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The Art of Designing Markets

by Alvin E. Roth

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Traditional economics views markets as simply the confluence of supply and demand. A new field of economics, known as "market design," recognizes that well-functioning markets depend on detailed rules. For example, supply and demand drive both stock markets and labor markets, but someone who wants to buy or sell shares in a company goes through very different procedures from those followed by a job seeker or an employer. Moreover, labor markets work differently from one another: Doctors aren't hired the way lawyers, professional baseball players, or new MBAs are. Market designers try to understand these differences and the rules and procedures that make various kinds of markets work well or badly. Their aim is to know the workings and requirements of particular markets well enough to fix them when they're broken or to build markets from scratch when they're missing.

Market designers have already had an impact on kidney exchange, the hiring of new doctors, school choice programs, and auctions of radio spectrum. Internet job markets and markets for takeoff and landing slots at airports are among the many other areas in which market malfunctions are likely and thus adjustments informed by the insights of this new discipline will be called for.

Two developments in economics came together to form the field of market design. One was game theory—the study of the "rules of the game" and the strategic behavior that they elicit. By the 1990s it had matured to the point where it could offer practical guidance. In this it was helped by another new methodology, experimental economics, which provided tools both for testing the reliability of game theory's predictions and for testing market designs before introducing them into operating markets. A primary motive for market design is the need to address market failures.

To function properly, markets need to do at least three things.

1. They need to provide *thickness*—that is, to bring together a large enough proportion

of potential buyers and sellers to produce satisfactory outcomes for both sides of a transaction.

2. They need to make it *safe* for those who have been brought together to reveal or act on confidential information they may hold. When a good market outcome depends on such disclosure, as it often does, the market must offer participants incentives to reveal some of what they know.

3. They need to overcome the *congestion* that thickness can bring, by giving market participants enough time—or the means to conduct transactions fast enough—to make satisfactory choices when faced with a variety of alternatives.

I'll focus on several market-design projects that my colleagues and I have undertaken after a market's failure to do one of these things caused a breakdown. Two of them, with their roots in the 1990s, were the design of labor clearinghouses, such as the one through which U.S. doctors get their first jobs, and the design of the auctions through which the Federal Communications Commission sells licenses for different parts of the radio spectrum.

Markets for labor and radio spectrum, while very different from each other, are both traditional kinds of markets, in which money (in the form of wages or prices) plays a critical role. More recently my colleagues and I have designed marketlike allocation procedures that involve neither prices nor an exchange of money. Some of these have allowed us to see even more clearly how markets can work or fail. These projects include the design of procedures for assigning children to schools in Boston and New York City and the allocation of organs for transplantation—in particular the facilitation of kidney exchange (sometimes called paired kidney donation).

Establishing and Maintaining Thick Markets

Here is how my colleagues and I helped two medical markets overcome problems relating to thickness.

Kidney exchange. More than 70,000 patients in the United States are waiting for a kidney transplant from a deceased donor, but because of a shortage of suitable donors and, sometimes, the difficulty of getting a kidney to a suitable patient while it is still viable, fewer than 11,000 a year receive such transplants. Every year several thousand patients die waiting for a transplant. But because people are born with two kidneys and can remain healthy with only one, a person can donate a kidney to a friend or loved one. More than 6,000 live-donor transplants are performed each year.

However, not everyone who is healthy enough to donate a kidney and also willing to do so can donate to a loved one in need. Incompatible blood types, for example, or antibodies to the donor's proteins in the would-be recipient's bloodstream may make donation impossible. A husband can't donate a kidney to his wife if she has antibodies produced by her exposure in childbirth to the proteins their newborn inherited from him.

Before 2004 in a few cases an incompatible patient-donor pair and their surgeon were able to locate another such pair and arrange an exchange in which the donor in one pair could give a kidney to the patient in the other pair and vice versa. Such exchanges were rare, because donors whose organs were found to be incompatible with their intended recipients were usually just sent home, and the detailed medical information that could establish their compatibility with another patient was not collected. In short, there was no thick market for incompatible patient-donor pairs who might be looking for an exchange.

