How Market Design Emerged from Game Theory: A Mutual Interview

Alvin E. Roth and Robert B. Wilson

We go back a fairly long way. Al was a PhD student at Stanford in Operations Research from 1971 to '74, and Bob was his dissertation advisor. Game theory was also young in those days; its offspring, mechanism design, was even younger; and practical market design by economists was not yet on the horizon.

To jog our memories about the history and development of game theory and how it shaped and was reshaped by market design, we interviewed each other over coffee during Fall 2018.[1] We also touched on what we think has been learned about markets and marketplaces by trying to design them.

What emerged from our discussion is that, when we learned game theory, games were modeled either in terms of the strategies available to the players ("noncooperative game theory") or in terms of the outcomes that could be attained by coalitions of players ("cooperative game theory"), and these were viewed as models appropriate for different kinds of games. In either case, the particular model was viewed as a mathematical object that could be viewed in its entirety by the theorist. Market design, however, has come to view these models as complementary approaches for

[1]We later added publication dates for the work to which we refer, and each of us inserted footnotes to our own comments where additional background seemed useful.

■ *Alvin E. Roth is the Craig and Susan McCaw Professor of Economics and Robert B. Wilson is the Adams Distinguished Professor of Management, Emeritus, Graduate School of Business, both at Stanford University, Stanford, California. Their email addresses are alroth@stanford.edu and rwilson@stanford.edu.*

examining different ways in which marketplaces operate within their economic environment. And, because that environment can be complex, there will be aspects of the game that are not entirely observable.

Mathematical models themselves play a less heroic, stand-alone role in market design than in the theoretical mechanism design literature. A lot of other kinds of investigation, communication, and persuasion play a role in crafting a workable design and in helping it to be adopted and implemented, and then maintained and adapted.

How Did Game Theory Look When You Began to Learn It, and Teach It?

Wilson: Before 1960, basic concepts of strategic analysis were established but had slight influence on economics. Studies of parlor games (for example, Borel 1921, 1953) influenced von Neumann's early work on minmax solutions of constant-sum two-player games. Von Neumann and Morgenstern (1944) showed existence of such solutions for all such games and then proposed a solution of cooperative games.[2] Nash's (1950a, 1951) definition of equilibrium for noncooperative games offered an alternative approach. The main applications to noncooperative contexts were military and about zero-sum two-player games until Schelling's (1960) broad view of "the strategy of conflict," which was nontechnical but informed by game theory and widely read. Axiomatic cooperative theory advanced via the "value" introduced by Shapley (1953) and the "bargaining solution" by Nash (1950b), and these were often invoked in theoretical economic models.[3]

Most influential for economists was Luce and Raiffa's (1957) book-length critique of game theory's potential for advancements in the social sciences; it was guardedly optimistic, with severe criticisms, widely read, and influenced a generation of scholars. Hayek's (1945) article on "the use of knowledge in society" set the stage for much-later use of models from game theory. He interpreted markets as mechanisms for eliciting preferences and equating marginal rates of substitution among diverse agents with local information about production and consumption opportunities. In the early 1960s, I read most of Luce and Raiffa (1957) and portions of von Neumann and Morgenstern (1944) and Karlin (1959).

Roth: I also found Luce and Raiffa much easier to read than von Neumann and Morgenstern.

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[2]Their book was heralded as the future of economics in reviews by Hurwicz (1945), Marschak (1946), Copeland (1945), and Wald (1947). Marschak concluded: "Ten more such books and the progress of economics is assured." Copeland wrote: "Posterity may regard this book as one of the major scientific achievements of the first half of the twentieth century." It took decades for these prospects to be realized, albeit in a form rather different than von Neumann and Morgenstern envisaged initially.
[3]An excellent complement to our discussion here is Myerson's (1999) history of Nash's contributions and their subsequent impact in economic theory.

Wilson: As an MBA student in 1960, I wrote a class report on how to bid in an auction that got a failing grade because it was not "managerial." My studies with Howard Raiffa were focused on decision theory, but discussions with Jacob Marschak and Lloyd Shapley turned me to game theory, initially to generalize the Lemke and Howson (1964) algorithm to find Nash equilibria of *N*-player games, then in papers on auctions, then in advising the brilliant Armando Ortega-Reichert (1969) on his dissertation about auctions that went far beyond Vickrey (1961). Social choice theory and auctions were main interests until 1978, although in 1968 I developed an MBA course on "competitive strategies" with broad coverage, and a PhD course on "multiperson decision theory."

Roth: When I began grad school at Stanford in 1971, there was no course offered in game theory. But Michael Maschler visited in academic year '72–73 and offered one.[4]

In those days, game theory was thought of as being divided into two parts: cooperative and noncooperative. These were entirely separate theories, differently formulated and thought to apply to different economic environments—namely, those with and without binding agreements. The idea was that for cooperative games, we would study what (binding) agreements rational agents would reach. For noncooperative games, we would study Nash (1950a) equilibria, interpreted either as the result of players' independent optimization in the light of others' presumed rationality, or as the agreements they could reach (in the absence of ways to enforce agreements) that would be self-enforcing in the sense that no player had an incentive to break the agreement if others were expected to follow it when they chose their strategies.

This division of game theory into two parts had its origins in von Neumann and Morgenstern (1944), although some of the particular ideas, interpretations, and models (including Nash's formulation of equilibria) came later.[5]

Also inherited from von Neumann and Morgenstern was that the goal of game theory should be to find the "solution" to each class of games, that would "solve" each kind of theory. They attached great importance to the idea that a solution, when found, would apply to all games in (at least) a very broad class, and therefore that an important property of prospective solutions should be that they should exist for all games. Indeed, an existence proof was often regarded as the main contribution of Nash (1950a), rather than his novel formulation of strategic equilibrium.

There were two complementary models of noncooperative games: the "normal" or strategic form of the game represented as an *n*-dimensional matrix when *n* players were involved, and Kuhn's (1950, 1953) formulation of extensive-form games. The extensive form is a tree with branches representing the actions

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[4] Jerusalem was the center of the game theory world at that time, with a thriving group that had grown up around Bob Aumann, which included Maschler and a growing group of top students at the Hebrew University and later also at Tel Aviv, which by 1972 already included Bezalel Peleg, David Schmeidler, and Shmuel Zamir.

[5] There weren't any up-to-date advanced textbooks in the 1970s, although Owen (1968) provided an introduction, and so Maschler taught from papers and his own notes.

available to particular players as a consequence of actions taken earlier in the tree, and "information sets" of nodes which indicated what a player knew about earlier decisions when it was his turn to move (with all the nodes in a given information set being indistinguishable to that player at the time when the choice of action was demanded). In this formulation, a strategy for a player was a complete plan of action: a function that specified for each of that player's information sets, what action he would take if the game reached that information set. The more compact "normal" or "strategic" form of the game came to be understood as specifying the (expected utility) payoffs that each player would receive as a consequence of each possible combination of strategy choices by the players.

The "solution concept" for predicting players' choices of strategies was Nash equilibrium.[6] Selten (1965) had already introduced, in German, the subgame perfect refinement of Nash equilibrium in the extensive form, but most English-speaking game theorists learned about that only from his 1975 article that introduced what came to be called "trembling hand perfection" as a further refinement. For many years, the search for increasingly powerful refinements was a hot topic in game theory. The idea behind refinements was very closely related to the conception of each game as being perfectly captured by its extensive or strategic form: if we knew everything about a game, then perhaps we could deduce from first principles which of the multiplicity of equilibria would be the one that would be picked by perfectly rational agents who knew one another to be perfectly rational.[7] While this was never achieved, some refinements, including various notions of perfection, and of sequential rationality (Kreps and Wilson 1982), have become useful tools for modern game theorists, and new refinements continue to be proposed and explored (for example, Milgrom and Mollner 2018; Myerson and Weibull 2015), because many if not most games have a plethora of Nash equilibria.

Harsanyi (1967–68) extended the extensive-form model with common knowledge to games of incomplete information, in which there was an initial common knowledge move by Nature that produced "types" of players who each knew his own type but knew only the distribution of other players' types. The idea that everything about the structure of the game (including the rationality of all the players) was known to all the players was made clearer by specifying precisely what it meant for something to be common knowledge (made formal by Aumann 1976 independently of, but in the spirit of, Lewis 1969).

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[6] The awkward term "solution concept" was widely used once it became clear that there were not readily going to be any perfect "solutions" forthcoming, although the word "perfect" would emerge as a term in the equilibrium refinement literature, which continued to seek a definitive solution for noncooperative games.

[7] The hope was that the "right" refinement would be a subset of all the others, possibly a unique equilibrium for each game that captured most fully the perfect rationality of all the players. However, refinements of equilibria turned out to be more like onions than like olives: applying all of the attractive refinement principles to peel away imperfect equilibria did not yield an irreducible center, but rather nothing at all. *Wilson:* I view the axioms in Govindan and Wilson (2012) that characterize Mertens (1989) stable sets as a surviving core.

