

## School Admissions Reform in Chicago and England: Comparing Mechanisms by their Vulnerability to Manipulation<sup>†</sup>

By PARAG A. PATHAK AND TAYFUN SÖNMEZ\*

*In Fall 2009, Chicago authorities abandoned a school assignment mechanism midstream, citing concerns about its vulnerability to manipulation. Nonetheless, they asked thousands of applicants to re-rank schools in a new mechanism that is also manipulable. This paper introduces a method to compare mechanisms by their vulnerability to manipulation. Our methodology formalizes how the old mechanism is at least as manipulable as any other plausible mechanism, including the new one. A number of similar transitions took place in England after the widely popular Boston mechanism was ruled illegal in 2007. Our approach provides support for these and other recent policy changes. (JEL C78, D82, H75, I21, I28)*

In the last few years, policymakers at several school districts have sought to simplify strategic aspects of school admissions in their open enrollment or school choice plans. A first change occurred to Boston's grade K–12 assignment system, known as the *Boston mechanism*, in place since 1999. Abdulkadiroğlu and Sönmez (2003) show that this mechanism is vulnerable to strategic manipulation, and suggest two alternatives which are not. Following a newspaper article describing these issues (Cook 2003), leadership at Boston Public Schools invited a team of economists to conduct an empirical evaluation of the mechanism. In June 2005, the Boston school committee voted to replace the Boston mechanism with the *student-optimal stable mechanism* (Gale and Shapley 1962), a mechanism where participants can do no better than report their preferences truthfully. The strategic complexity of the Boston mechanism along with its adverse effects on less sophisticated families were key factors in Boston's decision (Abdulkadiroğlu et al. 2006, Pathak and Sönmez 2008). Another factor was the potential to use

\*Pathak: Department of Economics, MIT, 50 Memorial Drive, Cambridge, MA 02142, and NBER (e-mail: ppathak@mit.edu); Sönmez: Department of Economics, Boston College, Chestnut Hill, MA 02467 (e-mail: sonmezt@bc.edu). John Coldron was extremely helpful in providing details about admissions reforms in England. Drew Fudenberg, Lars Ehlers, Bengt Holmström, Fuhito Kojima, Stephen Morris, Debraj Ray, and Muhamet Yıldız provided helpful suggestions, as did participants at numerous seminars. Pathak is grateful for the hospitality of the Graduate School of Business at Stanford University where parts of this paper were completed and thankful for financial support from the National Science Foundation.

<sup>†</sup> To view additional materials, visit the article page at <http://dx.doi.org/10.1257/aer.103.1.80>.

unmanipulated preference data generated by the student assignment mechanism in various policy-related issues including the evaluation of schools.<sup>1</sup>

The Boston episode challenges a paradigm in traditional mechanism design that treats incentive compatibility only as a constraint and not as a direct design objective, at least for the specific context of school choice. Given economists' advocacy efforts, one might think that this incident is isolated, and the Boston events do not adequately represent the desirability of nonconsequentialist objectives as design goals. To demonstrate otherwise, we provide further, and perhaps more striking, evidence that excessive vulnerability to "gaming" is considered highly undesirable in the context of school choice. Officials in England and Chicago have taken drastic measures to attempt to reduce it, and remarkably the Boston mechanism plays a central role in both incidents.

In England, forms of school choice have been available for at least three decades. The nationwide 2003 School Admissions Code mandated that Local Authorities, an operating body much like a US school district, coordinate their admissions practices. This reform provided families with a single application form and established a common admissions timeline, leading to a March announcement of placements for anxious 10 and 11 year-olds on National Offer Day. The next nationwide reform came with the 2007 School Admissions Code. While strengthening the enforcement of admissions rules, this legal code also prohibited authorities from using what they refer to as "unfair oversubscription criteria" in Section 2.13:

*In setting oversubscription criteria the admission authorities for all maintained schools must not:*  
*give priority to children according to the order of other schools named as preferences by their parents, including 'first preference first' arrangements.*

A *first preference first* system is any "oversubscription criterion that gives priority to children according to the order of other schools named as a preference by their parents, or only considers applications stated as a first preference" (School Admissions Code 2007, Glossary, p. 118). The 2007 Admissions Code outlaws use of this system at more than 150 Local Authorities across the country, and this ban continues with the 2010 Code. The best known first preference first system is the Boston mechanism, and since 2007 it is banned in England.<sup>2</sup> The rationale for this ban, as stated by England's Department for Education and Skills, is that "the 'first preference first' criterion made the system unnecessarily complex to parents" (School Code 2007, Foreword, p. 7). Moreover, Education Secretary Alan Johnson remarked

<sup>1</sup>The use of data generated by manipulable mechanisms presents challenges for empirical research and evaluation. For example, Hastings, Kane, and Staiger (2006) utilize preference data from Charlotte-Mecklenburg, which uses the Boston mechanism, to estimate preferences for school characteristics and examine implications for the local educational market. They argue that the vagueness of the description of the mechanism in the first year of implementation makes strategic manipulation less of an issue. Similarly, Lim et al. (2009) tie the limited presence of minorities at senior Army ranks to racial differences between cadet preferences over Army branches, but they are unable to offer an explanation of these differences since the ROTC mechanism used to generate their data is highly manipulable (Sönmez 2011). They indicate that the policy recommendation to increase diversity would depend on the extent of manipulation in the data.

<sup>2</sup>A formal definition of these mechanisms is presented in Section III.

that the first preference first system “forces many parents to play an ‘admissions game’ with their children’s future.”

While Local Authorities had some time to adjust their admissions rules in England, the adoption of a new mechanism was considerably more abrupt in Chicago. The district abandoned their selective high school mechanism halfway through running it in 2009. That is, after participants had submitted preferences under one mechanism, but before announcing placements, Chicago Public Schools asked the same participants to resubmit their preferences under another mechanism a few months later. This is the only case of a midstream change of an assignment mechanism we are aware of, and in our view it is stunning given the potential high stakes involved. The abandoned mechanism prioritized applicants based on how schools were ranked and is the most basic form of the Boston mechanism. Under it, Chicago authorities argued that “high-scoring kids were being rejected simply because of the order in which they listed their college prep preferences.” The vulnerability of the Boston mechanism to strategic manipulation led to its elimination in yet another district.

These new case studies from England and Chicago provide additional evidence that the use of strategically complex assignment mechanisms is considered undesirable in the context of school choice. Unlike the case of Boston, the reforms in England and Chicago developed without the guidance of economists (to the best of our knowledge). Not only were the Boston mechanism and its variants abandoned in both cases, but extreme measures were taken in the process. Given these circumstances, one would expect local authorities in England and Chicago to adopt strategy-proof mechanisms, which are immune to manipulation. And yet, several local authorities in England as well as Chicago adopted alternative mechanisms that are also vulnerable to manipulation. Therefore, the new mechanisms must be perceived to be “less manipulable” than the abandoned mechanisms. This motivates our goal to develop a rigorous methodology to compare mechanisms based on their vulnerability to manipulation. In this paper we propose a method to compare manipulable mechanisms by examining three increasingly more demanding notions and relating our notion to these policy changes.

Our most basic notion is based on the following simple idea. Given an economic environment, there are often cases where this environment is *vulnerable to manipulation* under a mechanism  $\psi$ , but not under an alternative mechanism  $\varphi$ . If this observation can be made systematic, then it can form the basis for a ranking. We formalize the approach as follows: A mechanism  $\psi$  is *at least as manipulable* as mechanism  $\varphi$  if any environment that is vulnerable under  $\varphi$  is also vulnerable under  $\psi$ , and it is *more manipulable* if in addition there is at least one environment that is vulnerable under  $\psi$  but not under  $\varphi$ . Applications of this notion are relevant for a number of recent school choice reforms including those in England and Chicago. While we focus on these recent reforms, our framework is also useful to formalize other policy debates that have so far remained informal. For instance, one application involves changes in the auction mechanism for US Treasury bonds from discriminatory to uniform-price format and informal arguments dating back to Milton Friedman (1960). Not only is the discriminatory auction more manipulable than the uniform-price auction (providing a formalization of Friedman’s position), but we can establish an even stronger comparison taking into account the intensity of manipulation.

### Related Literature

One approach to studying a mechanism's vulnerability to manipulation is to characterize domains under which the mechanism is not manipulable (see, e.g., Barberá 2010 for a survey). However, strategy-proof mechanisms may not exist, may not be practical, or even if they do exist, they may not be desirable for reasons other than their incentive properties. In such cases, our paper argues that reducing the vulnerability to manipulation is desirable. Several recent papers, many motivated by the school choice reforms, argue that strategy-proofness can also be thought of as a design objective (see, e.g., Abdulkadiroğlu et al. 2006; Abdulkadiroğlu, Pathak, and Roth 2009; Pathak and Sönmez 2008; and Roth 2008).