In May 2004, M. Utku Ünver, Tayfun Sönmez, and I published an article in the *Quarterly Journal of Economics* in which we explained how a centralized kidney exchange could be organized to permit the transplantation of many more kidneys in a cycle, with the donor in one patient-donor pair giving a kidney to the patient in the next pair, and so on. Such a system would raise a serious logistical challenge, however: Because as a matter of public policy courts will not enforce contracts promising the future delivery of kidneys, all the transplants would have to be done simultaneously. In subsequent work we discovered that when the market is thick enough—that is, when a large number of patient-donor pairs has been assembled—almost all feasible transplants can be accomplished through exchanges among no more than three patient-donor pairs.

We sent copies of our papers to many kidney surgeons, and one of them, Frank Delmonico

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(then the chief of renal transplantation at Massachusetts General Hospital), met with us to hear more. Out of that conversation, which grew to include a number of other people (and led to modifications of our original proposals), came the New England Program for Kidney Exchange. By bringing together the 14 kidney-transplant centers in New England, the program allows incompatible patient-donor pairs anywhere in the region to find other such pairs with whom to make exchanges. My colleagues and I now also advise the Alliance for Paired Donation, a consortium of regional centers in Ohio. Its ultimate goal is to organize the country's various regional transplant centers into a national system for kidney exchange. (In February 2007 the Senate passed the Living Kidney Organ Donation Clarification Act, intended to help clear away possible legal obstacles to a national kidney exchange. It is now being reconciled with a House version of the bill.) A national system would depend on the establishment of a database in which all incompatible patient-donor pairs throughout the United States were registered—a task posing not only logistical challenges. Regional systems might resist registering all incompatible pairs within their catchment area for fear of losing opportunities to perform transplants on their own patients. If the maximum benefits from exchange are to be realized, market designers need to develop rules and procedures that give transplant centers an incentive to enroll all of their eligible patients.

The problem with kidney exchange was a lack of thickness; the goal of regional—and eventually of national—kidney exchange is to establish thickness. But some markets, like the ones described below, start out thick and become less so, as participants try to transact outside the main market.

Medical labor markets. The market for new doctors was the first one my colleagues and I studied that had actually lost thickness. In the early 1900s medical students looked for positions with hospitals toward the end of their last year of medical school. Over time hospitals started competing for the best applicants by trying to lock them up before their competitors could. By the 1930s most medical students were being hired half a year before graduation, and by the 1940s many were being hired almost two years before graduation—well before they could be certain where they wanted to be, and before hospitals could reliably identify the top candidates. Offers came earlier and expired more quickly, and more and more students found themselves having to respond to their first offer before learning whether others would be forthcoming. Hospitals discovered that if they gave applicants time to consider offers that were ultimately declined, then other candidates to whom they would have liked to make offers would already be committed to hospitals that had pressured them to decide. To avoid such an outcome, hospital administrators kept pushing forward the selection deadline and curtailing the deliberation period.

In the 1950s the hospitals and medical student organizations collaborated to restore a thick market in which both applicants and employers could weigh multiple alternatives. They organized a clearinghouse that, after a brief period of adjustment, once again operated in students' final year of medical school. Students and hospitals interviewed each other as before, without the mediation of the clearinghouse and on their own timetable. Afterward they submitted rank-order lists of the positions they sought or the applicants they desired to the clearinghouse, which today is called the National Resident Matching Program (NRMP).

The system worked well for 40 years but then began to fray in response to changes in medicine and the world. (To name just one, in the 1950s virtually all medical students were men, but today many medical graduates are married to other MDs, and such couples would like to find jobs in the same vicinity.) In 1995, amid growing doubts that the clearinghouse could serve the modern market, I was asked to direct a redesign of how the clearinghouse worked. We wanted to eliminate any impulse that applicants and hospitals might have to transact with each other outside the main market (as they had done before the clearinghouse began operating) in the belief that they were likelier to realize their preferences by striking bargains independently.

