore it needs a formal analysis of this *strategic* behavior.

My research considers *strategic* multi agent systems from a *game theoretic viewpoint* – a tool used in mathematics and microeconomics to analyze the behavior of rational and intelligent agents. Using a game theoretic framework, we design protocols or *mechanisms* that are robust against any strategic manipulations of the agents and yield *efficient* solutions for the planner. However, it is not always possible to ensure efficient outcomes in face of a strategic behavior, and a large body of literature in *social choice theory* (a branch of microeconomics) deals with such impossibilities. From a computer science viewpoint, we circumvent such impossibilities with a precise answer of the minimal achievable inefficiency and provide approximations to the optimal, efficient outcomes. Our results, therefore, not only improve the design of multi agent systems using the ideas of game theory, but also improve the known results of social choice by giving the best achievable approximation guarantees. This integration of economics and computation makes our contributions novel both in the domains of AI and social choice theory, and paves the way for a broad spectrum of future research.

Economics and Computation: Topics of Mutual Benefit

Innovations in the computational and communication sciences have revolutionized the way we talk, disseminate information, aggregate our opinions or beliefs, and even trade with consumers. A large section of the Internet today is involved in creating content by the users, outsourcing tasks to individuals in a crowd, allocating computational or storage resources to users, and generating revenue through advertising. Technology has made this job easier by providing an environment where these applications can run efficiently on the Internet. However, these applications are run by machines that are programmed by humans. At an abstract level, every application has a global decision maker (e.g., the owner of the resource) and multiple *artificially intelligent* (AI) agents (e.g., the automated programs that compete for the resources), each of whom has conflicting interest. The AI agents pick their actions to maximize their individual payoffs, while a central planner wants to maximize the global payoff. For example, the advertisers want to maximize their reach to the users and the website owner wants to maximize her revenue. Clearly, a naïve algorithm that decides the outcome assuming the reports of the agents to be the true state of the world is vulnerable to agents' manipulations and will not work in practice. An efficient design of protocols in this ecosystem with such *rational* and *intelligent* agents demands a deep understanding of mechanism design theory (Myerson, 1989) that classically deals with strategic behaviors in a multi agent environment. Research in multi agent systems has also considered this fact and mechanism design today is a strong part of AI research (Shoham and Leyton-Brown, 2010).

Research contribution in strategic multi agent systems

My research considers a complementary approach where on one hand mechanism design is used for creating 'efficient' computational and communication ecosystems (economics help improve computer science applications), and on the other hand computational techniques are used to precisely predict the limits of achievability of the desirable economic properties in these applications (computer science helps analyze economic properties). With this research philosophy, in the following sections I present my research in the context of their motivating applications.

Crowdsourcing

The art of efficiently harnessing information, expertise, and labor from a diverse, unstructured, and heterogeneous *crowd*, often with a suitable monetary compensation, is known as crowdsourcing. Even large organizations today trust on crowdsourcing to solve problems without acquiring additional resources. A number of platforms have emerged, e.g., Amazon Mechanical Turk, oDesk, InnoCentive etc. that help connecting the tasks to the crowd-workers. My PhD thesis (Nath, 2013) has investigated a number of interesting questions in the context of crowdsourcing.

Skill elicitation In this problem we ask the questions: *how to crowdsource a task to the right set of experts (or workers) as their skill set is unknown to the designer? Can one accomplish this objective even without verifying the tasks performed by the experts?* We model this as a mechanism design problem with a set of agents having privately known skill levels. The crowdsourcer or the mechanism designer asks the experts to report their skills and takes the decision of picking the optimal subset of the experts with a suitable monetary compensation. This induces a game between the experts and the crowdsourcer. The payment is chosen in a way that ensures that the players report their skills truthfully. Our initial works in this direction (Nath et al., 2011; Nath, 2011) assume that the valuations of the experts are interdependent and their skills are stochastically varying over time. In the process, we provide an improvement over a classical result of mechanism design with interdependent valuations (Mezzetti, 2004) by proposing a mechanism that gives a strict truthfulness guarantee in static (Nath and Zoeter, 2013) and dynamic settings (Nath et al., 2015).