I'll come back to this, as the idea that the entire game—all the strategies available to all the participants—was common knowledge among the participants and completely known to the theorist seeking to analyze the game, was one of the features of early game theory that had to be overcome for practical market design to develop. Indeed, the idea that practical design should not depend on unrealistic common knowledge assumptions (or on assumed knowledge involving too much detail of players' private information) is widely known as the "Wilson doctrine," after Wilson (1987).

Wilson: At issue was whether the fine detail of game-theoretic models provided new economic insights.[8] Is it sufficient to assume that markets clear at whatever prices are required to do it, or should one examine institutional arrangements for eliciting demands and establishing prices, or even the informational content of prices as suggested by Hayek? It was hard to give up the beautiful welfare theorems implied by "perfect competition" if one were to take account of a welter of detail about agents' incentives in imperfect markets.[9]

Many game theorists and other economists attended summer seminars at Stanford, with prominent game theorists being among the regulars, notably Robert Aumann and colleagues from Israel, where mathematically rigorous work was most advanced. The focus was essentially about how to formulate and analyze economic models in which all agents are strategic players, and whether such efforts would be useful in economic theory and applications. Essential roles were played by Kenneth Arrow, whose influential 1963 article on markets for medical care and insurance recognized these ingredients as intrinsic to the problem of organizing such markets, and Leonid Hurwicz, whose 1973 article showed the impediments posed by agents' private information and strategic behavior, and the necessity of taking account of them in economic analysis.

Hurwicz formulated the concept of a mechanism for implementing social choices, specified as a procedure that uses messages received from agents to select an outcome. The messages could be reports of privately known preferences or information, and the outcome could be an allocation of goods and/or selection of public projects. He invoked Nash equilibrium as a predictor of agents' strategic behavior, and more generally, emphasized the constraints imposed by incentive

[8] Early on, economists recognized that the apparatus of game theory enabled precise description of "who knows what when" and their available actions. Its solution concepts were problematic, but its descriptive power exceeded the usual tools of microeconomics. The *International Journal of Game Theory* began publication in 1971. By the late 1970s, game theory was widely adopted as a basic tool for modeling and analysis in theoretical microeconomics.

[9] In economics, the roles of private information and imperfect observability of actions (hidden information and hidden actions in Arrow's phrasing) were suddenly on display in Akerlof (1970) on markets for "lemons" and Mirrlees (1971) on optimal taxation, and somewhat later in Spence (1973) on signaling in labor markets, Rothschild and Stiglitz (1976) on insurance markets with adverse selection, and Mirrlees (1979) and Holmstrom (1977) on optimal contracting. All posited simple behavior on one side of the market and studied optimal strategies of the other side, a style that came to characterize information economics.

compatibility as key to unifying classical and game-theoretic analyses. Familiar market institutions, such as auctions and exchanges, provided abundant examples of mechanisms. Moreover, his perspective encompassed descriptions of existing mechanisms (and perhaps understanding why market designs of ancient vintage work well in many contexts), and designing efficiency-improving modifications—the genesis of market design.

After 1976, it was well-established that game theory offered potentially useful models and analytical tools for studies of strategic behavior, especially in contexts with imperfect observability of agents' information and actions. Its impact was initially in industrial organization, where game-theoretic results rebutted some earlier conclusions; in labor, where it offered richer theories of contracting; and in experimental and empirical studies, where detailed structural models supplanted reduced-form regressions. Its use grew steadily until it was widely taught to PhD students in economics (who needed such skills to read proliferating journal articles that relied on it), the arrival of excellent texts for economists, and a surge of young scholars who invoked strategic analysis in their research.

Roth: Cooperative games were studied in "coalitional form" models that specified what each coalition of players could achieve on its own. The most tractable model was the "characteristic function with transferable utility" (or "with side payments"), which modeled a game among a set $N = \{1, \ldots, n\}$ of players by specifying what numerical payoffs each coalition—that is, each subset S of N—could assure for its members. The assumption of "transferable utility" meant that each coalition was able to distribute the maximum sum of payoffs that it could achieve in any way that it wished among its members. Hence a game could be represented by a vector of real numbers, one for each coalition. The "characteristic function form" of a game was a function v on the subsets of N, that is, a pair (v, N) with $v: 2^N \to R_+$ representing how much each coalition could achieve on its own. Outcomes of the game could then be represented as payoff vectors, one to each player in the game.

Von Neumann and Morgenstern (1944) defined how one payoff vector y could dominate another payoff vector x via a coalition S, if the coalition S, acting on its own, could guarantee each member i of S a payoff y_i greater than the corresponding payoff x_i at the outcome x. They defined a "solution" of the game to be a set of feasible payoff vectors of the game, none of which dominated another element in the solution, but at least one of whose elements dominated any element outside of the solution. It was easy to construct games with a multiplicity of solutions, but they conjectured that there would exist no game (v, N) for which no solution existed. This conjecture was eventually disproved (Lucas 1969), but even before that, von Neumann–Morgenstern solutions had not proved to be useful in understanding many games, and fell from use in economics.[10]

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[10] They didn't fall from use entirely, however, before I wrote my PhD dissertation on generalizations of von Neumann–Morgenstern solutions that had better existence properties (Roth 1975, 1976). Much progress in game theory was made by exploring and identifying dead ends.

However, their idea of domination proved quite useful, in coalitional games of all sorts and not just of the form (v, N), and particular attention started to be paid to the set of undominated outcomes of a game, named the core of the game. The core could gracefully be generalized to games without side payments, in which the set of outcomes that each coalition could guarantee to its members might have to be described by a set that could not be summarized by a single number.[11]

In either case, it is sometimes useful to think of the core as the set of outcomes for which no "blocking coalitions" can form and produce an outcome that its members prefer. In some of the applications to labor markets, we focus on small blocking coalitions, consisting of just a single firm and worker, who, if not matched to each other when they would prefer to be, can form a "blocking pair." Matchings of firms to workers that have no blocking pairs are called pairwise stable matchings, and in some simple models these coincide with the core (and of course core outcomes have no blocking pairs, since they have no blocking coalitions of any size). Even in applications in which the set of stable matchings is bigger than the core, it is often the subset of outcomes of the most interest, because it is easier for small blocking coalitions to form than it is for large ones. I'll come back to this when speaking of the clearinghouse through which American doctors find their first jobs.[12]

Models of games without side payments, which also had a long history, gradually replaced games with side payments as the primary models for particular kinds of cooperative games. For example, exchange economies were modeled as having each player endowed with a vector of continuously divisible commodities, and coalitions of players were able to trade freely among themselves. This was a model without side payments, in that the set of outcomes a coalition could achieve on its own couldn't be described by a single number but was rather the set of allocations to members of the coalition that could be reached by trade within the coalition.

Although the core is empty for many games, it is non-empty for these exchange economies since the core contains the competitive allocations. This reinforces the idea that, when it is non-empty, the core can be interpreted as a model of the outcomes that would result from perfect competition. This idea is reinforced by

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[11] A lot of creative effort went into generalizing the core in ways that would give a non-empty set for all games (v, N), such as the bargaining set (Aumann and Maschler 1964) and the kernel and nucleolus (Maschler 1992). A very different solution concept was the Shapley (1953) value, also well defined as a unique outcome of any game (v, N), which was meant to capture something like the expected utility of playing the game, in each of its positions (see Roth 1988 for a collection of articles on the Shapley value collected in honor of Shapley's 65th birthday). Despite heroic attempts, the generalizations of the bargaining set and Shapley value never caught on. Regarding the Shapley (1969) value for games without transferable utility, see my exchange with Aumann in Roth (1980, 1986) and Aumann (1985, 1986), all of which are reprinted in Aumann (2000) along with some other closely related papers.

[12] The term "blocking coalition" has become standard, despite the fact that it may not be the term that best expresses the manner in which these coalitions make outcomes outside of the core less likely. Shapley (1973) suggested that they be called "improving" coalitions, so that the core could be defined as the set of outcomes upon which no coalition can improve.

the observation that if the economy grows large in appropriate ways, then the core shrinks to become precisely the set of competitive allocations.

Models of cooperative games without side payments that became very important in my own work were the two-sided marriage model of Gale and Shapley (1962), in which individuals on opposite sides of the market could match to one another if they both agreed, and the exchange economy with indivisible goods of Shapley and Scarf (1974). Both papers demonstrated algorithms that, for any specification of the players' preferences, would produce an outcome (a matching of pairs, or a redistribution of initial endowments, respectively) in the core of the game. In this way, both papers showed constructively that, for any preferences, the core of the game was non-empty. (Gale and Shapley concentrated primarily on a model in which the core and the set of pairwise stable outcomes coincide.)

Despite the development of some important models and results, cooperative game theory was in decline by the late '70s, as more game theorists took the point of view that came to be called the "Nash program," which is that all games could be modeled strategically. The idea was that if binding agreements were possible, then how they were reached should be modeled in the extensive form, so that all games could/should be modeled strategically, as noncooperative games.[13] Of course, to model and analyze complex games is difficult, so one consequence of this approach was that games studied by game theorists would have strategy sets that could be generated by a small set of rules.