Our primary goal was to avoid having the clearinghouse assign hospitals and residents to matches they liked less than the ones they could arrange by themselves outside the clearinghouse. If even a few participants make their own arrangements, they under-mine the benefits of the clearinghouse, because those who opt out—either by refusing to participate or by failing to honor their commitments—may very well have been best matched with others who stay in. Soon the market unravels, and participants once again experience the problems the clearinghouse was meant to solve.

A second, related goal of the redesign was to encourage applicants to rank hospitals according to their true preferences. It was essential, for example, that a student whose first choice was a highly competitive position could reveal it without running the risk that if he didn't get it, he would have a lower chance of getting his second choice than he would have had if he had presented his second choice as his first. Such a student might hesitate to list his true first choice first and instead list first a less preferred job that he thought he had a better chance of getting. Besides, his genuine first choice might actually want to hire him if it could. Absent the confidence to declare their true preferences, the two parties would have reason to seek each other outside the main market.

Fortunately, an algorithm based on work initiated in the 1960s by the game theorists David Gale and Lloyd Shapley and on work I did in the early 1980s was able to fashion a market that met our primary goal. (See the sidebar "Efficient Matching in Markets.") Today the Roth-Peranson algorithm is at the heart of clearinghouses that fill the more than 20,000 positions for new medical graduates opening up each year. (Elliott Peranson is a coauthor of mine who runs the Toronto-based National Matching Services, which organizes clearinghouses and provides technical support for market makers like the NRMP.) The same algorithm organizes the markets for older physicians entering dozens of medical specialties and subspecialties; these markets had suffered from many of the same failures that beset the market for new doctors in the 1990s.

When Muriel Niederle and I studied the market for new gastroenterologists, for example, we found that in each of the previous few years jobs had been offered earlier and left open for less time than they had been the year before. In 2005 gastroenterology fellows were being selected for jobs that wouldn't begin for another year and a half. What was once a single national market had fragmented into many local markets, with hospitals recruiting mostly internists who worked nearby. Wanting more time and wider choice, both applicants and employers were ready for a change. They were familiar with medical

Efficient Matching in Markets

Lives and careers are shaped throughout their length by matches: student to school, employee to job, husband to wife. Matching is one of the fundamental functions of markets, and when it occurs inefficiently—because the marketplace has too few participants, or suffers congestion as a result of having too many, or participants' true preferences can't be safely expressed—a market may unravel.

In 1962 David Gale and Lloyd Shapley published a paper in the *American Mathematical Monthly* titled "College Admissions and the Stability of Marriage," presenting a simple model of two-sided matching in which men and women (or students and colleges) expressed preferences for individuals in the other set to whom they might be matched. The authors proposed an algorithm for finding a "stable" matching, meaning that no man or woman would be matched to an unacceptable mate, and no man and woman not matched to each other would both prefer to be (known as a "blocking pair").

The algorithm would work by having the men in a marriage market (or the colleges in an admissions market) make proposals to the women (or the students) in their order of preference. Women who received multiple proposals would reject their least preferred without committing themselves to any of the remaining. Men who had been rejected would make new proposals, resulting in new rejections (including of proposals that had been held but were now less preferred than a new proposal), until none of the rejected men who were left wished to make any further proposals. At this point all proposals that were being held would be accepted.

Similar ideas had been incorporated in the early 1950s into the clearinghouse through which even today most American doctors obtain their first jobs. In recent years admissions to high schools in New York City and to all public schools in Boston have been reorganized into clearinghouses that use deferred-acceptance algorithms adapted to local needs, which solve serious problems those school systems had previously encountered. In fact, deferred-acceptance algorithms have been independently discovered a number of times, in part because they capture commonsense notions of how markets operate. And seeing how clearinghouses differ from the less centralized marketplaces they replace has yielded new insights into the tasks that markets have to perform in order to work well, whether they are centralized or decentralized.