In Bhat et al. (2014), we consider a specific model of the crowdsourcing problem where experts' opinions about a binary outcome can be verified with the observable true state. In this setting, the owner of a task benefits from the high quality opinions provided by experts. We propose a mechanism that leverages the structure of this special class of problems and guarantees allocative efficiency, ex-post incentive compatibility, ex-post individual rationality, and strict budget balance, which even the classical mechanism (Mezzetti, 2004) cannot achieve in this setting. To the best of our knowledge, this is the first attempt in developing a quality assuring crowdsourcing mechanism in an interdependent value setting with quality levels held private by strategic agents.

Resource critical crowdsourcing tasks In crowdsourcing contests like finding an object or performing a time-limited task (DARPA, 2010, 2012), the goal of a designer is to minimize either time or cost of the search process. In these scenarios, certain novel form of strategic behavior is observed. For example, most of the crowdsourcing contests focus on creating a social network via referrals and reward is distributed over the participants of this referral tree. Creating fake nodes (known as *sybil* attack) is a new form of manipulative action that happens here. In Nath et al. (2012), we give an axiomatic characterization of *sybil-proof* mechanisms and prove that no mechanism can simultaneously satisfy certain desirable properties, and provide approximation guarantees. The results provide precise characterizations of certain cost critical and time critical mechanisms that have been used in practice.

Efficient team formation Another interesting question in crowdsourcing is that of the distribution of efforts of the agents in the referral network. The social network formed by the referral process tends to have a hierarchical structure. Considering the entire crowdsourcing system as a consolidated organization, a primary goal of a designer is to maximize the net productive output of this hierarchy using reward sharing as an incentive tool. Every individual in a hierarchy has a limited amount of effort that they can split between production and communication. Productive effort yields an agent a direct payoff, while the communication effort of an agent improves the productivity of other agents in her subtree. In Nath and Narayanaswamy (2014), we provide a detailed analysis of the Nash equilibrium efforts and a design recipe of the reward sharing scheme that maximizes the net productive output in crowdsourcing networks.

Resource allocation

Division of computational or storage resources on the cloud or the allocation of spectrum for mobile communication are game theoretic problems since the strategic consumers have private valuations over their shares of these resources while the resource owner (e.g., government in case of spectrum allocation) wants to efficiently allocate the resources. A fundamental question in these settings is to find a rule that is robust against strategic manipulations of the agents. In Nath and Sen (2015), we consider a general setup of this kind where agents have *selfish* valuations (only cares about their own consumptions). We characterize the rules that are implementable truthfully and show that they belong to a special class called *affine maximizers*.

The valuations we consider belong to a strict subset of the ones considered in a similar earlier work (Roberts, 1979) and therefore the structure of the mechanisms were unknown till our work.

General quasi-linear preferences

Money serves as a means of transferring an agent's payoffs in the classic social choice theory, and this model of utility helps implementing an important goal of the planner: *truthfulness* (Vickrey, 1961; Clarke, 1971; Groves, 1973). However, it is known that simultaneously ensuring zero net monetary transfer (budget balance) and taking an *efficient* decision is impossible (Green and Laffont, 1979). However, this result does not say how far we are from the 'exact' satisfiability of these two properties. We address this question in Nath and Sandholm (2016) and show that there exists budget-balanced mechanisms for which inefficiency vanishes asymptotically with the number of agents. We provide a precise rate of convergence for both deterministic and randomized mechanisms. We also show that no deterministic mechanism can converge at a rate faster than this in the general quasi-linear setting. This is an example where computational techniques provide quantitative guarantees for mechanism design.