What Was Missing That Was Needed for Practical Market Design?

Wilson: For market design to reach practice, the missing ingredients were theoretical and experimental studies that gave some confidence to predictions about how design features affect performance. Early applications were partly guesswork, but with accumulated experience and an increasing trove of scholarly studies, fewer informed guesses are needed. Game theory has been the principal analytical tool because it enables detailed modeling of agents' information, incentives, and feasible strategies and provides predictions about equilibrium behavior and outcomes. Theoretical and experimental exercises rely on simplistic models but they clarify and test the basic concepts applied in practical work where invariably the situation is more complicated than can be modeled precisely.

Designs of auctions and matching markets evolved from the disparate branches of noncooperative and cooperative game theory. Agents' private information is the main consideration in auctions, and designs focus on procedures that elicit demands and yield good outcomes. The goal is to implement Walras and Hayek using Hurwicz's scheme. This is straightforward when bidders simply know their own private values for items, but more complicated when their information includes

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[13]For example, the important *Game Theory* textbook of Fudenberg and Tirole (1991) contained no mention of the core, or of any other solution concepts from cooperative game theory.

estimates of unobserved factors that ex post will affect all their realized values (for example, in an auction of spectrum licenses, customers' ultimate demands for uses of spectrum), and then multiple rounds of bidding can enhance implicit revelation of bidders' estimates via their bids. Auction designs often take the set of bidders as a datum, but as Al describes below, a matching market presents the more formidable challenge of yielding an outcome so good it attracts participants.

Roth: A big missing part of cooperative game theory involved how some features of the game that could be expected to be private information, such as the preferences of the players, would become known. This concern actually fit in well with the Nash program of modeling games strategically: for example, if we asked participants in a game to reveal their preferences, then their strategies would include stating preferences different from their true preferences. Under what circumstances would a "revelation game" of this sort elicit the information we might wish to know?

Wilson: Hurwicz (1973) considered such revelation games and argued, using the example of an Edgeworth box, that they could not be viable unless "incentive compatibility" constraints were imposed on the mechanism.

Roth: A big missing part of noncooperative game theory was how we would know if a game produced "bad" outcomes that some participants might wish to circumvent by engaging in a larger game that might not be fully visible to the theorist. When I started to study labor markets, I saw that firms and workers had very large strategy sets that allowed them to approach each other in many ways, and at many times. For example, when professional organizations tried to organize job markets for new doctors, or new lawyers, they specified rules of engagement between applicants and employers, but for many years these rules didn't succeed in organizing those markets because there were incentives for applicants and employers to find creative ways to work around them, often reaching agreements well before the markets were officially supposed to begin (Roth and Xing 1994). Analyzing those markets under the assumption that everyone played by "the rules" would have yielded different outcomes than were observed, and indeed many observed outcomes in labor markets involved strategies that were either not imagined or explicitly forbidden under the official rules.

Mechanism design was in the spirit of studying fully known games—a game would be designed, in all its parts, that would specify all possible strategies, so the players would have no options outside of the game (except perhaps, not playing at all). That worked well when the designer could make players play the game: for example, a company or government that wanted to sell or buy something and could define the rules of the auction which those who wanted to transact must participate in.[14] But

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[14] Even in these cases, Klemperer (2004) for example emphasizes that governments' auctions of spectrum licenses or Treasury bonds may allow strategies outside the formal rules, such as pre-auction mergers of firms to reduce competition in auctions, and trades in post-auction secondary markets.

lots of markets don't have this kind of compulsory power and must persuade users to participate.

What cooperative game theory ideas like the core allow us to do is to see whether the equilibrium of a game played by the rules of a particular marketplace is an outcome in the core of the larger game in which coalitions can find ways to act on their own outside of the marketplace we are modeling strategically. If the equilibrium outcome of the strategic model is not in the core of the coalitional model, then there are some coalitions (for example, of firms and workers) who might have incentives to try to get a better outcome. Even if we don't know all the strategies available to them, that's a clue that the rules may be subject to attack and evasion by the dissatisfied parties. I'll say more about the complementary roles played by "noncooperative" and "cooperative" models of the same economic environment as I talk about the clearinghouse designs that were ultimately successful in organizing the market for new doctors, and the periodic market failures that continue to afflict the market for new lawyers.[15]

This is why market designers started to ask whether the equilibrium behavior elicited by particular rules led to outcomes that were in the core of the game. The idea is that trying to promote rules that lead to outcomes outside the core—that is, outcomes that leave some coalitions getting less than they might be able to get by acting on their own—might give potential marketplace participants incentives to transact outside the marketplace. The core and related formulations of stability give us a way of saying something about the fact that participants have strategies outside of the marketplace, and that successful marketplaces will be those that don't give participants reason to go elsewhere.

The big lesson of market design is that marketplaces are small institutions in a big economic environment: participants have bigger strategy sets than you can see, and there are lots of players, not all of whom may even be active participants in the marketplace, but can influence it. So we needed a way to design mechanisms that had both good equilibrium properties for the rules we knew about, and good stability properties for the strategies we didn't know about.

Thus, the connection between coalitional and strategic models as they can be used in market design is not as models of different kinds of games, but as models of a given game at different levels of detail, used for complementary purposes. For parts of the game that we're designing, we use "noncooperative" strategic models to precisely specify actions available to players. For parts of the game that we don't have complete control over, we use "cooperative" coalitional models to tell us something about the incentives that agents and coalitions of agents may have to circumvent the rules. The idea of focusing on, say, pairwise stability in two-sided matching models

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[15] In Roth (1991a), I wrote of the separation of cooperative and noncooperative game theory, saying that the less-detailed cooperative models, which try to represent a game without specifying all the rules, aspire to a spurious generality (because the omitted details matter), while the noncooperative, strategic models, which are analyzed as if they represented all the potential moves in a game, offer a spurious specificity when the game in question is a model of some observable situation (because we can seldom know all the potential moves).

is that if a pair of agents is eager to match with each other despite the fact that the rules of the marketplace mechanism prevent them from doing so, then maybe their strategy sets will be big enough to find a way to match with each other. (But if just one of them is interested in matching with the other, it may be difficult for the unhappy player to find a way to circumvent the marketplace and force a match with an unenthusiastic partner.)

For example, in the job market for new doctors, before a centralized clearinghouse was adopted, and in some of the markets for new lawyers still, candidates are often hired years before employment will begin, and before the official rules of the market allowed hiring to begin (Roth 1984; Roth and Xing 1994; Avery, Jolls, Posner, and Roth 2001, 2007). That is, firms and workers who were dissatisfied with the way the official marketplace functioned were able to circumvent it by signing contracts before it opened. This problem was effectively solved for the medical market by a clearinghouse that produces stable matchings (Roth and Peranson 1999).

Wilson: This perspective is analogous to one in the older literature on general equilibrium. A modern view might aim to determine whether a perfectly competitive market is a mechanism yielding an allocation that is efficient, or better yet, in the core. Because a competitive allocation is easily shown to be efficient and in the core, a theorem establishing existence of equilibrium prices and the resulting allocation is, in effect, an affirmative answer when competition is sufficient to justify traders' price-taking behavior in response to prevailing equilibrium prices. Such a theorem typically suppresses all detail about how the market is organized and how prices are established, summarizing it all in traders' budget constraints.

Roth: So general equilibrium theory shares with cooperative game theory the goal of identifying likely outcomes without focusing on all the details of how they are achieved.

Wilson: The focus on properties of the allocation began with Edgeworth's (1881) informal argument that the core shrinks to the competitive allocations as the market becomes more competitive (by replicating traders), established formally by Debreu and Scarf (1963), and culminated in Aumann's (1964) proof that the core consists only of the competitive allocations when the set of traders is a non-atomic measure space (so that no trader is large enough to have market power). These results led to the modern view that an ideal price-mediated perfectly competitive market might indeed be a mechanism largely immune to institutional details that yields a core allocation, but realistically the challenge in practice remains to design a mechanism that yields a core allocation. The focus on the core, and coalition stability more generally, stems from the prediction that the mechanism will miss some gains from trade if other opportunities attract away some potential participants. The design problem is most acute in those matching markets without transfer payments, but it is relevant whenever the mechanism's performance depends on attracting wide participation. Many of the most successful auction designs addressed contexts where

participation was mandated by a monopolist seller, such as government auctions of spectrum licenses or a system operator's auctions of access to power transmission, but attracting wide participation is paramount in newer applications such as the design of trading platforms that operate in competition with other venues.

Roth: Another way in which market design involves a bigger economic environment than a narrowly defined mechanism design problem is that it may have to take account of players who are not intended to be, and who do not intend to be, participants in the market. In particular, some transactions, and the markets that serve them, are "repugnant" in the sense that some people would like to participate in them, while other people (who may not have any apparent connection to these transactions) think that they shouldn't be allowed (Roth 2007). But successful markets require a degree of social support, so these concerns need to be taken into account if a marketplace is to succeed. Widely held feelings of repugnance often make it necessary for a market designer to study and understand the moral, ethical, and esthetic opinions of members of the society in which the market might function, as well as their professional and social codes of conduct and courtesy.