Azevedo and Budish (2011) is the closest paper in the spirit of our methodological contribution. Like us, they are concerned about vulnerability to manipulation when mechanisms are not strategy-proof. They take an entirely different, but equally plausible, approach and propose a relaxation of strategy-proofness based on the idea that vulnerability to manipulation disappears in large economies for some mechanisms, but not others. Their complementary approach can also be used to formulate the Friedman position in the context of US Treasury Auctions. The advantage of their approach is that they offer an explicit design desideratum, namely *strategy-proofness in large*. The advantage of our approach is its ability to compare two mechanisms each of which fail strategy-proofness even in large. Indeed, an evaluation based on strategy-proofness in large is not possible for our main applications in school choice. Focusing on voting applications, Carroll (2011) proposes another criterion to evaluate mechanisms based on the extent to which they encourage manipulation. Other papers that relate to our methodological contribution include Parkes et al. (2001); Day and Milgrom (2008); and Erdil and Klemperer (2011) who each seek to design a combinatorial auction that minimizes manipulability, and to a lesser extent Kesten (2006) and Dasgupta and Maskin (2008) who make comparisons across allocation rules based on inclusion of environments focusing on nonstrategic properties of student assignment and voting mechanisms, respectively.

Our paper also contributes to an ongoing debate on the features of the Boston mechanism, still the most widely used US school choice mechanism. While efficiency considerations have not been central during policy deliberations at Boston Public Schools, experimental evidence from Chen and Sönmez (2006) and theoretical results from Ergin and Sönmez (2006) show that the student-optimal stable mechanism is more efficient than the Boston mechanism in complete information environments. Ergin and Sönmez (2006) further observe that the efficiency advantage of the student-optimal stable mechanism may not persist in incomplete information environments, whereas Pathak and Sönmez (2008) show that strategic students are better off under the Boston mechanism in the presence of nonstrategic students in complete information environments. In a recent series of papers, Abdulkadiroğlu, Che, and Yasuda (2011); Featherstone and Niederle (2011); and Miralles (2008) argue that the earlier literature might be too quick to dismiss the Boston mechanism in favor of the student-optimal stable mechanism. They all provide examples of specific environments where the symmetric Bayes-Nash equilibria of the Boston mechanism dominates the dominant-strategy equilibria of the student-optimal stable mechanism. In our view, these papers promote the point of view that the efficiency

comparison between these two mechanisms is highly nonrobust, but the lack of robustness stems from the Boston mechanism.

### I. General Framework

There is a finite set  $I$  of players with a generic member  $i$ , and a finite set of outcomes  $A$ . Each player has a preference relation  $R_i$  defined over the set of outcomes, where  $P_i$  is the strict counterpart of  $R_i$ . Let  $R = (R_i)_{i \in I}$  and  $P = (P_i)_{i \in I}$  denote the profile of weak and strict preferences, respectively. The set of possible types for player  $i$  is  $T_i$  with generic element  $t_i$ . We adopt the convention that  $t_{-i}$  denotes the type profile of players other than player  $i$ , and define  $R_{-i}$  and  $P_{-i}$  accordingly. We sometimes refer to a type profile  $t = (t_i)_{i \in I}$  as a *problem*. Let  $T = \prod_{i \in I} T_i$ .

A direct mechanism is a function  $\varphi : T \rightarrow A$ , a single-valued mapping of a type profile to an element in  $A$ . Let  $\varphi(t)$  denote the outcome produced by mechanism  $\varphi$  under  $t$ . We do not always expect players to be truthful when reporting their types. This motivates the following definition.

**DEFINITION 1:** A mechanism  $\varphi$  is manipulable by player  $i$  at problem  $t$  if there exists a type  $t'_i$  such that  $\varphi(t'_i, t_{-i}) P_i \varphi(t)$ .

We will say that *profile  $t$  is vulnerable under mechanism  $\varphi$*  if  $\varphi$  is manipulable by some player at  $t$ .

A mechanism is manipulable by a player at a problem if he can profit by misrepresenting his type. Observe that each mechanism induces a natural game form where the strategy space is the set of types for each player and the outcome is determined by the mechanism. A mechanism is *strategy-proof* if truthful type revelation is a dominant strategy of this game for any player. Equivalently, a mechanism is strategy-proof if it is not manipulable by any player at any problem.

We next present a notion to compare mechanisms by their vulnerability to manipulation.

**DEFINITION 2:** A mechanism  $\psi$  is at least as manipulable as mechanism  $\varphi$  if any profile that is vulnerable under mechanism  $\varphi$  is also vulnerable under  $\psi$ .

Two mechanisms can be equally manipulable if they are manipulable for exactly the same set of problems. Our next definition rules out this possibility.

**DEFINITION 3:** A mechanism  $\psi$  is more manipulable than mechanism  $\varphi$  if

- (i)  $\psi$  is at least as manipulable as  $\varphi$  and
- (ii) there is a set of players  $I$ , a set of outcomes  $A$ , and a profile  $t$  where  $t$  is vulnerable under  $\psi$  but not under  $\varphi$ .

If mechanism  $\varphi$  is strategy-proof while mechanism  $\psi$  is not, then mechanism  $\psi$  is more manipulable than mechanism  $\varphi$ . Our main interest is the case where neither  $\psi$  nor  $\varphi$  are strategy-proof. Our notion is somewhat conservative in the sense that we

deem a mechanism to be more manipulable than another only if there is strict inclusion of profiles where they can be manipulated. For example, it is more demanding to compare a mechanism with this notion than an alternative notion that simply counts the number of profiles where the mechanisms are manipulable. However, this fact also means that any comparison we can make under our notion provides a stronger result.

Although our notion makes no explicit reference to an equilibrium concept, it is possible to provide it with an equilibrium interpretation. Consider the type revelation game induced by a direct mechanism. The contrapositive of the first part of the definition implies that for a problem, if  $\psi$  is not manipulable, then  $\varphi$  is not manipulable. This means that if at any problem, truth-telling is a Nash equilibrium of the type revelation game induced by mechanism  $\varphi$ , it is also a Nash equilibrium of the type revelation game induced by mechanism  $\psi$  (even though the converse does not hold). Recall that if truth-telling is a Nash equilibrium of the type revelation game induced by mechanism  $\varphi$  for all problems, then  $\varphi$  is strategy-proof (see, e.g., Austen-Smith and Banks 2005).

While these definitions are general, in the applications in this paper, we mostly focus on assignment or matching problems. In such problems,  $A$  is the set of possible assignments, each player has strict preferences, and we assume that each only cares about her own assignment. We let  $\varphi_i(t)$  denote the assignment obtained by player  $i$  under type profile  $t$ .

## II. School Choice Applications

Throughout this section and the next, the type space of each agent is the set of his preferences. Hence the focus of Sections II and III is on preference revelation mechanisms.

### A. Reform at Chicago's Public Schools in 2009

To describe the assignment problem for Chicago's selective high schools, we begin by introducing some notation. There is a finite set  $I$  of students and a finite set  $S$  of schools. School  $s$  has capacity  $q_s$ , so the total capacity is  $Q = \sum_{s \in S} q_s$ . We assume that  $|I| > Q$  so the seats are in short supply. In 2009, there were over 14,000 applicants for the 9 selective Chicago Public Schools (CPS) high schools, consisting of 3,040 seats.<sup>3</sup>

Each student  $i$  has a strict preference ordering  $P_i$  over schools and being unassigned. Since each student must take an admissions test as part of their application, each student also has a composite score. We assume that no two students have the same composite score. In practice, if two students have the same test scores, the younger student is coded by CPS as having a higher composite score. The outcome of the admissions process is a matching  $\mu$ , a function which maps each student

<sup>3</sup>In practice, Chicago Public Schools splits selective high schools into five parts. The first "unrestricted" part is reserved for all applicants. The other four groups are reserved for students from particular neighborhoods, where students are ordered by their test scores within their neighborhood group. To implement this, the district simply modifies the rank order list of participants to accommodate this neighborhood constraint. That is, a student who ranks a school is interpreted by the assignment algorithm to rank both the "unrestricted" part and the part in their neighborhood tier in that order. We abstract away from this modification.

either to her assigned school or to being unassigned.<sup>4</sup> Let  $\mu(i)$  denote the assignment of student  $i$ .

The mechanism that was abandoned in Fall 2009 works as follows:

Round 1: In the first round, only the first choices of students are considered. At each school, students who rank the school as their first choice are assigned one at a time according to their composite score until either there are no students who have ranked the school as their first choice left or there are no additional seats at the school.

Round  $\ell$ : In round  $\ell$ , each student who is not yet assigned is considered at her  $\ell$ th choice school. At each school with remaining seats, these students are assigned one at a time according to their composite score until either there are no students who have ranked the school as their  $\ell$ th choice left or there are no additional seats at the school.