The curse of exploding early offers is by no means limited to medical markets: Consider college early-admissions programs.

clearinghouses, having gone through the internship and residency matching processes. Still, hospital administrators worried that they would be at a competitive disadvantage if they waited to hire their new fellows. At the same time, there was no way for hospitals or even professional gastroenterology organizations to prevent other hospitals from making early offers.

Together with Deborah D. Proctor, a gastroenterologist at Yale University, Professor Niederle and I successfully urged the specialty's four major professional organizations to adopt a resolution stating that if an applicant received an offer before the clearinghouse began, he was free to accept it, but he was also free subsequently to change his mind and participate in the clearinghouse. The aim of the resolution was to prevent a gastroenterology program that broke ranks from being able to lock up desirable candidates. If programs could not benefit from breaking ranks, the thinking went, then few would do so. Moreover, compliant program managers could be confident that candidates who had accepted early offers would still be able to avail themselves of opportunities that emerged while the clearinghouse was operating.

There was some concern that too often the resolution might cause fellows to accept offers that they would later decline. In fact it discouraged all but a few early offers when the gastroenterology match was held, in June 2006—almost a year later than many hospitals would otherwise have made offers.

The curse of exploding early offers is by no means limited to medical markets. Over the years we have seen it in markets for lawyers, in the matching of college football teams to postseason bowl games, and even in college admissions, with a variety of early-acceptance programs now accounting for a substantial percentage of the entering classes at many elite colleges (although Harvard, for example, recently abolished its early-admission program). In general, a thick market requires the participation of a large proportion of the potential transactors at the same time.

Making It Safe to Reveal Preferences

Failure to maintain thickness isn't the only thing that can cause markets to fail. As we saw in the case of the residents' clearinghouse, markets and allocation procedures tend not to work well when participants can't safely reveal or act on their true preferences. We can see this clearly in the two stories below.

Boston schools. Until 2005 children were assigned to schools in Boston according to the following system. Each child fell into one of several priority classifications at each school. (Having an older sibling at the school gave the child a higher priority, for example, than living within walking distance of the school.) Families were invited to submit a rank-order list of schools they had chosen for their children. The old algorithm assigned as many children as possible to their first-choice school, considering priorities only when a school had too few places for the number of students that chose it. The system then assigned as many of the remaining students as possible to their second-choice school, and so forth.

What could be wrong with a system that gives as many people as possible their first choice? Think about a family whose first choice was a school where its child didn't enjoy a high priority and whose second choice was a local school, where the child did. If the family stated those preferences and failed to get its first choice, it ran the risk of not getting its second choice either, because the old algorithm might have filled the local school with students whose families had listed it as their first choice. But if the disappointed family *had* listed its second choice first, it could have been confident of getting it.

A study of how the old Boston system worked in practice showed that some families paid close attention to the capacities of and the demand for schools, and made careful strategic decisions. Most of the time such families got their stated first choice, which may not have been their actual first choice. Families that didn't game the system sometimes got none of their choices, forcing them to send their children to administratively assigned schools, whether local or not, that weren't to their liking. (Because all school places are ultimately assigned by a central school board, families couldn't strike side deals with individual principals, as physicians had done with hospitals.)

Faced with evidence of these outcomes, the Boston public school system in 2006 adopted a procedure proposed by Atila Abdulkadiroğlu, Parag Pathak, Tayfun Sönmez, and me that was very similar to the clearinghouse used in medical matches. The system now uses a deferred-acceptance algorithm to match students with schools. Because individual schools may not exercise preferences, the algorithm relies on the priorities of the children at each school. (The criteria for awarding priorities remain unchanged.) The new procedure is strategy proof, meaning that it never penalizes a family for listing its true preferences—a benefit perhaps even greater for inner-city parents than it would be for highly educated physicians. In proposing the new approach, Thomas Payzant, then the superintendent of Boston's public schools, wrote, "A strategy-proof algorithm *levels the playing field* by diminishing the harm done to parents who do not strategize or do not strategize well."