Much of my work in facilitating kidney transplants through the design of exchange mechanisms can be viewed as arising from the widespread repugnance to, and laws against, the purchase of organs for transplants.[16] And some of my current work on expanding kidney exchange internationally, while gaining gratifying support in some quarters, is also meeting with a repugnance reaction in others, including concerns that it might expand black markets in poor countries.[17]

Note that it is also a market design task to think about how and whether particular kinds of markets can be effectively banned, since laws seeking to ban markets often inadvertently serve to design illegal black markets. Like other kinds of marketplace designs, legal bans on markets also occupy a place in a larger economic environment, and may be difficult to effectively enforce without wide social support, or if the markets in question are available in other jurisdictions. Markets and marketplaces that are legal in some places but banned in others include markets for prostitution, surrogacy, marijuana, etc.

Finally, in addition to requiring an expanded view of what strategies players may have access to, and which players may be involved, market design also has to take into account that players may fail to coordinate on equilibrium behavior. In this regard, experiments have played an important role in exploring the gap between what perfectly rational players might deduce, and what ordinarily competent

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[16] For examples, see Roth, Sönmez, and Ünver (2004, 2005a, b), Roth, Sönmez, Ünver, Delmonico, and Saidman (2006), Rees et al. (2009), Leider and Roth (2010), and Ashlagi, Gilchrist, Roth, and Rees (2011a, b). Notice that this selection of papers is drawn equally from analyses appearing in economics journals and in medical journals, which reveals something about how practical market designs are developed.

[17] Rees, Dunn et al. (2017) offer a new proposal to expand kidney exchange internationally, Delmonico and Ascher (2017) express opposition, and Rees, Paloyo et al. (2017) and Roth et al. (2017) reply.

humans might find difficult,[18] particularly in the absence of common knowledge that all players were perfectly rational (see Roth 2016 on experiments specifically aimed at market design).

Why Were Auctions and Two-Sided Matching Markets Such Fertile Ground for Market Design? How and Why Did Auction Design Proceed Differently from the Design of Matching Markets?

Wilson: Centralized auctions and matching markets were fertile grounds for market design due to coincidence of several features. The key design element specifies rules of a game. The contexts are often sufficiently circumscribed that, if the design yields efficient (or better, core) outcomes, then one can expect agents to play that game rather than some larger game with myriad other possibilities. And the contexts usually justify assumptions of rational optimizing behavior rather than various behavioral possibilities. Moreover, the game is sufficiently simple that it can, to a limited extent, be modeled and analyzed, or in any case rough predictions of performance can be based on applications of basic concepts, simulations, experimental evidence, and prior experience.

This simplicity accounts also for the profusion in academic journals of scholarly studies of these kinds of markets, including theoretical, experimental, and empirical studies. But the methodologies employed for studies of auction and matching markets differ.

Auction studies usually rely on preferences represented as expectations of net monetary values, the mechanism translates static or dynamically adjusted bids into an allocation, the objective is an equilibrium allocation that is efficient or revenue maximizing for the seller, and beyond that objective, the design task often focuses on rules that suppress "gaming the system." Except in Vickrey auctions, there is no attempt to elicit agents' true preferences; instead, one elicits a willingness-to-pay that already "shades" the bid to exploit monopoly power derived from small numbers of bidders and their private information, often called informational rents. Efficiency is hard to assure in cases, like spectrum auctions, where agents want to acquire packages of complementary goods, so designs aim for approximate efficiency. Ex post efficiency is the actual goal, but this is tenuous due to agents' private information or estimates about common-value components.[19]

In contrast, studies of prominent matching markets rely on ordinal preferences solely about one's assigned partner(s), the mechanism translates directly reported preferences into recommended assignments, and the objective is a core

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[18] See, for example, Roth and Erev (1995) for discussion of games in which players learn quickly to play equilibrium and others (such as the ultimatum game) in which learning may be very slow, and see Li (2017) for discussions of how strategy-proof mechanisms may not be transparent to participants.

[19] The modern state-of-the-art in auction design is presented superbly in the two books by Milgrom (2014, 2017).

allocation. This stronger criterion discourages matches outside the mechanism (as Al described above), and in simple cases, such as a "marriage market," a core allocation based on reported preferences is obtained via Gale and Shapley's deferred acceptance algorithm, or Shapley and Scarf's (1974) top trading cycles. Moreover, truthful reporting is a dominant strategy for the proposing side (Dubins and Friedman 1981; Roth 1982), so only the other side might gain from other strategies.

Roth: "Design" is a noun as well as a verb, and market design has its origins in the noun, in the study of the designs of existing marketplaces, and how different designs—different marketplace institutions, rules, and customs—can induce different strategies and produce different outcomes. Centralized marketplaces are a good place to start the study of market designs, because, by virtue of being centralized, a significant portion of their design may reside in well-codified rules and procedures that are easy to observe. For the same reason, when it becomes necessary to design new rules and procedures, the work involved in designing centralized marketplaces can have a very mechanism-design "look and feel," with well-defined kinds of messages communicated and processed in precisely specified ways that offer a concrete path to implementation in practice.

Auctions are centralized marketplaces in which the messages are bids, and the auction rules determine the form that bids take, how they are communicated, and how they determine the resulting payments and allocation of the items being auctioned. Because auctions are ancient tools of demand elicitation, practical knowledge about auctions began to be developed fairly early and game theory allowed auction theory to be formalized and extended as one of the early successes of the theory of mechanism design (for example, Vickrey 1961; Milgrom and Weber 1982). The view that auction rules can be designed was enhanced by Cassidy's (1967) survey of the vast variety of auctions used in practice, with differing incentives and performance.

In addition, if the goods being sold are available only from a single seller, then an auction satisfies the implicit assumption of mechanism design theory that purchasers must participate in the auction if they wish to buy. (For example, oil drilling or timber cutting licenses sold by the Department of the Interior, spectrum licenses sold by the Federal Communications Commission, and advertisements sold by Google connected to searches on their search engine are each sold by a single seller.) Thus, at least to a first approximation, the strategies that the auction designer makes available are the strategies that the bidders must use, and (some appropriate refinement of) strategic equilibrium among those strategies may be a good guide to designing the market and predicting the outcome.

Wilson: Of course, the seller should also abide by the rules, or have an incentive to do so to the extent observable by bidders. This criterion is implied by the definition of a credible mechanism proposed by Akbarpour and Li (2018); for an historical application, see Engelbrecht-Wiggans (1988).

Mechanism design theory usually imposes an "individual rationality" constraint that no agent is worse off from participating, but this constraint is very weak compared to the stronger requirement that agents prefer the centralized market to contracting outside the market, which is achieved by a mechanism yielding a core allocation. Electricity markets suggest another paradigm: actual energy flows must be determined by bids in the transmission operator's centralized market, but participants often contract bilaterally via long-term contracts or buy financial hedges pegged to the operator's real-time prices for energy and transmission. Decentralized hedging markets ameliorate price volatility in the operator's market, and each relies on the other to function well.

Roth: In contrast to auctions, labor markets, kidney transplants, and other matching markets start off very decentralized. Labor markets have many applicants and employers, and kidney transplants in the US are performed at hundreds of hospitals, each with considerable autonomy. So rather than being able to design a marketplace that all participants must use, the design of marketplaces for many matching markets involves finding designs that will entice users to try them, and satisfy them well enough that they will accept the outcomes and continue to come back to the marketplace. But when these designs lead to centralized clearinghouses, the marketplace itself nevertheless has considerable mechanism design flavor (as a stand-alone game) when one concentrates on the options available to participants within the marketplace. So these marketplaces were also a good starting point for market design.

The American marketplace for new doctors, the National Resident Matching Program, developed such a clearinghouse in the early 1950s in response to widespread market failures of the various decentralized market designs that had been employed in the first half of the 20th century. When I studied it in Roth (1984), I found that, by a process involving more than a little trial and error, the market had become organized since 1952 by a centralized clearinghouse in which candidates and employers submitted rank order lists of one another, and a centralized algorithm produced a suggested match. The algorithm that had been settled on turned out to be essentially equivalent to the hospital-proposing deferred acceptance algorithm studied a decade later by Gale and Shapley (1962). So on the one hand, this was a "mechanism" whose design could be studied, but on the other hand, one question that had to be answered was why this design had been enticing enough to attract the lion's share of the market. This was a pressing question when the marketplace needed to be redesigned in the mid-1990s. A critical fact, discovered by comparing successful and unsuccessful clearinghouses (Roth 1991b) and by experimentation (Kagel and Roth 2000), was that the stability of the resulting outcome was an important factor in its success. This was a clear example of the complementary uses of strategic and coalitional models in understanding the success of a marketplace.