Let  $CH^k$  be the version of this mechanism that stops after  $k$  rounds. At CPS in Fall 2009, the district employed  $CH^4$ , with only 4 rounds. After eliciting preferences from applicants throughout the city, CPS officials computed assignments internally for discussion. The *Chicago Sun-Times* reported on November 12, 2009 (Rossi 2009):

*Poring over data about eighth-graders who applied to the city's elite college preps, Chicago Public Schools officials discovered an alarming pattern.*

*High-scoring kids were being rejected simply because of the order in which they listed their college prep preferences.*

*"I couldn't believe it," schools CEO Ron Huberman said. "It's terrible."*

*CPS officials said Wednesday they have decided to let any eighth-grader who applied to a college prep for fall 2010 admission re-rank their preferences to better conform with a new selection system.*

To help understand this quote, let us consider the situation for an applicant who is interested in applying to both Northside and Whitney Young, two of Chicago's most competitive college preps. Under  $CH^k$ , it is possible that a student who ranks Northside and Whitney Young in that order ends up unassigned, while had she only ranked Whitney Young, she would have been assigned. If the student does not have a high enough composite score to obtain a placement at Northside, then when she ranks Northside and Whitney Young, she will only obtain a seat at Whitney Young if there are seats left over after the first round. This scenario is unlikely given the popularity of that school, so the student ends up unassigned. Had the student only ranked Whitney Young, she would be considered alongside first choice applicants

<sup>4</sup>If a student is not assigned a seat at one of Chicago's selective high schools, she typically later enrolls in a neighborhood school, pursues other public school options such as charter and magnet schools, or leaves the public school system for either private or parochial schools.

and her score may be high enough to obtain an offer of admissions there. Hence, it is possible for a high-scoring applicant to be rejected from a school because of the order in which preferences are listed.

The *Chicago Sun-Times* article continues:

*Previously, some eighth-graders were listing the most competitive college preps as their top choice, forgoing their chances of getting into other schools that would have accepted them if they had ranked those schools higher, an official said.*

*Under the new policy, Huberman said, a computer will assign applicants to the highest-ranked school they qualify for on their new list.*

*“It’s the fairest way to do it.” Huberman told the Chicago Sun-Times editorial board Wednesday.*

After eliciting preferences under mechanism  $CHI^4$  but not reporting assignments to applicants, CPS officials announced a new selection system that works as follows:

The student with the highest composite score is placed into her top choice. The student with the next highest score obtains her top choice among those she ranked with remaining capacity. If there are no schools left with remaining capacity, then the student is unassigned. The mechanism continues with the student with the next highest composite score until either all schools are filled or each student is processed.

Let  $SD^k$  be the version of the mechanism where only the first  $k$  choices of a student’s rank order list are considered. When all choices on a student’s rank order list are considered, it is well known that this *serial-dictatorship* mechanism is strategy-proof. Indeed, in the letter sent from CPS to all students who submitted an application under  $CHI^4$ , the district explains:

*...the original application deadline is being extended to allow applicants an opportunity to review and re-rank their Selection Enrollment High School choices, if they wish. It is recommended that applicants rank their school choices honestly, listing schools in the order of their preference, while also identifying schools where they have a reasonable chance of acceptance.*

It would be unnecessary for students to consider what schools they have a reasonable chance of acceptance at if all choices were considered in this mechanism because the serial-dictatorship is strategy-proof. But when only a subset of choices are considered, a student’s likelihood of acceptance becomes an important consideration, and a student may obtain a more preferred assignment by manipulating her preferences. Just like the old Chicago mechanism,  $SD^k$  is also manipulable.

These two mechanisms are versions of widely studied assignment mechanisms for assigning students to schools. As we have already mentioned, the new mechanism adopted in Chicago is a variant of a serial-dictatorship, where only the first four choices are considered. The old Chicago mechanism is a variant of the Boston mechanism that

was used by Boston Public Schools until June 2005, with two important differences. First, although there are nine selective high schools in Chicago, the mechanism considers only the top four choices on a student's application form. This was not a feature of Boston's old school choice system, where all of a student's choices were potentially considered. Second, in Chicago the *priority ranking* of applicants is the same at all schools and it is based on student composite scores. Under the Boston mechanism, priority rankings of applicants potentially differ across schools. (In the case of Boston Public Schools, these rankings depend on sibling and walk zone priority.)

Any version of the Boston mechanism, including the version abandoned in Chicago, is manipulable. This shortcoming evidently played a role in its elimination in Chicago. However, the new mechanism in Chicago is also manipulable and the school district appears to be aware of this fact since it explicitly suggests that applicants list schools where they have a reasonable chance of acceptance. CPS officials must have felt that the old mechanism is more vulnerable to manipulation. Our first result justifies this point of view.

**PROPOSITION 1:** *Suppose there are at least  $k$  schools and let  $k > 1$ . The old Chicago mechanism ( $CHI^k$ ) is more manipulable than truncated serial-dictatorship ( $SD^k$ ) CPS adopted in 2009.*

We find it remarkable that one of the largest public school districts in the United States abandoned a mechanism after about 14,000 participants submitted their preferences citing reasons like those in the newspaper article.<sup>5</sup> The outrage expressed in the quotes from the *Chicago Sun-Times* suggests that the old mechanism was considered quite undesirable. Our next result allows to formalize the sense in which the old mechanism stands out among other reasonable mechanisms.

A desirable goal of a student assignment mechanism is to produce a "fair" outcome. One basic fairness notion in the context of priority-based student placement was proposed by Balinski and Sönmez (1999) and it is based on the well-known stability notion for two-sided matching markets: If student  $i$  prefers school  $s$  to her assignment  $\mu(i)$  and under matching  $\mu$ , either school  $s$  has a vacant seat or is assigned another student with a lower composite score, then student  $i$  may have a legitimate objection to her assignment. An individually rational matching that cannot be blocked by such a pair  $(i, s)$  is a *stable* matching.

The notion of stability has long been studied in the literature on two-sided matching problems for both normative and positive reasons (see Roth and Sotomayor 1990). In the operations research literature, the stability condition is often treated as a sort of feasibility requirement and two-sided matching problems are often described as the "stable matching problem." And yet many school choice mechanisms do not produce stable outcomes. That is perhaps why there is a long gap between the introduction of two-sided matching problems by Gale and Shapley (1962) and formal analysis of school choice mechanisms by Abdulkadiroğlu and Sönmez (2003). The old CPS mechanism ( $CHI^k$ ) is one of those mechanisms that is not stable. A key reason why so many school districts use mechanisms that

<sup>5</sup>We only became aware of the policy change in Chicago after this newspaper article. Since then, we have corresponded with CPS officials.

fail stability is that many school districts wish to pay special attention to the first choices of applicants. For instance, the class of mechanisms recently banned in England are known as “first preference first” mechanisms. This observation motivates the following definition.

Define matching  $\mu$  to be *strongly unstable* if there is a student  $i$  and school  $s$  such that student  $i$  is not assigned to  $s$  under  $\mu$ , student  $i$ 's top choice is school  $s$ , and either school  $s$  has a vacancy or there is another student assigned there with lower composite score. A matching is *weakly stable* if it is not strongly unstable. This notion is a relaxation of stability because a student is allowed to block a matching only with its top choice school. While there are quite a few school districts that use unstable mechanisms, we are unaware of any school district which prioritizes students at schools with some criteria and yet uses a mechanism that fails weak stability. In that sense, weak stability is a natural requirement in the context of priority-based student admissions. In particular, both the old abandoned CPS mechanism in 2009 and its replacement are weakly stable.

We are ready to present our next result which may explain why CPS CEO Ron Huberman was frustrated enough with the mechanism in 2009 to abandon it in the middle of the assignment process.

**THEOREM 1:** *Suppose each student has a complete rank ordering and  $k > 1$ . The old CPS mechanism ( $CHI^k$ ) is at least as manipulable as any weakly stable mechanism.*

We assume that students have complete rank orderings to keep the proof relatively simple. It is possible to state a version of this result without this assumption, but at the expense of significant expositional complexity. This and all other proofs are contained in the online Appendix.

Based on Proposition 1 and Theorem 1, the new mechanism in Chicago is an improvement in terms of discouraging manipulation. That being said, the lack of efficiency in the 2009 mechanism is due to constraining choices. Any mechanism that restricts reported student preferences to only four choices suffers a potential efficiency loss. Moreover, it is possible to have a completely nonmanipulable system (a strategy-proof one) by not constraining the choices of applicants. These observations beg the question of what Chicago Public Schools should do in future years. For the 2010–2011 school year, Chicago Public Schools decided to consider up to six (out of a total of nine choices) from applicants.

In the next section, we demonstrate that even though the new 2010 mechanism is still manipulable, its incentive properties are an improvement over the 2009 mechanism under our notion.

### B. Comparing Constrained Versions of Student-Optimal Stable Mechanism

Understanding the properties of constrained school choice mechanisms is relevant for districts other than Chicago. To describe these issues, it is necessary to present a richer model of student assignment where students may be ordered in different ways across schools.

Vulnerability of school choice mechanisms to manipulation played a role in the adoption of new student assignment mechanisms not only in Chicago, but also in

Boston and New York City.<sup>6</sup> An important difference between Chicago and these two cities is that the priority rankings of students are not the same at all schools. To handle this situation, both cities currently employ versions of the student-optimal stable mechanism.<sup>7</sup> For given student preferences and list of priority rankings at schools, the outcome of this mechanism can be obtained with the following *student-proposing deferred acceptance* algorithm:

Round 1: Each student applies to her first choice school. Each school rejects the lowest-ranking students in excess of its capacity and all unacceptable students among those who applied to it, keeping the rest of students temporarily (so students not rejected at this step may be rejected in later steps).