In an ongoing work with Mishra and Roy, we consider mechanisms with money for alternatives that can be split into components. For example, a department wants to acquire hardware and software parts for its employees but is budget constrained – therefore wants to know the valuations of the employees for the available alternatives to take a decision. We characterize mechanisms that elicit the valuations truthfully from the agents.

Strategic voting

Agents are often comfortable with representing their preferences in an ordinal order even though the actual preferences could be cardinal. Designing mechanisms with the ordinal information reduces the complexity of the decision process, however, it can be inefficient from the actual cardinal valuations viewpoint. It is an interesting question to what extent the ordinal rules deviate from the efficient ones. To extend the existing results that consider this question with selecting one alternative (Boutilier et al., 2015), we consider a subset of alternatives being selected (Caragiannis et al., 2016), and derive analytical bounds on the performance of optimal (deterministic as well as randomized) rules in terms of two widely-used measures of inefficiency. This result explains the gradual decrease in these metrics of inefficiency as the size of the selected set increases with a precise bound. Experiments with real and synthetic data shows the efficacy of the rules in practice.

Future Research Plans

Each domain of research mentioned above has immense potential for future investigations. The research in the intersection of economics and computation is fairly new and therefore there are many unsolved questions, some of which are listed below.

Theoretical considerations My research has been primarily a theoretical investigation of strategic multi agent systems. A rich set of problems of similar nature as described below exists to be explored.

- Classical social choice theory is mainly *axiomatic* in nature. These axioms represent a list of socially desirable properties and sometimes they are incompatible with each other. The results reflect similar impossibilities in multi agent AI systems. However, there has been little work on *exploring these impossibilities quantitatively*, i.e., how restrictive are these impossibilities or can we achieve a fair approximate guarantees of these axioms. It turns out that there are a lot of special settings in practice where the limits are not very restrictive and therefore it is possible to extract positive results and worth finding the limits of achievability in these settings.
- In my research, I have explored a very desirable property of truthfulness in multi agent systems. However, the mechanisms designed this way often are biased to a few agents and *unfair* to others. Fairness is another interesting socially desirable property that often conflicts with truthfulness. The literature on fairness has not explored truthfulness as a necessity. Hence a detailed understanding the *trade-off between fairness and truthfulness* is an interesting future research direction.
- Classical machine learning involves learning from examples. Intelligent agents can also learn in games, and from their payoffs and actions a designer can elicit their private information that can potentially help in taking efficient decision in future. *Integrating learning theory with mechanism design* to build dynamic multi agent systems is a novel future research direction.
- In a major part of my research, I have considered scenarios where agents take simultaneous actions. However, another interesting setting is when agents take turns which gives rise to dynamic games. The situation is similar to a control system (widely used in electrical, communication, and robotics) with an

additional feature of agent rationality. By *introducing game-theoretic models in the standard control system models*, we can, on one hand, leverage on the rich set of mathematical primitives of control theory and on the other hand, extend the stability results in presence of multiple rational agents.

Experimental considerations In my future research, I want to spend a significant effort in developing real web-based applications that transform the theoretical investigations into a thing of everyday use.

- To understand the needs of a mechanism that will work well with human behavior on the web, a behavioral study involving human subjects over the Internet is necessary. My future plan of experimental research involves designing experiments that aim to understand the human decision making process in multi agent scenarios.
- I am enthusiastic about making *social* algorithms (or mechanisms) available for the users to make more informed and efficient decision in their daily lives. I have created one such application for matching students to advisors based on their mutual preferences (Nath, 2015) which implements the classic algorithm due to Gale and Shapley (1962). My goal is to create more such web applications that help applications like matching students to universities or allocating resources among competing agents etc. I want to make them available to the users on the Internet and get user feedback and data for research.

Summary The research agenda encompassing the vibrant areas of mechanism design and multi agent systems shows a promising future as it impacts every user of the Internet and the social applications. From both the theoretical and practical viewpoints, research in this domain ensures a steady and sustainable growth.