Note how this reflects how game-theoretic ideas about the core and stable matchings have evolved as they have been confronted by the realities of market design. When we used to think of a game as a whole world, we often thought of the

core as a model of what players would coordinate on, based on complete information about the game. So if players didn't know each other's preferences, blocking coalitions would be difficult to identify, and the core (that is, the set of outcomes for which there aren't any blocking coalitions) might not have much predictive power. But in a labor clearinghouse like the medical match, no one knows everyone else's preferences: it's a game of massively incomplete information. Yet, empirically, matching algorithms that produce unstable outcomes fail. Because the clearinghouse is part of a larger economic environment, it's no mystery how this can happen. If I am matched to my third-choice residency program, I only have to make two phone calls to find out if I am part of a blocking pair—that is, if one of the residency programs I prefer might also prefer me to one of the doctors it has been matched with. If in previous years many matches were found that way, then this year people will make those phone calls too, and the clearinghouse will fail to organize the market because residency programs and individual doctors will make deals on their own, and not accept those produced by the clearinghouse. But a stable matching algorithm will be robust to phone calls, since there aren't any blocking pairs to find. Those phone calls aren't part of the description of the clearinghouse, they are part of the larger economic environment in which the clearinghouse is just a small marketplace.

In contrast to the market for new doctors, the market for judicial clerks uses rules that have been regularly designed and subsequently abandoned by judges themselves, and have yet to find a market design that entices judges to participate according to the rules (Avery et al. 2001, 2007, and my blog post at https://marketdesigner.blogspot.com/search/label/clerks).

Wilson: I was fascinated by the Roth and Xing (1994) article describing many markets that work imperfectly because they fail to deter contracting outside the market including prior contracting (to snag a good partner before others do), as well as backup plans to try again in a decentralized aftermarket among those not satisfied by the recommended assignment.

A novel feature of some matching markets is assignments recommended to agents, rather than binding contracts, and most agents voluntarily accept their recommended matches: the deferred acceptance algorithm assures that no two agents prefer each other to their assigned partners. Some simple auctions have this property, and there are designs that aim for it, but generally the prevalence of private information precludes assurance of a core allocation based on revealed preferences and information.[20] Government agencies typically use auctions designed to

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[20] Day and Milgrom (2008) derive key properties of a core-selecting auction when one exists, and relate this to the stable matching literature. Kelso and Crawford (1982) consider an auction that closely resembles the deferred acceptance algorithm, in a labor market context in which the auction chooses both a matching and the associated market-clearing doubly personalized wages (that is, wages for each firm-worker pair).

yield an efficient allocation, but alternative designs forego efficiency to maximize the seller's expected revenue.

Roth: How about in electricity markets?

Wilson: Just as you said before, participants in electricity markets have big strategy sets, and there are interested parties who aren't participants in the market. Firms can bid in the spectrum auctions of the Federal Communications Commission, buy licenses in secondary markets (if the FCC approves the transfer), or rent spectrum from those with licenses. In wholesale electricity markets, firms must bid in the system operator's daily and hourly energy auctions to get power scheduled for transmission, and the operator also runs various auxiliary auction markets for transmission rights (which hedge transmission charges) and reserves of capacity available in various time frames. But these are minor parts of the overall market because most power is contracted long term. A typical bilateral contract for delivery has an agreed price, and the parties settle the difference between their price and the operator's price.

There are also financial markets for financial instruments that hedge against volatility of the operator's prices. On the supply side there are further markets for fuel, especially long-term contracts for natural gas that ensure priority when supplies are tight. And on the demand side there are markets for demand reduction by firms who can curtail or interrupt power usage when prices are high.

Thus, no one of these auctions is isolated; rather, each operates within a loosely coordinated system of related markets. This system need not yield an outcome in the core like in a matching market because no analog of the deferred acceptance algorithm has been found, so it relies on competitive pressures to ensure efficient outcomes—and part of the design task is to promote vigorous competition. Besides participants, there are other important actors who affect the system design, most importantly the Federal Energy Regulatory Commission that prescribes standards for system operators, each state's public utility commission, which regulates retail distribution (and in some cases appoints the board of the system operator), and federal agencies that regulate commodity trading and financial markets for commodity futures contracts.

Roth: And are aspects of electricity sales repugnant?

Wilson: The repugnance factor can be traced in the history of the restructuring of electricity markets. Some view electricity as a necessary service that is best provided by vertically integrated utilities. Prior to restructuring, this was implemented in each state by tight regulation that set retail service standards and prices and in return provided utilities with an assured rate of return on capital. In most states, this regime dissolved because high prices for retail service were attributed to distorted incentives, resulting in excessive capital intensity manifest in massive power plants, and monopolization of transmission that disadvantaged independent power producers.

After political battles, the industry was restructured by most states requiring utilities to divest their generation assets, and federal requirements for open access to transmission via auction markets conducted by independent system operators. Not all states restructured. But even in those that did, lesser battles continue, represented for example by newly formed municipal or cooperative power distribution companies that opt out of utilities' retail services by buying supplies directly from system operators' markets. Basically, market design for electricity markets aspires to the ideal service that vertically integrated utilities were intended to achieve, but now implemented in an open-access decentralized system with stronger incentives.

How Was Your Work Influenced by Your Teachers, Colleagues, and Students?

Wilson: The interests of my advisor Howard Raiffa had turned to statistical decision theory, but I retained interest in game theory, motivated by a colleague's study of investment banking syndicates formed to bid for corporate bonds. After some early consulting on corporate strategies, my practical work on market design began in consulting with the US Department of Interior's section on oil exploration led by Darius Gaskins. He hired me because he had concluded that game theory was needed to analyze their auctions of licenses. There were aspects of auction design, but I focused mainly on algorithms for bidding strategies based on models that included adverse selection—aka "the winner's curse"—and methods for ex post analyses of auction performance. This was also a focus in the late 1970s of my consulting with oil companies, especially with George Harwell at Natomas, but in these cases my primary job was to help them understand the effects of adverse selection. I learned a lot from being inside a company, watching how bids were derived by interpreting geological data to obtain (vaguely probabilistic) estimates that were then combined with data about costs and predictions of future oil prices. Equally educational was to hear insistence on finding the minimum bid that would win. Some dismissed adverse selection as hokum, but a few old sages insisted it was real and claimed they had survived in a fiercely competitive industry by using rules of thumb that severely cut engineers' estimates to be on the safe side.

Roth: The adverse selection that Bob is referring to, the "winner's curse," is that when each bidder gets an estimate of how much oil is under the ground at a given site, the bidder who has the highest estimate is very likely to have an overestimate. And the more bidders there are, the bigger the amount of the overestimation. Wilson (1977) introduced the model of common-value auctions (sometimes called the "mineral rights model"). The model and its equilibrium initiated a large body of theoretical, experimental, and applied work. One important insight from this model is that winning an auction contains "bad" news, since it implies in equilibrium that the winner's estimate is the highest. In equilibrium, rational bidders fully account for this, but the paper raises the empirical question of the extent to which actual

bidders are able to fully discount for the fact that, if they win the auction, they likely overestimated the value of winning. Thus, Wilson's work initiated a new research program on the winner's curse, involving systematic overbidding compared to equilibrium, sometimes involving losses to the winning bidder.[21] The private-value model of Vickrey (1961) and the common-value model of Wilson (1977) together form the basis of much of modern auction theory and practice, since most auctions have elements of both private and common value.

Wilson: Another formative experience was at the Electric Power Research Institute in a section led by Steven Peck and Hung-po Chao, working with them and my co-consultant Shmuel Oren. It focused initially on innovative contracts for utilities' retail services, but over the ensuing 40 years its scope expanded to include all the issues posed by fundamental restructuring of the industry, and most relevant here, the design of centralized markets for energy, transmission, and reserves.

I was deeply affected in the early 1990s by working with Paul Milgrom on design of the FCC spectrum auctions. I marveled at his insights and creativity in constructing rules for a "simultaneous ascending auction" that would have good prospects of yielding an approximately efficient outcome in an environment afflicted with strong complementarities, dispersed private information about market fundamentals, and substantial market power. And we were greatly influenced by Evan Kwerel, who was the main protagonist at the FCC seeking innovative auction designs for allocating spectrum licenses.

Roth: I was also much influenced by Paul when we developed and co-taught what may have been the first courses in market design, in 2000 and again in 2001 when he was on leave at Harvard and MIT.

Wilson: The strongest influences on my work in game theory came from Robert Aumann's articles and lectures, and later, collaborations with David Kreps and Srihari Govindan. Even after I pursued market design, I continued my interest in foundations, seeking the full implications of rationality in multiperson interactions. I was also deeply influenced by superb PhD students, of which some directly affected my work in game theory and ultimately market design. Before 1980 they included Armando Ortega-Reichert, Robert Rosenthal, Alvin Roth, Jean-Pierre Ponssard, Claude d'Aspremont, Paul Milgrom, and Bengt Holmstrom. Later, the chief influence was Peter Cramton.