In general, at

Round  $\ell$ : Each student who was rejected in Round  $\ell - 1$  applies to her next highest choice (if any). Each school considers these students *and* students who are temporarily held from the previous step together, and rejects the lowest-ranking students in excess of its capacity and all unacceptable students, keeping the rest of students temporarily (so students not rejected at this step may be rejected in later steps).

The algorithm terminates either when every student is matched to a school or every unmatched student has been rejected by every acceptable school. Since there are a finite number of students and schools, the algorithm terminates in a finite number of steps. Gale and Shapley (1962) show that this algorithm results in a stable matching that each student weakly prefers to any other stable matching. Moreover, Dubins and Freedman (1981) and Roth (1982) show that truth-telling is a dominant strategy for each student under this mechanism. Their result implies that student-optimal stable mechanism is strategy-proof in the context of school choice where only students are potentially strategic agents.

Interaction of matching theorists with officials at New York City and Boston lead to adoption of versions of student-optimal stable mechanism by these school districts in 2003 and 2005, respectively. In New York City, however, the version of the mechanism adopted only allows students to submit a rank order list of 12 choices. Based on the strategy-proofness of the student-optimal stable mechanism, the following advice was given to students: “You must now rank your 12 choices according to your true preferences.”

For a student with more than 12 acceptable schools, truth-telling is no longer a dominant strategy under this version of the mechanism. In practice, between 20 to

<sup>6</sup>More details on these cases are presented in Abdulkadiroğlu et al. (2005) and Abdulkadiroğlu, Pathak, and Roth (2005).

<sup>7</sup>Abdulkadiroğlu and Sönmez (2003) first advocated using the celebrated student-optimal stable mechanism (Gale and Shapley 1962) when priorities differ across schools. Earlier, Balinski and Sönmez (1999) advocated the use of student-optimal stable mechanism in a centralized student placement model where priorities at schools are determined by standardized exams.

30 percent of students rank 12 schools, even though there are over 500 choice options in New York City.<sup>8</sup> This issue was first theoretically investigated by Haeringer and Klijn (2009) and experimentally by Calsamiglia, Haeringer, and Klijn (2010).

Some authorities using the student-optimal stable mechanism have increased the number of choices participants can express. For instance, Ajayi (2011) reports that the secondary school admission system in Ghana moved from  $GS^3$  to  $GS^4$  in 2007, and then to  $GS^6$  in 2008. Newcastle England switched from  $GS^3$  to  $GS^4$  by 2010. We next show that the greater the number of choices a student can make, the less vulnerable the constrained version of student-optimal stable mechanism is to manipulation. Let  $GS$  be the student-optimal stable mechanism, and  $GS^k$  be the constrained version of the student-optimal stable mechanism where only the top  $k$  choices are considered.

**PROPOSITION 2:** *Let  $\ell > k > 0$  and suppose there are at least  $\ell$  schools. Then  $GS^k$  is more manipulable than  $GS^\ell$ .*

When there is a unique priority ranking across all schools (as in the case of Chicago), mechanism  $GS^k$  reduces to mechanism  $SD^k$ . Hence the following corollary to Proposition 2 is immediate:

**COROLLARY 1:** *Let  $\ell > k > 0$ . Mechanism  $SD^k$  is more manipulable than mechanism  $SD^\ell$ .*

Just like the change in length list in Newcastle England, Chicago switched from  $SD^4$  to  $SD^6$  in 2010. In terms of promoting truth-telling, this is a further improvement although the unconstrained version of the mechanism would completely eliminate the possibility of manipulation.

### *C. The Ban of the Boston Mechanism in England*

The mechanism that was abandoned in Chicago midstream in 2009 is a special case of the widely studied Boston mechanism. For given student preferences and school priorities, the outcome of the *Boston mechanism* is determined with the following procedure:

Round 1: Only the first choices of students are considered. For each school, consider the students who have listed it as their first choice and assign seats of the school to these students one at a time following their priority order until there are no seats left or there is no student left who has listed it as her first choice.

In general, at

Round  $\ell$ : Consider the remaining students. In Round  $\ell$ , only the  $\ell$ th choices of these students are considered. For each school with still

<sup>8</sup>These details together with the entire description of the new assignment procedure are contained in Abdulkadiroğlu, Pathak, and Roth (2009).

available seats, consider the students who have listed it as their  $\ell$ th choice and assign the remaining seats to these students one at a time following their priority order until there are no seats left or there is no student left who has listed it as her  $\ell$ th choice.

The procedure terminates when each student is assigned a seat at a school.

Aside from Boston, variants of the mechanism have been used in several US school districts including: Cambridge, MA; Charlotte-Mecklenburg, NC; Denver, CO; Miami-Dade, FL; Minneapolis, MN; Providence, RI; and Tampa-St. Petersburg, FL.<sup>9</sup> However, the United States is not the only country where versions of the Boston mechanism are used to assign students to public schools. As we discussed in the introduction, a large number of English Local Authorities had been using what they referred to as “first preference first” systems until it became illegal in 2007. Formally, a *first preference first* (FPF) mechanism is a hybrid between the student-optimal stable mechanism and the Boston mechanism: under this mechanism, a school is either a *first preference first school* or an *equal preference school*, and the outcome is determined by the student-proposing deferred acceptance algorithm, where

- (i) the base priorities for each student are used for each equal preference school, whereas
- (ii) the base priorities of students are adjusted so that
  - any student who ranks school  $s$  as his first choice has higher priority than any student who ranks school  $s$  as his second choice,
  - any student who ranks school  $s$  as his second choice has higher priority than any student who ranks school  $s$  as his third choice,
  - ...

for each first preference first school.<sup>10</sup>

Observe that the Boston mechanism is a special case of this mechanism when all schools are first preference first schools and the student-optimal stable mechanism is a special case when all schools are equal preference schools.

For given fixed sets of first preference first schools and equal preference schools, let  $FPF$  be the first preference first mechanism and  $FPF^k$  be the version that only considers the top  $k$  student choices. Let  $\beta$  be the Boston mechanism and  $\beta^k$  be the Boston mechanism when only the top  $k$  student choices are considered. It will be convenient to let a matching in this and the next section indicate not only which school a student is assigned, but also which students are assigned to a school. Let  $FPF_s(P)$  denote the set of students assigned to school  $s$  by the FPF mechanism under

<sup>9</sup>Many school districts using variants of the Boston mechanism limit the number of schools that participants may rank. In Providence Rhode Island, students may only list four schools (out of 28 schools), while in Cambridge Massachusetts, students may only list three schools (out of nine schools).

<sup>10</sup>The relative priority ranking of two students do not change, unless one ranks the first priority first school higher than the other.

profile  $P$ , and similarly  $\beta_s(P)$  denote the set of students assigned to school  $s$  by the Boston mechanism under profile  $P$ .

One of the key reasons for the ban of the first preference first mechanism (and hence the Boston mechanism as well) was the strong incentives it gives parents to distort their submitted preferences. Even before the 2007 ban, this issue was central in several debates comparing the first preference first mechanism with the student-optimal stable mechanism (known as equal preference system in England). The following statement from the Coldron et al. (2008) report prepared for the Department for Children, Schools and Families summarizes what is at the heart of the debate:

*Further, the difference between the two systems in the numbers of parents gaining their first preferences should not be interpreted as necessarily meaning that equal preference systems lead to less parental satisfaction overall. In a first preference first area, if the schools a parent puts as first, second or third are oversubscribed they risk not getting in to their first preference school and are also likely not to get their second or third choice because they do not fit the first preference over-subscription criterion of those schools. This means that the first preference system to some extent restricts parents' room for manoeuvre, reduces their options and constrains them to put preferences for schools that are not their real preferred choice.*

According to the report, a large number of Local Authorities in England abandoned the first preference first mechanism as a result of the 2007 ban. Table 1 provides a list of districts where we have been able to obtain documentation on systems, building on a large list due to Coldron (2006). The list shows that Local Authorities switched from a constrained version of the first preference first mechanism to a constrained version of the student-optimal stable mechanism, where the constraint is typically greater in more populated areas like London. As in the case of Chicago, the vulnerability of the Boston mechanism to manipulation resulted in its removal throughout England along with its first preference first generalizations, while several Local Authorities adopted a constrained version of the student-optimal stable mechanism.

Our next result shows that not only is the FPF mechanism more manipulable than the student-optimal stable mechanism, its constrained version is more manipulable than the constrained version of the student-optimal stable mechanism. This result suggests that recent reforms throughout England involve adoption of less manipulable mechanisms.

**PROPOSITION 3:** *Suppose there are at least  $k$  schools where  $k > 1$ . Then  $FPF^k$  is more manipulable than  $GS^k$ .*

The following result is immediate.

**COROLLARY 2:** *Suppose there are at least  $k$  schools where  $k > 1$ . Then  $\beta^k$  is more manipulable than  $GS^k$ .*

Another corollary that immediately follows from Proposition 2 and Proposition 3 is of interest based on the reforms in Newcastle and Kent, which both moved from  $\beta^3$  to  $GS^4$ .

