Complexity and Simplicity in Economic Design

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Abstract As more and more economic activity moves to the Internet, familiar economic mechanisms are being deployed at unprecedented scales of size, speed, and complexity. In many cases this new complexity becomes the defining feature of the deployed economic mechanism and the quantitative difference becomes a key qualitative one. We suggest to study this complexity and understand in which cases and to what extent it is necessary.

As more and more economic activity moves to the Internet, familiar economic mechanisms are being deployed at unprecedented scales of size, speed, and complexity. In many cases this new complexity becomes the defining feature of the deployed economic mechanism and the quantitative difference becomes a key qualitative one.

A paradigmatic example is that of an auction. Classic economic theory has studied in considerable detail the question of how to sell an indivisible item in an auction. Auctions were mathematically modeled as to study a host of issues: revenue, social welfare, risk, partial information, different formats, players' strategies, etc. As a result of much work in economic theory one may comfortably say that single item auctions are very well understood. Then enter computational platforms, and especially the Internet. While auction theory is obviously applicable to many economic scenarios on computational platforms, in these settings we often see the humble auction grow to amazing sizes and complexities. Classic examples include the FCC spectrum auctions that seek to auction off thousands of spectrum licenses worth Billions of dollars and Internet ad-auctions that sell many billions of "ad-impressions", each worth less than a penny but together giving Google, for example, its Billions of dollars of revenue. In each of these applications, the computational platform allows us to sell multiple items in new complicated and sophisticated ways, and this capability allows us to achieve unprecedented economic benefits (in various senses).

There has been much recent work in the computer science community that deals with these as well as many other instances of large or "complex" auctions or markets.

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In fact, large and complex auctions are the central focus of a young and vibrant field called *Algorithmic Mechanism Design* (Noam Nisan et al. 2007). We can probably fit much of the research done in these fields in the last two decades into the following high-level template:

1. A theoretical point of departure is some well-known issue in classic economic theory or game theory (e.g. a single item auction).
2. A motivational goal is some complex scenario that seems to be addressable by some variant of this classic departure point (e.g. allocating a large number of items).
3. The research challenge is to masterfully combine the economic or game-theoretic sensibilities of the simple departure point with the size, interactions, and constraints of the complex setting.

Such a combination must deal with the various new "complexities" of the new scenario and often requires new ideas both in the game-theoretic/economic analysis and in the computational/algorithmic treatment. The results obtained may vary across several dimensions: to what extent we can recover the "good" properties of the original simple scenario, to what extent simple mechanisms are sufficient (as opposed to complex ones), which trade-offs exist, which natural special cases behave better than the general case, etc.

This note advocates the development of an organized theory along these lines. A theory that can look at a complex economic scenario and understand the crucial ways in which it differs from or is similar to simple related economic scenarios. Such a coherent theory should serve as a general framework that guides our attempts of addressing complex economic problems such as those routinely found on the Internet. Such a theory should be able to tell which parameters of the complex scenario can be "aggregated" toward a simple view, which ones must be addressed in more sophisticated and complex ways, and which ones cause unavoidable losses. A good theory of "complex economics" can guide our attempts of solving complex economic challenges in a similar way that *computational complexity theory* (Papadimitriou 2003) guides our approaches to addressing algorithmic problems: identifying crucial bottlenecks (like time or space), suggesting required compromises (like approximations or special cases), and highlighting connections between different problems (like reductions and classes).[1]

We have so far left the key notions of "complexity" and "simplicity" rather vague. We argue that there are multiple interesting meanings to these notions, and suggest that multiple ones should be addressed by the proposed theory of complexity in economics. At the most concrete level, one may study notions of complexity that are of direct interest from an economic point of view in many applications. More generally, one may hope that studying several different notions of complexity will paint a general picture of the studied landscape and will enable insights that transcend

[1] An existing research field often termed "Complexity Economics" applies notions and ways of thinking from "Complexity Science" (e.g. James Gleick 1997) to economic systems. The suggestion here however is to proceed in a different direction, one whose view of "complexity" is taken from theoretical computer science rather than from physics.

any particular mathematical model. At the highest level, various concrete notions of complexity should capture important aspects of the *computational complexity* of economic problems (in the usual algorithmic sense).