References

Bhat, S., S. Gujar, S. Nath, O. Zoeter, Y. Narahari, and C. Dance (2014): "A Novel Incentive Compatible Mechanism for High Quality Crowdsourcing of Tasks," in *Proceedings of the Conference on Autonomous Agents and Multi Agent Systems (AAMAS)*, 917–924.

Boutilier, C., I. Caragiannis, S. Haber, T. Lu, A. D. Procaccia, and O. Sheffet (2015): "Optimal Social Choice Functions: A Utilitarian View," *Artificial Intelligence*, 227, 190–213.

Caragiannis, I., S. Nath, A. Procaccia, and N. Shah (2016): "Subset Selection Via Implicit Utilitarian Voting," in *Proceedings of International Joint Conference on Artificial Intelligence (IJCAI)*, accepted.

Clarke, E. (1971): "Multipart Pricing of Public Goods," *Public Choice*, 19–33.

DARPA (2010): "DARPA Network Challenge Project Report," .

——— (2012): "DARPA CLIQR Quest Challenge," .

Gale, D. and L. S. Shapley (1962): "College admissions and the stability of marriage," *The American Mathematical Monthly*, 69, 9–15.

Green, J. R. and J.-J. Laffont (1979): *Incentives in public decision making*, North-Holland.

Groves, T. (1973): "Incentives in Teams," *Econometrica*, 41, 617–31.

Mezzetti, C. (2004): "Mechanism Design with Interdependent Valuations: Efficiency," *Econometrica*, 72, 1617–1626.

Myerson, R. B. (1989): *Mechanism design*, Springer.

Nath, S. (2011): "Dynamic Learning-based Mechanism Design for Dependent Valued Exchange Economies," in *Proceedings of the World Wide Web (WWW 2011)*, 397–402, phD Proposal Paper.

——— (2013): "Mechanism Design for Strategic Crowdsourcing," Ph.D. thesis, Indian Institute of Science, Bangalore.

——— (2015): "Match advisors to students," https://www.facebook.com/adstudmatch/, facebook app for matching advisors to students using Gale-Shapley algorithm.

Nath, S., P. Dayama, D. Garg, Y. Narahari, and J. Zou (2012): "Mechanism Design for Time Critical and Cost Critical Task Execution via Crowdsourcing," in *Proceedings of Internet and Network Economics (WINE 2012)*, 212–226.

Nath, S. and B. Narayanaswamy (2014): "Productive Output in Hierarchical Crowdsourcing," in *Proceedings of the Conference on Autonomous Agents and Multi Agent Systems (AAMAS)*, 469–476.

Nath, S. and T. Sandholm (2016): "Efficiency and Budget Balance," Tech. rep., Carnegie Mellon University.

Nath, S. and A. Sen (2015): "Affine Maximizers in Domains with Selfish Valuations," *ACM Transactions on Economics and Computation*, 3, 26:1–19.

Nath, S. and O. Zoeter (2013): "A strict ex-post incentive compatible mechanism for interdependent valuations," *Economics Letters*, 121, 321–325.

Nath, S., O. Zoeter, Y. Narahari, and C. Dance (2011): "Dynamic Mechanism Design for Markets with Strategic Resources," in *Proceedings of the Conference on Uncertainty in Artificial Intelligence (UAI 2011)*, 539–546.

Nath, S., O. Zoeter, Y. Narahari, and C. R. Dance (2015): "Dynamic Mechanism Design with Interdependent Valuations," *Review of Economic Design*, 19, 211–228.

Roberts, K. (1979): *The Characterization of Implementable Choice Rules*, North Holland Publishing, chap. Aggregation and Revelation of Preferences, 321–348.

Shoham, Y. and K. Leyton-Brown (2010): *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*, Cambridge University Press.

Vickrey, W. (1961): "Counterspeculation, auctions, and competitive sealed tenders," *The Journal of Finance*, 16, 8–37.