TABLE 1—SCHOOL ADMISSIONS REFORMS

Allocation system	Year	From	To	Manipulable (More or less?)	Source
Boston Public Schools (K, 6, 9)	2005	Boston	GS	Less	A,B,E
Chicago Selective High Schools	2009	Boston <sup>4</sup>	SD <sup>4</sup>	Less	A,B,C
	2010	SD <sup>4</sup>	SD <sup>6</sup>	Less	A,B,C
Ghana—Secondary schools	2007	GS <sup>3</sup>	GS <sup>4</sup>	Less	E
	2008	GS <sup>4</sup>	GS <sup>6</sup>	Less	E
Denver Public Schools	2012	Boston <sup>2</sup>	GS <sup>5</sup>	Less	A,B
Seattle Public Schools	1999	Boston	GS	Less	A,B,C,E,F
	2009	GS	Boston	More	A,B,C,F
England					
Bath and North East Somerset	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Bedford and Bedfordshire	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Blackburn with Darwen	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Blackpool	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Bolton	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Bradford	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Brighton and Hove	2007	Boston <sup>3</sup>	GS <sup>3</sup>	Less	A,C,D,E
Calderdale	2006	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,C
Cornwall	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Cumbria	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Darlington	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Derby	2005*	FPF <sup>4</sup>	GS <sup>4</sup>	Less	A,D
Devon	2006*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Durham	2007	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Ealing	2006*	FPF <sup>6</sup>	GS <sup>6</sup>	Less	A,D
East Sussex	2007	Boston <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Gateshead	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Halton	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Hampshire	2007	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Hartlepool	2007	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Isle of Wight	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Kent	2007	Boston <sup>3</sup>	GS <sup>4</sup>	Less	A,D
Kingston upon Thames	2007*	FPF <sup>3</sup>	GS <sup>4</sup>	Less	A
Knowsley	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Lancashire	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Lincolnshire	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Luton	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Manchester	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Merton	2006	FPF <sup>6</sup>	GS <sup>6</sup>	Less	A,D
Newcastle	2005	Boston <sup>3</sup>	GS <sup>3</sup>	Less	A
	2010	GS <sup>3</sup>	GS <sup>4</sup>	Less	A
North Lincolnshire	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
North Somerset	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
North Tyneside	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Oldham	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Peterborough	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Plymouth	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Poole	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Portsmouth	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Richmond	2005	FPF <sup>6</sup>	GS <sup>6</sup>	Less	D
Sefton primary	2007	Boston <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Sefton secondary	2007	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Slough	2006*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Somerset	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
South Gloucestershire	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
South Tyneside	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Southampton	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Stockton	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
Stoke-on-Trent	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Suffolk	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Sunderland	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D

(Continued)

TABLE 1—SCHOOL ADMISSIONS REFORMS (*Continued*)

Allocation system	Year	From	To	Manipulable (More or less?)	Source
Surrey	2007	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A,D
	2010	GS <sup>3</sup>	GS <sup>6</sup>	Less	A
Sutton	2006	FPF <sup>6</sup>	GS <sup>6</sup>	Less	A,D
Swindon	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Tameside	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Telford and Wrekin	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Torbay	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Warrington	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Warwickshire	2007*	FPF <sup>7</sup>	GS <sup>7</sup>	Less	D
Wilgan	2007*	FPF <sup>3</sup>	GS <sup>3</sup>	Less	D
Wales					
Wrexham County Borough	2011	FPF <sup>3</sup>	GS <sup>3</sup>	Less	A

Note: \* For changes in the 2007 code, an asterisk indicates that we assume the number of choices allowed has not changed.

Sources: A) Documentation from schools (brochures) or official policy minutes; B) Direct communication with school officials; C) Documentation from press clippings; D) Coldron report; E) Other academic papers; F) Other online materials. In some cases, we do not know the exact year the mechanism changed, the years correspond to the last possible year. The documentation Appendix includes sourcing for all mechanism changes.

**COROLLARY 3:** *Let  $\ell > k > 0$  and suppose there are at least  $\ell$  schools. Then  $FPF^k$  is more manipulable than  $GS^\ell$ .*

When each school orders applicants using the same criteria, the old Chicago mechanism  $CHI^k$  is a special case of the  $\beta^k$  and the new Chicago mechanism  $SD^k$  is a special case of  $GS^k$ . As a result, Proposition 1 is a corollary of Proposition 3.

#### D. Seattle's Unusual Experience

Chicago and England are the only places we know about where the Boston mechanism has stopped being used aside from Boston itself. The fact that these changes occurred without economists' prompting might suggest that the debate over the Boston mechanism has now been resolved. Nevertheless, the majority of US school districts continue to employ versions of the Boston mechanism, and in some districts the debate about its merits rages on.<sup>11</sup>

Seattle Public Schools has undertaken a series of important changes to their student assignment system. After the first draft of this paper, we learned that Seattle switched from the Boston mechanism to the student-optimal stable mechanism in 1999, though it was called the Barnhart-Waldman (BW) amendment in honor of two school board members who proposed the modification. But, it seems that this change was not advertised well, if at all, or well understood by participants.

There are many symptoms that the BW amendment was not well understood, even though strategy-proof mechanisms allow for straightforward advice. For instance, in a court challenge to the Seattle choice plan by *Parents Involved in Community Schools*, a case eventually decided by the US Supreme Court, confusion surrounding

<sup>11</sup> For another example, see Abebe (2009) describing the debate in Cambridge Public Schools.

the BW amendment came up in the school board president's deposition.<sup>12</sup> Eventually, in 2007, a parent obtained the computer code and verified that the BW amendment actually corresponds to the student-optimal stable mechanism (MacGregor 2007). Interestingly, researchers did not learn about the change until Seattle returned to the Boston mechanism in 2009.<sup>13</sup>

At first glance, the return to the Boston mechanism may seem to contradict the desirability of reducing a school choice mechanism's vulnerability to manipulation. However, there are other factors at play and the recent Seattle decision generated considerable controversy. Opponents of going back to the Boston mechanism raised points like those discussed in Boston, Chicago, and England. For instance, in her parent guide to the Seattle choice system, Walkup (2009) writes:

*The new choice algorithm can punish naive players. The best strategy for listing school choices for the old algorithm has been to list them in your true order of preference. You did not need to know how likely you were to get into a school to know the right order to list them.*

The Seattle situation highlights the importance of considering communication and guidance as key parts of a mechanism's design. When a mechanism is vulnerable to manipulation, it is not easy to provide advice. Walkup (2009) continues:

*During the first few years of the new plan it is likely that many families will still be repeating the previously correct advice to list schools in the actual order you prefer them.*

The Seattle case also makes clear that additional benefits of a strategy-proof mechanism are lost with a manipulable mechanism. Walkup continues:

*Since the algorithm is no longer blind to strategy, many people will use strategy when listing schools. The district will therefore no longer have accurate information about which programs families prefer.*

The fact that family groups were lobbying against the elimination of the BW amendment suggests that the Seattle change was deliberate. Intrigued by this episode, we corresponded with some of the school committee members involved.<sup>14</sup> While they

<sup>12</sup>Page 58 of the US Court of Appeals for the Ninth Circuit, No. 01-35450, *Parents Involved in Community Schools v. Seattle School District, No.1*, 2001 states:

Q: Can you explain for me what the Barnhart/Waldman Amendment is and how it works?

A: If I could I'd be the first. The Barnhart/Waldman—this is my understanding. The Barnhart/Waldman Amendment affects the way that choices are processed. Before we adopted that amendment, all the first choices were processed in one batch and assignments made. If you did not get your first choice, it is my understanding that all the students who did not get the first choice fell to the bottom of the batch processing line, and then they would process the second choices, et cetera. Barnhart/Waldman says that after all the first choices are processed, in the next batch, if you don't get your first choice, you don't fall to the bottom of the list but you are then processed, your second choice, with all the other second choices together. The result is that instead of a high degree of certainty placed—or of value placed on first choice, people can list authentically their first, second and third choices and have a higher degree of getting their second and third choice if they do not get their first choice. Now, was that clear as mud?

<sup>13</sup>The first reference to Seattle is in Abdulkadiroğlu, Che, and Yasuda (2011), who describe the episode as the "clock turning back."

<sup>14</sup>Not all committee members were willing and available to discuss the issue with us.

mentioned a few hard-to-square reasons (such as computer implementation costs), one suggested that the BW amendment encouraged mobility among students since parents could freely express their choices. By forcing families to adopt more conservative strategies such as ranking their neighborhood schools, the policy change could discourage student movement and therefore reduce transportation costs.

As a result, we do not believe that Seattle's return to the Boston mechanism is a counterexample to the desirability of a less manipulable mechanism, but rather illustrates that mechanisms can change for multiple reasons. Surely, the original motivation for the BW amendment involved limiting manipulation, and the district may not have reaped the benefits of the earlier policy change given the ongoing confusion. It appears that some policymakers were uncomfortable with the idea of school choice in the first place, but they did not succeed in bringing back a neighborhood school system. Returning to the Boston mechanism was a politically attractive alternative to entirely giving up school choice since it could decrease mobility across neighborhood zones. Whether Seattle continues with the Boston mechanism in future years remains to be seen.