Payzant's point also applies to many other markets in which a given participant's preference may rest on private information that other participants could use to refine their preferences and thus produce a better outcome for all concerned. The market for radio spectrum is a case in point.

Auctions of radio spectrum. For a long time the U.S. government licensed parts of the radio spectrum without charging for them. But in 1993 Congress directed the FCC to design and conduct auctions of such licenses instead. Congress was anticipating that in view of the many developing uses of radio spectrum, including pagers, cell phones, and wireless Internet, continuing to give away licenses would prevent the most valuable uses of that electronic real estate from emerging. Legislators wanted to let the market decide how spectrum should be used, with licenses going to businesses that had the most valuable plans for using it rather than to those that lobbied most effectively. But how should such a market, which had never operated before, be organized?

After a series of extended discussions in which Paul Milgrom, Robert Wilson, and the late John McMillan, then all Stanford economists and business professors, played particularly prominent roles, the FCC realized that if it auctioned off single licenses (for the right to use a particular frequency band in a particular region of the country) one at a time, it would prevent bidders from putting together packages of licenses that corresponded to different business plans. For example, although a taxi dispatcher might want a single pager band at a given location, a telephone company might want to assemble licenses that gave it wide—even national—coverage, and an Internet provider might want to control enough adjacent frequency bands to offer broadband service. The goal of the market should therefore be to allow bidders that imagine different uses for radio spectrum to compete against one another, so that the final bids reflect its highest-value use.

With this goal in mind, the FCC decided on a design involving simultaneous multiround auctions of many licenses, with no auction for a particular license permitted to close until the bidding had stopped in all the other auctions. This would allow bidders to decide which licenses to bid on in response to the activity of other bidders. For example, it would allow a taxi dispatcher that was outbid on a particular license by a national phone company to bid on another frequency, rather than having to bid up the price in one auction, only to find that identical licenses later went for a lower price. Similarly, it would allow a national phone company to assemble the package of licenses it needed from among those that weren't being most actively sought for other purposes.

It goes without saying that for such a market to work well, bidders have to be willing to bid, even though doing so conveys confidential information to competitors. Bidders reluctant to share their intentions would want to wait almost until the end of the auction before bidding. If everyone did that, however, the information needed to produce an efficient allocation would not be transmitted. To avoid this result, the design for the spectrum auction included activity rules to prevent bidders from making late bids unless they had made bids on equivalent numbers of licenses (measured in terms of population served) earlier in the auction. Thus big bidders can be identified early, and all bidders can adjust their bids in light of the competition.

Simultaneous multiround auctions with activity rules enabled many bidders to compete simultaneously for many licenses, creating a thick market in which price discovery could take place. More prosaically, the activity rules also kept the auctions from dragging on interminably—another possible side effect of thick markets' having to cope with the congestion of many possible transactions.

Dealing with Congestion

The design of the school-choice system in New York City directly addressed just that problem. In 2003 the New York City Department of Education approached me about helping to revise its system for assigning students to high schools—but not because the existing system had any problem maintaining thickness. On the contrary, almost 100,000 students needed to be placed in roughly that many ninth-grade seats. Under the existing procedure each student filled out a rank-order list of schools to which he or she sought admission, and these lists were distributed to the individual schools, which then admitted students without coordinating with one another. After the high schools made their initial acceptance decisions, the Department of Education would send out letters notifying students which schools had accepted them and which had placed them on a waiting list, and requiring those who had been accepted by more than one school to select just one. Students could also choose to remain on the waiting list of a school they preferred. Schools that had places declined could make new offers to students on their waiting lists, and these offers were conveyed in a second set of letters.

Because about 17,000 students received multiple offers, only about 50,000 students, half the total, received offers in the first round of letters. Even after the third round of letters approximately 30,000 students remained unassigned and had to be placed in schools at the last minute, without regard for the preferences they had expressed.