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[21] In an early use of experimental economics to elucidate this issue, Bob invented the now famous "jar of coins" experiment, in which the value of the coins in a jar is auctioned off to the highest bidder. If every bidder forms his own estimate of the value of the coins (for example, of how many coins are in the jar), then the high bidder almost invariably has an overestimate, and, failing to account for this, bids more than the jar is worth. Used as a demonstration, this helps convince skeptics that the winners' curse is real (for a fuller account, see Roth 2016).

Roth: I would have had a very brief academic career if not rescued by Bob after flunking my qualifying exams. As I've learned also from my students, the teacher–student relationship can be one of life's big ones, although less appreciated than the other big relationships.[22] I've learned from (and designed with) students, postdocs, research fellows, and colleagues, some of whom fall in more than one category (and who I refrain from enumerating here only because the list has such ill-defined boundaries and includes so many of my students and coauthors that I would inevitably err by omission). I've also profited enormously from collaborating with practitioners. I think that virtually all of the market designs I've been involved in that were adopted and successfully implemented benefited from collaboration with someone involved in the market who became the champion of the new design.

How Have Other Domains of Market Design Developed?

Roth: I'd like to highlight two other domains I think foreshadow further ways market design is developing into a robust part of economics. The first is the design of school choice systems, which in its origins closely resembles the stable matching deployed in the clearinghouse marketplaces for doctors (Abdulkadiroğlu and Sönmez 2003; Abdulkadiroğlu, Pathak, and Roth 2005, 2009; Abdulkadiroğlu, Pathak, Roth, and Sönmez 2005). School choice has now opened a new window for the empirical study of schools, as econometric tools take advantage of the particular elements of the market design to measure not only the effects of the new designs on how students are assigned to schools, but also the importance to students of being well matched to a school (for example, Abdulkadiroğlu, Agarwal, and Pathak 2017; Abdulkadiroğlu, Angrist, Narita, and Pathak 2017; Agarwal and Somaini 2018).[23] I think of this as a kind of third generation of market design, since those of us initially involved in design were game theorists, who of necessity became engineers to help new designs be implemented and maintained, and we are now seeing those designs and their outcomes subjected to, and enabling, sophisticated empirical scrutiny by applied economists able to develop new econometric tools informed by the details of the markets' designs.

Another area of market design involves decentralized markets. Most markets are decentralized at least to some degree, and many almost entirely. Even markets

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[22] A brief account of our subsequent teacher–student interactions, along with some other remembrances related to the present essay, is included in my intellectual autobiography at the Nobel Prize website: https://www.nobelprize.org/prizes/economics/2012/roth/auto-biography/. The rabbinic literature does not overlook teacher–student relations. In the Talmud, for example, one is enjoined: "Provide for yourself a teacher and get yourself a friend …" See my related blog post for more on this: https://marketdesigner.blogspot.com/2013/06/notes-on-teachers-and-students-from.html. The martial arts also value teacher–student relations, and I benefited from that too, as I describe at https://marketdesigner.blogspot.com/2013/06/honorary-7th-dan-black-belt-in-jka.html.

[23] Agarwal (2015) similarly uses econometric tools that leverage the stable matchings arising from the resident match to do a demand analysis of the market for different residency programs.

that employ centralized marketplaces may be preceded or followed by decentralized interaction. For example, the market for new academic economists has a somewhat centralized marketplace for interviews, preceded by decentralized applications and followed by decentralized campus visits, offers, acceptances, and rejections.[24]

Designers who wish to introduce more centralized marketplaces into existing markets need to understand how this will interact with pre-existing decentralized markets. In this respect, changing the presumptions about how (decentralized) offers were made, and until when they should remain open, helped pave the way for a centralized clearinghouse for gastroenterologists to become successful (Niederle and Roth 2003, 2009; Niederle, Proctor, and Roth 2006, 2008; McKinney, Niederle, and Roth 2005). PhD programs similarly are expected to leave offers of admission open until April 15 (Roth and Xing 1994). Design in decentralized markets may involve helping to form expectations and customs to promote and to guide decentralized transactions among market participants, rather than crafting precise rules and algorithms that can be rendered in computer code.

Wilson: A remarkable application is the conversion in the United States of spectrum from television broadcast to smartphones (Leyton-Brown, Milgrom, and Segal 2017). Ultimately this was done by one auction that bought spectrum from broadcasters and another that re-sold it to phone companies. The major complication was development of algorithms to reassign retained broadcast rights to new spectrum so as to avoid electromagnetic interference among broadcasting stations.

What's Next for Game Theory and Market Design?

Wilson: The ongoing computerization of marketplaces will continue to make market design a multidisciplinary endeavor, which already occupies computer scientists as well as economists.[25] And economic engineering more broadly—"design economics"—will likely continue to grow in its ability to help structure contracts, firms, and organizations and collaborations of all sorts.

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[24] There have been some modest further efforts to aid coordination through centralized signaling before interviews and a scramble afterwards (Coles, Cawley, Levine, Niederle, Roth, and Siegfried 2010).

[25] For examples of some collaborations between economics and computer science, see Anderson, Ashlagi, Gamarnik, and Roth (2015) and Leyton-Brown, Milgrom, and Segal (2017). As computer and communication technologies increase the proportion of transactions conducted over highly automated and tightly coordinated platforms, we foresee the design of these platforms as a major area for market design involving joint efforts among economists, computer scientists, and software engineers relying on developments in "algorithmic game theory." Already, parameters of some markets are adjusted automatically by machine learning algorithms, and we are entering a time when market participants themselves may be designed—to some extent this has already happened in the realm of high-speed algorithmic trading of securities (as discussed in Budish, Cramton, and Shim 2015).

Roth: Smartphones have put marketplaces in our pockets, and as computerized marketplaces become ever more ubiquitous, we will also generate data trails that will continue to extend the reach of markets, socially and personally. We will learn more about privacy and fairness, and there will be new opportunities, some of which will come to be seen as repugnant, for which new market mechanisms, rules, customs, and regulations will have to be designed.

What's Your Last Word for Now?

Wilson: We've learned that maximizing gains from trade is more about participants' information and incentives than intersecting demand and supply curves. So concepts from game theory have been useful guides in efforts to improve the performance of trading platforms. But scholarly theorizing is minor compared to hands-on engineering using knowledge of an industry's technology and practices, and familiarity with participants' concerns is necessary if one is to help them obtain better outcomes overall. Deep involvement discovers key features unanticipated by abstract views of markets. I foresee more economists improving the allocation of scarce resources rather than (just) studying it.

Roth: Market design is an outward-facing part of economics, so designers have to be good listeners, prepared to learn from everyone. And learning from markets and their participants is a great driver of economic theory. One of my favorite quotes from Wilson (1993) is "for the theorist, the problems encountered by practitioners provide a wealth of topics."

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References

Abdulkadiroğlu, Atila, Nikhil Agarwal, and Parag A. Pathak. 2017. "The Welfare Effects of Coordinated Assignment: Evidence from the New York City High School Match." *American Economic Review* 107(12): 3635–89.

Abdulkadiroğlu, Atila, Joshua D. Angrist, Yusuke Narita, Parag A. Pathak. 2017. "Research Design Meets Market Design: Using Centralized Assignment for Impact Evaluation." *Econometrica* 85(5): 1373–1432.

Abdulkadiroğlu, Atila, Parag A. Pathak, and Alvin E. Roth. 2005. "The New York City High School Match." *American Economic Review* 95(2): 364–67.

Abdulkadiroğlu, Atila, Parag A. Pathak, and Alvin E. Roth. 2009. "Strategy-Proofness versus Efficiency in Matching with Indifferences: Redesigning the NYC High School Match." *American Economic Review* 99(5): 1954–78.

Abdulkadiroğlu, Atila, Parag A. Pathak, Alvin E. Roth, and Tayfun Sönmez. 2005. "The Boston Public School Match." *American Economic Review*

95(2): 368–71.

Abdulkadiroğlu, Atila, and Tayfun Sönmez. 2003. "School Choice: A Mechanism Design Approach." *American Economic Review* 93(3): 729–47.

Agarwal, Nikhil. 2015. "An Empirical Model of the Medical Match." *American Economic Review* 105(7): 1939–78.

Agarwal, Nikhil, and Paulo Somaini. 2018. "Demand Analysis Using Strategic Reports: An Application to a School Choice Mechanism." *Econometrica* 86(2): 391–444.

Akbarpour, Mohammed, and Shengwu Li. 2018. "Credible Mechanisms." Stanford University. Available at SSRN: https://ssrn.com/abstract=3033208.

Akerlof, George A. 1970. "The Market for 'Lemons': Quality Uncertainty and the Market Mechanism." *Quarterly Journal of Economics* 84(3): 488–500.

Anderson, Ross, Itai Ashlagi, David Gamarnik, and Alvin E. Roth. 2015. "Finding Long Chains in Kidney Exchange Using the Traveling Salesman Problem." *PNAS* 112(3): 663–68.

Arrow, Kenneth J. 1963. "Uncertainty and the Welfare Economics of Medical Care." *American Economic Review* 53(5): 941–73.