### III. Agent-by-Agent Comparisons

#### A. Definitions

So far we compared real-life mechanisms based on set inclusion of their associated vulnerable profiles. Our next application involves the following stronger comparison of mechanisms.

**DEFINITION 4:** *A mechanism  $\psi$  is as strongly manipulable as mechanism  $\varphi$  if for any profile mechanism  $\varphi$  is vulnerable,  $\psi$  is (not only vulnerable but also) manipulable by any player who can manipulate  $\varphi$ .*

**DEFINITION 5:** *A mechanism  $\psi$  is strongly more manipulable than mechanism  $\varphi$  if*

- (i)  *$\psi$  is as strongly manipulable as mechanism  $\varphi$ , and*
- (ii) *there is a set of players  $I$ , a set of outcomes  $A$ , and a profile  $t$  where  $t$  is vulnerable under  $\psi$  but not under  $\varphi$ .*

Clearly if mechanism  $\psi$  is strongly more manipulable than mechanism  $\varphi$ , then mechanism  $\psi$  is also more manipulable than mechanism  $\varphi$ .

#### B. Two-Sided Matching Markets

Our next application pertains to college admissions model of Gale and Shapley (1962). Let  $J$  be the set of students with generic element  $j$ ,  $C$  be the set of colleges with generic element  $c$ , and the set of players are  $I = J \cup C$ . Here, both sides of the market are active players, in that both submit preference lists over the other side of the market. Following most of the literature, we assume that colleges have

responsive preferences (Roth 1985). That is, the ranking of a student is independent of her colleagues, and any set of students exceeding the quota is unacceptable. Given this assumption, we sometimes abuse notation and let  $P_c$  denote the preferences of college  $c$  defined over singleton student sets and the empty set.

As we have discussed in the context of school choice, truth-telling is a dominant strategy for each student under the student-optimal stable mechanism. We denote this mechanism as  $GS^{\mathcal{J}}$ . Gale and Shapley (1962) show that there exists an analogous stable matching that favors colleges. We refer to this mechanism as the college-optimal stable mechanism, and denote it as  $GS^{\mathcal{C}}$ .

While truth-telling is a dominant strategy for each student under  $GS^{\mathcal{J}}$ , an analogous result does not hold for colleges under  $GS^{\mathcal{C}}$ . Indeed, there is no stable mechanism where truth-telling is a dominant strategy for colleges in the college admissions model (Roth 1985). Our next result allows us to compare stable mechanisms by their vulnerability to manipulation for colleges. We need to extend definitions 4 and 5 before we present our next result. Fix a subset of agents  $I' \subset I$ .

A mechanism  $\psi$  is as strongly manipulable as mechanism  $\varphi$  for members of  $I'$  if for any profile  $t \in T$ , and any agent  $i \in I'$ ,

$$\exists t'_i \in T_i \text{ s.t. } \varphi(t'_i, t_{-i}) P_i \varphi(t) \quad \Rightarrow \quad \exists t_i^* \in T_i \text{ s.t. } \psi(t_i^*, t_{-i}) P_i \psi(t).$$

A mechanism  $\psi$  is strongly more manipulable than mechanism  $\varphi$  for members of  $I'$  if

- (i)  $\psi$  is as strongly manipulable as  $\varphi$  for members of  $I'$ , and
- (ii) there is a set of players  $I$ , a set of outcomes  $A$ , and a profile  $t$  where  $\psi$  can be manipulated by an agent in  $I' \subseteq I$  although  $\varphi$  cannot.

Results in this section follow from the following Lemma.

LEMMA 1: Fix a set of agents  $I' \subset J \cup C$ . Let  $\varphi$  and  $\psi$  be two stable mechanisms such that, for any preference profile  $P$ , and any agent  $i \in I'$ ,

$$\varphi_i(P) R_i \psi_i(P).$$

Then mechanism  $\psi$  is as strongly manipulable as mechanism  $\varphi$  for members of  $I'$ .

We are ready to present our next result.

PROPOSITION 4:  $GS^{\mathcal{J}}$  is strongly more manipulable than  $GS^{\mathcal{C}}$  for colleges.

Another natural question is whether it is possible to compare vulnerability of stable mechanisms to manipulation when both students and colleges are able to manipulate. Unfortunately, no comparison is possible because of the well-known conflict of interest between the two sides of the market. This tension is apparent in the following result.

**THEOREM 2:** *Let  $\varphi$  be an arbitrary stable mechanism. Then*

- (i)  $\varphi$  is as strongly manipulable as  $GS^c$  for colleges,
- (ii)  $GS^{\mathcal{J}}$  is as strongly manipulable as  $\varphi$  for colleges, and
- (iii)  $GS^c$  is as strongly manipulable as  $\varphi$  for students.

These results are related to discussions about the National Resident Matching Program (NRMP), the job market clearinghouse that annually fills more than 25,000 jobs for new physicians in the United States. Prior to 1998, its mechanism of choice was the college-optimal stable mechanism under which truth-telling is not a dominant strategy for students or colleges. In the mid-1990s, the NRMP came under increased scrutiny by students and their advisors who believed that the NRMP did not function in the best interest of students and was open to the possibility of different kinds of strategic behavior (Roth and Rothblum 1999). The mechanism was changed to one based on the student-optimal stable mechanism (Roth and Peranson 1999). One rationale was that truth-telling is a dominant strategy for students. For instance, the minutes of the Committee of the American Medical Student Association (AMSA) and the Public Citizen Health Research Group (cited in Ma 2010) state:

*...Since it is impossible to remove all incentives for hospitals to misrepresent, it would be best to choose the student-optimal algorithm to remove incentives, at least for students. In other words, within the set of stable algorithms, you either have incentives for both the hospitals and the students to misrepresent their true preferences or only for the hospitals.*

Theorem 2 and Proposition 4 imply that an unavoidable consequence of selecting a stable mechanism that removes incentives for manipulation among students is that the mechanism is the most vulnerable to manipulation for colleges.

#### IV. Comparisons Based on Intensity of Manipulation

##### A. Definitions

All of our applications up to this point are for models where agents are endowed with ordinal preferences. The magnitude of gain from a manipulation is not well-defined in these models without a cardinal utility representation. In many models, however, agents are endowed with cardinal preferences and one may want to compare magnitude of gain from potential manipulations when comparing two competing mechanisms for such models. We make one observation before proposing such a notion. To avoid interpersonal utility comparisons, a notion that incorporates the magnitude of manipulation will have to be even more demanding than the stronger of our two notions. That is, to deem mechanism  $\psi$  more vulnerable to such a notion of manipulation than mechanism  $\varphi$ ,

- (i) any agent who can manipulate  $\varphi$  will need to manipulate  $\psi$  as well, and

- (ii) the benefit from the latter manipulation will have to be at least as large.

Hence one can compare fewer mechanisms with this notion (even compared to our stronger notion). Notwithstanding, we present two important applications of this demanding notion later in this section.

For each agent  $i \in I$ , let  $u_i : A \rightarrow \mathbb{R}$  be a utility function that represents preferences of agent  $i$  over the set of allocations. Having defined these cardinal preferences, we can present the next definition:

**DEFINITION 6:** A mechanism  $\psi$  is as intensely and strongly manipulable as mechanism  $\varphi$  if for any agent  $i$ , problem  $t$ , type  $t'_i$ , and arbitrarily small  $\epsilon > 0$ ,

$$u_i(\varphi(t'_i, t_{-i})) - u_i(\varphi(t)) > 0$$

$$\Rightarrow \exists t_i^* \text{ s.t. } u_i(\psi(t_i^*, t_{-i})) - u_i(\psi(t)) > u_i(\varphi(t'_i, t_{-i})) - u_i(\varphi(t)) - \epsilon.$$

It is worth noting that we allow the benefit from the manipulation of mechanism  $\psi$  to be marginally smaller than the benefit from the manipulation of mechanism  $\varphi$ . This minor adjustment helps us avoid complications associated with choice of tie-breakers in applications and thus significantly increases the scope of our most demanding comparison.

**DEFINITION 7:** A mechanism  $\psi$  is intensely and strongly more manipulable than mechanism  $\varphi$  if

- (i)  $\psi$  is as intensely and strongly manipulable as mechanism  $\varphi$ , and
- (ii) there is a set of players  $I$ , a set of outcomes  $A$ , and a profile  $t$  where  $t$  is vulnerable under  $\psi$  but not under  $\varphi$ .

## B. Multi-Unit Auctions

Our next application involves the auctioning of multiple units of identical objects. The US Treasury's bond issue auctions, auctions for electricity and other commodities, and financial market auctions such as the opening batch auctions at the NYSE, Paris, and Amsterdam exchanges are examples of auctions involving multiple identical objects.<sup>15</sup> We are interested in comparing two sealed-bid auction formats. In each format, a bidder is asked to submit bids for each of the  $k$  units indicating how much she is willing to pay for each unit.