To demonstrate the potential of a general theory of complexity in economic settings, let us proceed with a list of examples of various notions of complexity in various economic settings that have already been studied. Not only do these demonstrate the richness of notions of complexity, but the connections between them also demonstrate the potential for a coherent theoretical framework. For each of these examples there exists a long thread of research papers, of which we will only reference a single one, often a survey or recent paper that can point to further papers.

- **Communication Complexity of Markets and Auctions**. It is well accepted in economic theory that a critical part of any market mechanism is that of communication, and that markets are rather efficient "communication devices" in classical "convex" scenarios. However, in complex scenarios such as combinatorial auctions, it turns out that one can quantify that an intractable, exponential, amount of communication is needed in order to obtain efficiency, highlighting the limitations of market mechanisms (as well as others) in such situations. Much work has been done in studying trade-offs between communication complexity, efficiency losses, and additional constraints in various scenarios (Shahar Dobzinski et al. 2014).
- **Bidding Languages**. In complex computerized settings it is very clear that eliciting the preferences of the participants is a crucial bottleneck in the path to a desired outcome. A basic approach is that of specifying a "bidding language" (Noam Nisan 2006) by which users can describe their preferences, where "stronger" languages allow smaller complexity in describing preferences but "simpler" ones may be easier to deal with algorithmically, strategically, and conceptually.
- **Queries for Preference Elicitation**. A more general approach to preference elicitation would be for the mechanism to "query" the preferences of each of the player using some natural specific set of allowed queries. This can be more general that bidding languages since the elicitation process can be adaptive. The interesting questions here concern the trade-offs between the number of types of queries and the quality of the obtainable solution. There are various types of natural queries to consider depending on the exact scenario, and for example in the context of combinatorial auctions, "value queries" and "demand queries" have received much attention (Nisan et al. 2007). At the extreme level of generality, such models turn out to capture natural notions of communication complexity.
- **Complexity of Convergence to Equilibrium**. It is commonly assumed that in strategic situations, players would reach (or at least approach) equilibrium. While this may seem to be a reasonable assumption in classical simple scenarios, the question of how (and whether) do players reach an equilibrium in complex situations is much more mysterious. Are there any realistic "learning strategies" by the participants that will lead them to a Nash equilibrium? There are various ways of quantifying the complexity of reaching equilibria (Sergiu Hart and Andreu Mas-Colell 1997), and very strong exponential complexity intractability results are known for many general models.

- **Mechanism Specification Complexity**. An economic mechanism specifies the rules for interaction between economic parties and the outcome from that interaction. How complex must we make our mechanism in order to obtain desired economic properties? For example, when auctioning a single item, Myerson shows that the very simple mechanism of a second price auction with a reserve price already ensures optimal revenue (in rather general scenarios). Unfortunately, this simplicity no longer suffices for even slight generalizations of a single-item auction, e.g. even when selling two items to a single buyer! In this case, as well as more complex ones, it turns out that there is a trade-off between the complexity of describing the mechanism and the revenue that it can ensure. There are several interesting ways of measuring the complexity of a mechanism, the simplest of which is counting the number of possible outcomes, a measure termed the "menu-size" (Sergiu Hart and Noam Nisan 2013).
- **Equilibrium Structure Complexity**. The notion of equilibrium is central in economic settings, and Many types of equilibria are considered in the economic literature: in games pure or mixed Nash equilibria, as well as "correlated" and "coarse-correlated" ones, in markets, various types based on prices, notions like stable marriage in yet other settings, etc. Some of these equilibria are always simple (e.g. pure-Nash equilibria), while others (like correlated ones) can be significantly more complex. On the other hand, complex types of equilibria may exist when simpler ones do not, and may allow improved efficiency. Imposing some simplification on the underlying economic system may simplify equilibria, perhaps at the cost of some loss of efficiency. In particular, much recent work has studied the inefficiency incurred by equilibria when multiple items are sold simultaneously but separately, as well ass possible generalizations (Tim Roughgarden and Inbal Talgam-Cohen 2015).
- **Complexities, Incentives, and Approximation**. Some of the basic tools of mechanism design, specifically, the Vickrey–Clarke–Groves payment scheme generalize to complex scenarios. However in such complex scenarios obtaining optimal solutions is often intractable due to this very complexity (whether the complexity is measured by computation, communication, queries, or other notions). While tractable *approximate* solutions are known in many cases, it turns out that these will often not "play well" with the strategic tools of mechanism design. This type of clash between complexity and strategic tools has been at the center of focus for the field of Algorithmic Mechanism Design (Noam Nisan 2014).

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