Ashlagi, Itai, Duncan S. Gilchrist, Alvin E. Roth, and Michael A. Rees. 2011a. "Nonsimultaneous Chains and Dominos in Kidney-Paired Donation—Revisited." *American Journal of Transplantation* 11(5): 984–94.

Ashlagi, Itai, Duncan S. Gilchrist, Alvin E. Roth, and Michael A. Rees. 2011b. "NEAD Chains in Transplantation." *American Journal of Transplantation* 11(12): 2780–81.

Aumann, Robert J. 1964. "Markets with a Continuum of Traders." *Econometrica* 32(1–2): 39–50.

Aumann, Robert J. 1976. "Agreeing to Disagree." *Annals of Statistics* 4(6): 1236–39.

Aumann, Robert J. 1985. "On the Non-Transferable Utility Value: A Comment on the Roth–Shafer Examples." *Econometrica* 53(3): 667–78.

Aumann, Robert J. 1986. "On the Non-Transferable Utility Value: Rejoinder." *Econometrica* 54(4): 985–89.

Aumann, Robert J. 2000. *Collected Papers*, vol. 2. Cambridge, MA: MIT Press.

Aumann, Robert J., and Michael Maschler. 1964. "The Bargaining Set for Cooperative Games." Chap. 21 in *Advances in Game Theory*, edited by M. Dresher, L. S. Shapley, and A. W. Tucker. Annals of Mathematics Studies 52. Princeton University Press.

Avery, Christopher, Christine Jolls, Richard A. Posner, and Alvin E. Roth. 2001. "The Market for Federal Judicial Law Clerks." *University of Chicago Law Review* 68(3): 793–902.

Avery, Christopher, Christine Jolls, Richard A. Posner, and Alvin E. Roth. 2007. "The New Market for Federal Judicial Law Clerks." *University of Chicago Law Review* 74(2): 447–86.

Borel, Emile. 1921. "La theorie du jeu et les equations integrales anoyau symmetrique gauche." *Comptes Rendus de l'Academie des Sciences* 173: 1304–08.

Borel, Emile. 1953. "The Theory of Play and Integral Equations with Skew Symmetric Kernels." [Translation by L. J. Savage of Borel (1921)] *Econometrica* 21(1): 97–100.

Budish, Eric, Peter Cramton, and John Shim. 2015. "The High-Frequency Trading Arms Race: Frequent Batch Auctions as a Market Design Response." *Quarterly Journal of Economics* 130(4): 1547–1621.

Cassidy, Ralph, Jr. 1967. *Auctions and Auctioneering.* University of California Press.

Coles, Peter, John Cawley, Phillip B. Levine, Muriel Niederle, Alvin E. Roth, and John J. Siegfried. 2010. "The Job Market for New Economists: A Market Design Perspective." *Journal of Economic Perspectives* 24(4): 187–206.

Copeland, Arthur H. 1945. "Review: John von Neumann and Oskar Morgenstern, Theory of Games and Economic Behavior." *Bulletin of the American Mathematical Society* 51(7): 498–504.

Day, Robert, and Paul Milgrom. 2008. "Core-Selecting Package Auctions." *International Journal of Game Theory* 36(3–4): 393–407.

Debreu, Gerard, and Herbert Scarf. 1963. "A Limit Theorem on the Core of an Economy." *International Economic Review* 4(3): 235–46.

Delmonico, Francis L., and Nancy L. Ascher. 2017. Opposition to Irresponsible Global Kidney Exchange. *American Journal of Transplantation* 17(10): 2745–46.

Dubins, Lester E., and Daniel A. Friedman. 1981. "Machiavelli and the Gale–Shapley Algorithm." *American Mathematical Monthly* 88(7): 485–94.

Edgeworth, Francis Ysidro. 1881. *Mathematical Psychics: An Essay on the Application of Mathematics to the Moral Sciences.*

Engelbrecht-Wiggans, Richard. 1988. "An Example of Auction Design: A Theoretical Basis for 19th Century Modifications to the Port of New York Imported Goods Market." Unpublished paper, University of Illinois.

Fudenberg, Drew, and Jean Tirole. 1991. *Game Theory.* MIT Press.

Gale, David, and Lloyd S. Shapley. 1962. "College Admissions and the Stability of Marriage." *American Mathematical Monthly* 69(1): 9–15.

Govindan, Srihari, and Robert Wilson. 2012.

"Axiomatic Equilibrium Selection for Generic Two-Player Games." *Econometrica* 80(4): 1639–99.

Harsanyi, John C. 1967–68. "Games with Incomplete Information Played by 'Bayesian' Players." Parts I–III. *Management Science*, 14 (3, 5, 7): 159–82, 320–34, 486–502.

Hayek, F. A. 1945. "The Use of Knowledge in Society." *American Economic Review* 35(4): 519–30.

Holmstrom, Bengt. 1977. *On Incentives and Control in Organizations.* PhD dissertation, Stanford University.

Hurwicz, Leonid. 1945. "The Theory of Economic Behavior." *American Economic Review* 35(5): 909–25.

Hurwicz, Leonid. 1973. "The Design of Mechanisms for Resource Allocation." *American Economic Review* 63(2): 1–30.

Kagel, John H., and Alvin E. Roth. 2000. "The Dynamics of Reorganization in Matching Markets: A Laboratory Experiment Motivated by a Natural Experiment." *Quarterly Journal of Economics* 115(1): 201–35.

Karlin, Samuel. 1959. *Mathematical Methods and Theory in Games, Programming, and Economics*, 2 vols. New York: Wiley.

Kelso, Alexander S., and Vincent P. Crawford. 1982. "Job Matching, Coalition Formation, and Gross Substitutes." *Econometrica* 50(6): 1483–1504.

Klemperer, Paul. 2004. *Auctions: Theory and Practice.* Princeton University Press.

Kreps, David M., and Robert Wilson. 1982. "Sequential Equilibria." *Econometrica* 50(4): 863–94.

Kuhn, Harold W. 1950. "Extensive Games." *PNAS* 36(10): 570–76.

Kuhn, Harold W. 1953. "Extensive Games and the Problem of Information." Chap. 11 in *Contributions to the Theory of Games*, vol. 1, edited by Harold W. Kuhn and Albert W. Tucker. Princeton University Press.

Leider, Stephen, and Alvin E. Roth. 2010. "Kidneys for Sale: Who Disapproves, and Why?" *American Journal of Transplantation* 10(5): 1221–27.

Lemke, Carlton E., and J. T. Howson, Jr. 1964. "Equilibrium Points of Bimatrix Games." *Journal of the Society for Industrial and Applied Mathematics* 12(2): 413–23.

Lewis, David. 1969. *Convention: A Philosophical Study.* Cambridge, MA: Harvard University Press.

Leyton-Brown, Kevin, Paul Milgrom, and Ilya Segal. 2017. "Economics and Computer Science of a Radio Spectrum Reallocation." *PNAS* 114(28): 7202–09.

Li, Shengwu. 2017. "Obviously Strategy-Proof Mechanisms." *American Economic Review* 107(11): 3257–87.

Lucas, William F. 1969. "The Proof that a Game May Not Have a Solution." *Transactions of the American Mathematical Society* 137: 219–29.

Luce, R. Duncan, and Howard Raiffa. 1957. *Games and Decisions: Introduction and Critical Survey.* New York: John Wiley and Sons.

Marschak, Jacob. 1946. "Neumann's and Morgenstern's New Approach to Static Economics." *Journal of Political Economy* 54(2): 97–115.

Maschler, Michael. 1992. "The Bargaining Set, Kernel, and Nucleolus." Chap. 18 in *Handbook of Game Theory with Economic Applications,* vol. 1, edited by Robert J. Aumann and Sergiu Hart. Elsevier.

McKinney, C. Nicholas, Muriel Niederle, and Alvin E. Roth. 2005. "The Collapse of a Medical Labor Clearinghouse (and Why Such Failures Are Rare)." *American Economic Review* 95(3): 878–89.

Mertens, Jean-Francois. 1989. "Stable Equilibria—A Reformulation: Part I. Definition and Basic Properties." *Mathematics of Operations Research* 14(4): 575–625.

Milgrom, Paul. 2004. *Putting Auction Theory to Work.* Cambridge, MA: Cambridge University Press.

Milgrom, Paul. 2017. *Discovering Prices: Auction Design in Markets with Complex Constraints.* New York: Columbia University Press.

Milgrom, Paul, and Joshua Mollner. 2018. "Equilibrium Selection in Auctions and High Stakes Games." *Econometrica* 86(1): 219–61.

Milgrom, Paul R., and Robert J. Weber. 1982. "A Theory of Auctions and Competitive Bidding." *Econometrica* 50(5): 1089–1122.

Mirrlees, James A. 1971. "An Exploration in the Theory of Optimum Income Taxation." *Review of Economic Studies* 38(2): 175–208.

Mirrlees, James A. 1979. "The Implications of Moral Hazard for Optimal Insurance." Paper presented at conference in honor of Karl Borch, Bergen, Norway, 1979.

Myerson, Roger B. 1999. "Nash Equilibrium and the History of Economic Theory." *Journal of Economic Literature* 37(3): 1067–82.