In the discriminatory format, also known as the pay-your-bid auction, each bidder pays an amount equal to the sum of her bids that are winning bids. The discriminatory auction is a natural multi-unit extension of the first-price sealed bid auction. Milton Friedman (1960) initially proposed a uniform-price auction, where all

<sup>15</sup> See Krishna (2002) for more examples and discussion.

$k$  units are sold at a “market-clearing” price such that the total amount demanded is equal to the total amount supplied.

Formally, a seller wishes to sell  $k$  units of identical items to a set  $I$  of bidders, where  $|I| \geq 2$ . The bidders, who are the agents in our framework, are asked to report their valuations for the  $k$  objects, where  $v_i^\ell$  is bidder  $i$ 's valuation for the  $\ell$ th unit. The vector  $v_i = (v_i^1, \dots, v_i^k) \in \mathbb{R}_+^k$  is the type of bidder  $i$  in our framework.

In both auctions we consider, each bidder submits a vector  $b_i = (b_i^1, \dots, b_i^k) \in \mathbb{R}_+^k$ , and the  $k$  units are awarded to the bidders with the  $k$  highest reported valuations.<sup>16</sup>

The utility of bidder  $i$  who wins  $\ell$  objects at a total cost of  $c$  is

$$u_i = v_i^1 + \dots + v_i^\ell - c.$$

The two payment rules we consider are:

- (i) **Discriminatory auction:** For the units awarded, the bidder pays the value declared for each unit.
- (ii) **Uniform-price auction:** For the units awarded, the bidder pays the  $(k + 1)$ th highest declared value for each unit.<sup>17</sup>

The US Treasury first adopted the discriminatory format in 1929 for the sale of short-term treasury securities. In the 1970s, the US Treasury also adopted a discriminatory format to auction Treasury bonds. In 1992, the US Treasury switched to a uniform-price auction for two and five year notes and since September 1998, all Treasury auctions use the uniform-price format.

Throughout these policy changes, the Treasury has been influenced by a number of arguments. Milton Friedman's influential testimony to the Joint Economic Committee of the US Congress in 1959 argued that a uniform-price format levels the playing field by reducing the importance of specialized knowledge among dealers. According to Friedman, more bidders would be induced to bid directly in uniform-price auctions because the fear of being awarded securities at too high a price is eliminated. Merton Miller supported this argument stating, “All of that [gaming] is eliminated if you use the [uniform-price] auction. You just bid what you think it's worth.” A US government report issued around that time jointly signed by the Treasury Department, SEC, and Federal Reserve Board states: “Moving to a uniform-price award method permits bidding at the auction to reflect the true nature of investor preferences.”<sup>18</sup>

Neither the discriminatory nor the uniform-price auction is strategy-proof. In particular, in both formats, bidders have an incentive to shade their bids. In a discriminatory auction, bidders have an incentive to report that their bids are just above the lowest bid that wins a unit. In a uniform-price auction, a bidder has an incentive to

<sup>16</sup>For both the discriminatory and uniform-price auction, we adopt the convention that when there is a tie, it is broken in favor of the bidder with the lower index  $i$ .

<sup>17</sup>It is possible to consider other “market clearing” rules such as paying the  $k$ th value or paying a value between the  $k$ th and  $(k + 1)$ th value. The comparison between formats is not sensitive to this choice.

<sup>18</sup>For more discussion on the influence of Friedman's argument, see Malvey, Archibald, and Flynn (1995) and Ausubel and Cramton (2002).

shade her bid for the units other than the first one because these bids have the potential to influence the market-clearing price if she wins. This “demand-reduction” feature of the uniform-price auction prevents it from being strategy-proof.

The next proposition supports Milton Friedman’s original argument about the incentive properties of the uniform-price auction relative to the discriminatory auction.

**PROPOSITION 5:** *The discriminatory auction is intensely and strongly more manipulable than the uniform-price auction.*

An alternative and complementary formalization of Milton Friedman’s argument has been recently given by Azevedo and Budish (2011): while both auction formats are manipulable, the discriminatory auction persists to be manipulable even in large economies even though the uniform-price auction is no longer manipulable in large economies when agents are “price-takers.”

### C. Keyword Auctions

Our final application involves the model for Internet advertising pioneered by Edelman, Ostrovsky, and Schwarz (2007) and Varian (2007). When an Internet user enters a search term into an online search engine, she obtains a web page with search results and sponsored links. The advertisements are ordered on the web page in different positions, with an advertisement shown at the top of the page more likely to be clicked than one at the bottom of the page. The process by which these advertisement slots are allocated to web pages is currently one of the largest auction markets (Edelman, Ostrovsky, and Schwarz 2007).

Our notation and model follow Edelman, Ostrovsky, and Schwarz (2007). There is a set  $I$  of bidders, and  $k < |I|$  ordered slots on a web page. For any  $\ell \in \{1, \dots, k\}$ , slot  $\ell$  has a *click-through rate* of  $\alpha_\ell$ , where  $\alpha_1 > \alpha_2 > \dots > \alpha_k > 0$ . The type  $t_i$  of bidder  $i$  is his valuation  $v_i \in \mathbb{R}_+$  per click. If bidder  $i$  wins the slot  $m$  at the cost of  $c$ , then his utility is:

$$u_i = \alpha_m v_i - c.$$

Edelman, Ostrovsky, and Schwarz (2007) present a detailed historical overview of the origins of this market. In 1997, Overture introduced an auction for selling Internet advertising. In the original design, each advertiser simultaneously bids for a slot for a particular keyword. The highest bidder receives the first slot at a price of his bid times the click-through rate of slot 1, the second highest bidder receives the second slot at a price of his bid times the click-through rate of slot 2, and so on. Overture’s search platform was adopted by major search engines including Yahoo! and MSN. This auction format is known as the *Generalized First Price* (GFP) auction.

In February 2002, Google introduced its own pay-per-click system, AdWords Select, based on a different payment rule. The highest bidder receives the first slot at a price of the second highest bid times the click-through rate of slot 1, the second highest bidder receives the second slot at a price of the third highest bid times the

click-through rate of slot 2, and so on. This auction format has come to be known as the *Generalized Second Price* (GSP) auction. Once Google introduced this new format, many search engines including Yahoo!/Overture also switched to the GSP.

While neither mechanism is strategy-proof, Edelman, Ostrovsky, and Schwarz (2007) argue that “The second-price structure makes the market more user friendly and less susceptible to gaming.”

Our final result formalizes their insight.

**PROPOSITION 6:** *The Generalized First Price Auction is intensely and strongly more manipulable than the Generalized Second Price Auction.*

## V. Conclusion

Recent school admission reforms are motivated in part by the desire to reduce strategic considerations among participants, even though many new mechanisms are still not completely immune to manipulation. These changes motivate the methodology we propose to rank mechanisms by their vulnerability to manipulation. In Chicago, the abandoned mechanism is at least as manipulable as any other weakly stable mechanism. In England, the 2007 School Code outlawed first preference first mechanisms and numerous districts have adopted an equal preference system. According to our notion, numerous English districts have done away with more manipulable mechanisms.

The changes to school assignment systems in recent years are widespread. The list of reforms in Table 1 implies that hundreds of thousands of students have been affected. Every listed change, except Seattle, involves a move toward a less manipulable mechanism. It is therefore clear that vulnerability to manipulation is perceived as an undesirable feature of school choice mechanisms.

While school choice reforms provide our main motivation, the methodology has applications in other matching and assignment models, including the college admissions model. We have also illustrated applications for auction settings, and examined manipulation definitions that take intensity of manipulation into account. Certainly, we have not exhausted possible applications of these concepts. For instance, work in progress by Dasgupta and Maskin (2010) explores a similar idea in voting problems, comparing Condorcet and Borda rules, and similar ideas have been recently studied in problems of fair division with indivisible objects (see, e.g., Andersson, Ehlers, and Svensson 2010).

The case studies we have explored all involve widespread condemnation of the Boston mechanism, and the participants themselves (and not matching theorists) advocated reorganizing market designs. In this respect, the school admissions reforms parallel changes in marketplace rules for the placement of medical residents in the early 1950s documented by Roth (1984). Following Boston Public Schools' abandonment of the mechanism in 2005, there has been a renewed interest in understanding its properties. Some researchers have cautioned against a hasty rejection of the Boston mechanism in favor of the student-optimal stable mechanism (Abdulkadiroğlu, Che, and Yasuda 2011; Featherstone and Niederle 2011; Miralles 2008). When interpreted through the lens of the public and policymaker's

revealed preferences, events in Chicago and England weigh against the desirability of the Boston mechanism.

It is worth emphasizing that vulnerability to manipulation is not the only criterion to consider when comparing mechanisms. That being said, manipulation seems to have been a critical reason for the 2009 policy change in Chicago and changes throughout England. Of course, it is important to consider different properties of a mechanism and the alternatives (as well as political and practical issues) when deciding on the best mechanism. In situations where strategy-proof mechanisms do not have obvious drawbacks, as one might argue for eliminating restrictions on the number of choices allowed in school choice, an interesting question for future work is to understand the reasons they are not used.