When Parag Pathak, Atila Abdulkadiroğlu, and I began to study the old system, we found that the large majority of students who received multiple offers chose the schools they had ranked highest. So the small benefit to some students of getting multiple offers was far outweighed by the harm the many students who got no offers suffered as a result of the time consumed by the issuance and rejection of offers made to students on the waiting lists. We therefore advised the department to establish a clearinghouse that would essentially process all the lists immediately and give each student only the admission offer issued by the school that he or she had ranked the highest. This clearinghouse, which has now completed its fourth year of operation, solved a number of problems along the way. One was a problem of participation: Under the old system, high school principals sometimes failed to disclose to the Department of Education their total number of empty seats, so as to retain control over how some of them were filled. In particular, the principals wanted to be able to enroll students they preferred, and who likewise wanted to attend their school, but who under the old system might be assigned elsewhere. The clearinghouse ensures that students fail to get their first-choice school only if the class has been filled with students the school prefers. Thus neither party has an incentive to seek a deal outside the system.

The clearinghouse also makes it safe for students to reveal their true preferences. Under the old system, high schools saw the students' rank-order lists before composing their own, and the students knew that some schools would admit only those who had ranked them first. The knowledge that applicants' lists now reflect their true preferences, revealing the undistorted demand for each school, has enabled administrators to make better-informed decisions about which schools to close. Most important, under the new system fewer than 3,000 students—as opposed to the previous 30,000—have had to be placed administratively in recent years.

Congestion is a problem in many markets, and in some of them it leads to the sort of unraveling observed in medical labor markets. If managers don't have enough time to make all the offers they would like to make, they may start making offers early and leaving them open only briefly.

Where Do We Go from Here?

Market design turns out to be about details, such as the nature of the transactions in question, the opportunities to conduct transactions outside the market, and the distribution of information. But it also provides some general lessons.

For example, information is of particular importance when the value of some transactions depends on what other transactions are taking place. Two medical residents married to each other can't evaluate the desirability of a given position unless they know whether a

Smart markets combine the inputs of users in complex ways. Kidney exchange is an example of this.

second good position is available nearby. Likewise, a broadcaster seeking to supply broadband service can't assess the value of a particular band of spectrum unless it knows whether an adjacent frequency band is also available. And just as markets sometimes need to move information around, at other times they need to allow participants to protect their private information. This is probably what some buyers on eBay are doing when they wait until the final seconds of an auction to bid.

Because computers are now cheap and ubiquitous, we can design "smart markets" that combine the inputs of users in complex ways. Kidney exchange is an example of a smart market. By running through every possible combination of donors and patients, it can arrange the highest possible number of transplants.

Computers could also enable the auction of many kinds of bundled goods, such as takeoff and landing slots at airports. In some cases the winning bids would be decided only after a computer had identified the particular division of goods that would maximize total revenues or serve some other purpose. As these markets got larger, so would the number of possible combinations, and determining the best outcome would become correspondingly more difficult. I expect that economists and computer scientists will interact productively in solving such problems.

Market design is not solely or even primarily a matter of hardware and algorithms. As we saw in the market for gastroenterology fellows, elements of "market culture," such as how offers are accepted or rejected, may be as decisive as other elements of the market design. In that market the critical step in restoring order was to discourage exploding early offers by allowing applicants to reconsider early acceptances later. Laws and regulations have a role to play in this kind of design, and there is room for exchanges of views among economists, lawyers, and regulators.

The Internet has only increased the rate at which new markets, including dating and job markets, arise and grow in size and importance. (Probably the most active auctions in the world are those conducted to link ads to Internet search terms. Which ads appear every time someone does a Google search, for example—and the order in which they appear—depend on which sponsors win a match to those search terms in an auction conducted automatically by Google at the time of each search.) Every new market has to attract enough participants and then help those participants cope with the resulting congestion. And markets like eBay need to convey information about sellers, not just products. The proliferation of new kinds of markets will enhance not only our economic life but also our understanding of markets in general.

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