Myerson, Roger B., and Jörgen Weibull. 2015. "Tenable Strategy Blocks and Settled Equilibria." *Econometrica* 83(3): 943–76.

Nash, John F., Jr. 1950a. "Equilibrium Points in *n*-Person Games." *PNAS* 36(1): 48–49.

Nash, John F., Jr. 1950b. "The Bargaining Problem." *Econometrica* 18(2): 155–62.

Nash, John F., Jr. 1951. "Noncooperative Games." *Annals of Mathematics* 54: 289–95.

Niederle, Muriel, Deborah D. Proctor, and Alvin E. Roth. 2006. "What Will Be Needed for the New GI Fellowship Match to Succeed?" *Gastroenterology* 130(1): 218–24.

Niederle, Muriel, Deborah D. Proctor, and Alvin E. Roth. 2008. "The Gastroenterology Fellowship Match—The First Two Years." *Gastroenterology* 135(2): 344–46.

Niederle, Muriel, and Alvin E. Roth. 2003.

"Unraveling Reduces Mobility in a Labor Market: Gastroenterology With and Without a Centralized Match." *Journal of Political Economy* 111(6): 1342–52.

Niederle, Muriel, and Alvin E. Roth. 2009. "Market Culture: How Rules Governing Exploding Offers Affect Market Performance." *American Economic Journal: Microeconomics* 1(2): 199–219.

Ortega-Reichert, Armando. 1969. *Models for Competitive Bidding Under Uncertainty*. PhD dissertation, Stanford University.

Owen, Guillermo. 1968. *Game Theory*. Academic Press.

Rees, Michael A., Ty B. Dunn, Christian S. Kuhr, Christopher L. Marsh, Jeffrey Rogers, Susan E. Rees, Alejandra Cicero, Laurie J. Reece, Alvin E. Roth, Obi Ekwenna, David E. Fumo, Kimberly D. Krawiec, Jonathan E. Kopke, Samay Jain, Miguel Tan, and Siegfredo R. Paloyo. 2017. "Kidney Exchange to Overcome Financial Barriers to Kidney Transplantation." *American Journal of Transplantation* 17(3): 782–90.

Rees, Michael A., Jonathan E. Kopke, Ronald P. Pelletier, Dorry L. Segev, Matthew E. Rutter, Alfredo J. Fabrega, Jeffrey Rogers, Oleh G. Pankewycz, Janet Hiller, Alvin E. Roth, Tuomas Sandholm, Utku Ünver, and Robert A. Montgomery. 2009. "A Non-Simultaneous Extended Altruistic Donor Chain." *New England Journal of Medicine* 360(11): 1096–1101.

Rees, Michael A, Siegfredo R. Paloyo, Alvin E. Roth, Kimberly D. Krawiec, Obi Ekwenna, Christopher L. Marsh, A. J. Wenig, Ty B. Dunn. 2017. "Global Kidney Exchange: Financially Incompatible Pairs Are Not Transplantable Compatible Pairs." *American Journal of Transplantation* 17(10): 2743–44.

Roth, Alvin E. 1975. "A Lattice Fixed-Point Theorem with Constraints." *Bulletin of the American Mathematical Society* 81(1): 136–38.

Roth, Alvin E. 1976. "Subsolutions and the Supercore of Cooperative Games." *Mathematics of Operations Research* 1(1): 43–49.

Roth, Alvin E. 1980. "Values for Games without Sidepayments: Some Difficulties with Current Concepts." *Econometrica* 48(2): 457–65.

Roth, Alvin E. 1982. "The Economics of Matching: Stability and Incentives." *Mathematics of Operations Research* 7(4): 617–28.

Roth, Alvin E. 1984. "The Evolution of the Labor Market for Medical Interns and Residents: A Case Study in Game Theory." *Journal of Political Economy* 92(6): 991–1016.

Roth, Alvin E. 1986. "On the Non-Transferable Utility Value: A Reply to Aumann." *Econometrica* 54(4): 981–84.

Roth, Alvin E., ed. 1988. *The Shapley Value: Essays in Honor of Lloyd S. Shapley*. Cambridge University Press.

Roth, Alvin E. 1991a. "Game Theory as a Part of Empirical Economics." *Economic Journal* 101: 107–114.

Roth, Alvin E. 1991b. "A Natural Experiment in the Organization of Entry-Level Labor Markets: Regional Markets for New Physicians and Surgeons in the United Kingdom." *American Economic Review* 81(3): 415–40.

Roth, Alvin E. 2007. "Repugnance as a Constraint on Markets." *Journal of Economic Perspectives* 21(3): 37–58.

Roth, Alvin E. 2016. "Experiments in Market Design." Chap. 5 in *Handbook of Experimental Economics*, vol. 2, edited by John H. Kagel and Alvin E. Roth. Princeton University Press.

Roth, Alvin E., and Ido Erev. 1995. "Learning in Extensive-Form Games: Experimental Data and Simple Dynamic Models in the Intermediate Term." *Games and Economic Behavior* 8: 164–212.

Roth, Alvin E., Kimberly D. Krawiec, Siegfredo Paloyo, Obi Ekwenna, Christopher L. Marsh, Alexandria J. Wenig, Ty B. Dunn, and Michael A. Rees. 2017. "People Should Not Be Banned from Transplantation Only Because of Their Country of Origin." *American Journal of Transplantation* 17(10): 2747–48.

Roth, Alvin E., and Elliott Peranson. 1999. "The Redesign of the Matching Market for American Physicians: Some Engineering Aspects of Economic Design." *American Economic Review* 89(4): 748–80.

Roth, Alvin E., Tayfun Sönmez, and M. Utku Ünver. 2004. "Kidney Exchange." *Quarterly Journal of Economics* 119(2): 457–88.

Roth, Alvin E., Tayfun Sönmez, and M. Utku Ünver. 2005a. "A Kidney Exchange Clearinghouse in New England." *American Economic Review* 95(2): 376–80.

Roth, Alvin E., Tayfun Sönmez and M. Utku Ünver. 2005b. "Pairwise Kidney Exchange." *Journal of Economic Theory* 125(2): 151–188.

Roth, Alvin E., Tayfun Sönmez, M. Utku Ünver, Francis L. Delmonico, and Susan L. Saidman. 2006. "Utilizing List Exchange and Nondirected Donation through 'Chain' Paired Kidney Donations." *American Journal of Transplantation* 6(11): 2694–2705.

Roth, Alvin E., and Xiaolin Xing. 1994. "Jumping the Gun: Imperfections and Institutions Related to the Timing of Market Transactions." *American Economic Review* 84(4): 992–1044.

Rothschild, Michael, and Joseph Stiglitz. 1976. "Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information." *Quarterly Journal of Economics* 90(4): 629–49.

Schelling, Thomas C. 1960. *The Strategy of Conflict*. Harvard University Press.

Selten, Reinhard. 1965. "Spieltheoretische Behandlung eines Oligopolmodells mit Nachfrageträgheit." *Zeitschrift für die gesamte Staatswissenschaft*

121: 301–29, 667–89.

Selten, Reinhard. 1975. "Reexamination of the Perfectness Concept for Equilibrium Points in Extensive Games." *International Journal of Game Theory* 4(1): 25–55.

Shapley, Lloyd S. 1953. "A Value for *n*-Person Games." Chap. 17 in *Contributions to the Theory of Games*, vol. 2, edited by Harold W. Kuhn and Albert W. Tucker. Princeton University Press.

Shapley, Lloyd S. 1969. "Utility Comparison and the Theory of Games." In *La Décision: Agrégation et Dynamique des Ordres de Préférence,* pp. 251–263. Paris: Editions du CNRS.

Shapley, Lloyd S. 1973. "Let's Block 'Block.'" *Econometrica* 41(6): 1201–02.

Shapley, Lloyd, and Herbert Scarf. 1974. "On Cores and Indivisibility." *Journal of Mathematical Economics* 1(1): 23–37.

Spence, Michael. 1973. "Job Market Signaling." *Quarterly Journal of Economics* 87(3): 355–74.

Vickrey, William. 1961. "Counterspeculation, Auctions, and Competitive Sealed Tenders." *Journal of Finance* 16(1): 8–37.

von Neumann, John, and Oskar Morgenstern. 1944. *Theory of Games and Economic Behavior.* (2nd edition, 1947; 3rd edition, 1953). Princeton University Press.

Wald, Abraham. 1947. Review of "Theory of Games and Economic Behavior" by John v. Neumann and Oskar Morgenstern. *Review of Economics and Statistics* 29(1): 47–52.

Wilson, Robert B. 1977. "A Bidding Model of Perfect Competition." *Review of Economic Studies* 44(3) 511–18.

Wilson, Robert B. 1987. "Game-Theoretic Analyses of Trading Processes." In *Advances in Economic Theory: Fifth World Congress*, edited by Truman F. Bewley, pp. 33–77. Cambridge University Press.

Wilson, Robert B. 1993. *Nonlinear Pricing.* Oxford University Press.

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