## REFERENCES

- Abdulkadiroğlu, Atila, Yeon-Koo Che, and Yosuke Yasuda.** 2011. "Resolving Conflicting Preferences in School Choice: The 'Boston Mechanism' Reconsidered." *American Economic Review* 101 (1): 399–410.
- 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 Pathak, Alvin E. Roth, and Tayfun Sönmez.** 2005. "The Boston Public School Match." *American Economic Review* 95 (2): 368–71.
- Abdulkadiroğlu, Atila, Parag Pathak, Alvin E. Roth, and Tayfun Sönmez.** 2006. "Changing the Boston School Choice Mechanism." National Bureau of Economic Research Working Paper 11965.
- Abdulkadiroğlu, Atila, and Tayfun Sönmez.** 2003. "School Choice: A Mechanism Design Approach." *American Economic Review* 93 (3): 729–47.
- Abebe, Rediet.** 2009. "School Assigning Process Criticized: MIT Professor Presents a Possible Solution to the Problem." *The Harvard Crimson*, November 25. <http://www.thecrimson.com/article/2009/11/25/cambridge-school-choice> (accessed December 18, 2011).
- Ajayi, Kehinde.** 2011. "A Welfare Analysis of School Choice Reforms in Ghana." Unpublished.
- Andersson, Tommy, Lars Ehlers, and Lars-Gunnar Svensson.** 2010. "Budget-Balance, Fairness and Minimal Manipulability." Unpublished.
- Austen-Smith, David, and Jeffrey S. Banks.** 2005. *Positive Political Theory II: Strategy and Structure*. Michigan Studies in Political Analysis. Ann Arbor: University of Michigan Press.
- Ausubel, Larry, and Peter Cramton.** 2002. "Demand Reduction and Inefficiency in Multi-Unit Auctions." Unpublished.
- Azevedo, Eduardo, and Eric Budish.** 2011. "Strategyproofness in the Large as a Desideratum for Market Design." Unpublished.
- Balinski, Michel, and Tayfun Sönmez.** 1999. "A Tale of Two Mechanisms: Student Placement." *Journal of Economic Theory* 84 (1): 73–94.
- Barberá, Salvador.** 2010. "Strategy-proof Social Choice." Barcelona Economics Working Paper Series, Working Paper No. 420.
- Calsamiglia, Caterina, Guillaume Haeringer, and Flip Klijn.** 2010. "Constrained School Choice: An Experimental Study." *American Economic Review* 100 (4): 1860–74.
- Carroll, Gabriel.** 2011. "A Quantitative Approach to Incentives: Application to Voting Rules." Unpublished.
- Chen, Yan, and Tayfun Sönmez.** 2006. "School Choice: An Experimental Study." *Journal of Economic Theory* 127 (1): 202–31.
- Coldron, John.** 2006. "Survey of Local Education Authorities with First Preferences or Equal Preferences." Sheffield, UK: Sheffield Hallam University, Centre for Education Research.
- Coldron, John, Emily Tanner, Steven Finch, Lucy Shipton, Claire Wolstenholme, Ben Willis, Sean Demack, and Bernadette Stiell.** 2008. *Secondary School Admissions*. Research Report DCSF-RR020. Sheffield, UK: Sheffield Hallam University; London: National Centre for Social Research.
- Cook, Gareth.** 2003. "School Assignment Flaws Detailed: Two Economists Study Problem, Offer Relief." *Boston Globe*, September 12.

- Dasgupta, Partha, and Eric Maskin.** 2008. "On the Robustness of Majority Rule." *Journal of the European Economic Association* 6 (5): 949–73.
- Dasgupta, Partha, and Eric Maskin.** 2010. Elections and Strategic Voting: Condorcet and Borda. University of California, Irvine, Conference on Adaptive Systems and Mechanism Design. Unpublished slides.
- Day, Robert, and Paul Milgrom.** 2008. "Core-Selecting Package Auctions." *International Journal of Game Theory* 36 (3): 393–407.
- Dubins, Lester E., and David A. Freedman.** 1981. "Machiavelli and the Gale-Shapley Algorithm." *American Mathematical Monthly* 88 (7): 485–94.
- Edelman, Benjamin, Michael Ostrovsky, and Michael Schwarz.** 2007. "Internet Advertising and the Generalized Second-Price Auction: Selling Billions of Dollars Worth of Keywords." *American Economic Review* 97 (1): 242–59.
- Erdil, Aytek, and Paul Klemperer.** 2010. "A New Payment Rule for Core-Selecting Package Options." *Journal of the European Association* 8 (2–3): 537–47.
- Ergin, Haluk, and Tayfun Sönmez.** 2006. "Games of School Choice under the Boston Mechanism." *Journal of Public Economics* 90 (1–2): 215–37.
- Featherstone, Clayton, and Muriel Niederle.** 2011. "School Choice Mechanisms under Incomplete Information: An Experimental Investigation." Unpublished.
- Friedman, Milton.** 1960. *A Program for Monetary Stability*. Bronx, NY: Fordham University Press.
- Gale, David, and Lloyd Shapley.** 1962. "College Admissions and the Stability of Marriage." *American Mathematical Monthly* 69 (1): 9–15.
- Great Britain, Department for Education and Skills.** 2007. *School Admissions Code*. Norwich, UK: Her Majesty's Stationery Office.
- Haeringer, Guillaume, and Flip Klijn.** 2009. "Constrained School Choice." *Journal of Economic Theory* 144 (5): 1921–47.
- Hastings, Justine S., Thomas J. Kane, and Douglas O. Staiger.** 2006. "Preferences and Heterogeneous Treatment Effects in a Public School Choice Lottery." National Bureau of Economic Research Working Paper 12145.
- Kesten, Onur.** 2006. "On Two Competing Mechanisms for Priority-Based Allocation Problems." *Journal of Economic Theory* 127 (1): 155–71.
- Krishna, Vijay.** 2002. *Auction Theory*. Amsterdam: Elsevier Science, Academic Press.
- Lim, Nelson, Jefferson P. Marquis, Kimberly C. Hall, David Schulker, and Xiaohui Zhuo.** 2009. *Officer Classification and the Future of Diversity Among Senior Military Leaders: A Case Study of the Army ROTC*. A RAND Corporation Report. Santa Monica, CA: RAND Corporation.
- Ma, Jinpeng.** 2010. "The Singleton Core in the College Admissions Problem and Its Application to the National Resident Matching Program (NRMP)." *Games and Economic Behavior* 69 (1): 150–64.
- MacGregor, Chris.** 2007. "The REAL Truth about Seattle Public Schools Kindergarten Assignments." <http://www.cybermat.com/projects/school-assignments/> (accessed December 12, 2011).
- Malvey, Paul, Christine Archibald, and Sean Flynn.** 1995. "Uniform-Price Auctions: Evaluation of the Treasury Experience." Washington, DC: Office of Market Finance, US Treasury.
- Miralles, Antonio.** 2008. "School Choice: The Boston Mechanism Reconsidered." Unpublished.
- Parkes, David C., Jayant Kalnjanam, and Marta Eso.** 2001. "Achieving Budget-Balance with VCG-Based Payment Schemes in Combinatorial Exchanges." IBM Research Report RC 22218 10/23.
- Pathak, Parag A., and Tayfun Sönmez.** 2008. "Leveling the Playing Field: Sincere and Sophisticated Players in the Boston Mechanism." *American Economic Review* 98 (4): 1636–52.
- Providence School Department.** 2010. "Parent Handbook 2010–2011." Providence, RI: Office of Communications, Providence Public School Department. <http://www.providenceschools.org/media/93431/parent%20handbook%201011%20eng.pdf/> (accessed January 31, 2011).
- Rossi, Rosalind.** 2009. "8th-Graders' Shot at Elite High Schools Better." *Chicago Sun-Times*, November 12.
- 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.** 1985. "The College Admissions Problem Is Not Equivalent to the Marriage Problem." *Journal of Economic Theory* 36 (2): 277–88.
- Roth, Alvin E.** 2008. "Deferred Acceptance Algorithms: History, Theory, Practice, and Open Questions." *International Journal of Game Theory* 36 (3–4): 537–69.
- 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., and Uriel G. Rothblum.** 1999. "Truncation Strategies in Matching Markets—In Search of Advice for Participants." *Econometrica* 67 (1): 21–43.
- Roth, Alvin E., and Marilda A. Oliveira Sotomayor.** 1990. *Two-Sided Matching: A Study in Game-Theoretic Modeling and Analysis*. Econometric Society Monographs, no. 18. New York: Cambridge University Press.
- Sönmez, Tayfun.** 2011. "Bidding for Army Career Specialties: Improving the ROTC Branching Mechanism." Boston College Department of Economics, Working Paper 783.
- Varian, Hal R.** 2007. "Position Auctions." *International Journal of Industrial Organization* 25 (6): 1163–78.
- Walkup, Elizabeth.** 2009. "Seattle Public Schools' Proposed Student Assignment Plan: the Good, the Bad, the Ugly." [http://www.teriyakidonut.com/schools/SAP\\_gbu.pdf/](http://www.teriyakidonut.com/schools/SAP_gbu.pdf/) (accessed December 18, 2011).