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ABSTRACT

We study a mechanism design version of matching computation in graphs that models the game played by hospitals participating in pairwise kidney exchange programs. We present a new randomized matching mechanism for two agents which is truthful in expectation and has an approximation ratio of $3/2$ to the maximum cardinality matching. This is an improvement over a recent upper bound of 2 (Ashlagi et al., 2010 [2]) and, furthermore, our mechanism beats for the first time the lower bound on the approximation ratio of deterministic truthful mechanisms. We complement our positive result with new lower bounds. Among other statements, we prove that the weaker incentive compatibility property of truthfulness in expectation in our mechanism is necessary; universally truthful mechanisms that have an inclusion-maximality property have an approximation ratio of at least 2.

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1. Introduction

In an attempt to address the wide need for kidney transplantation and the scarcity of cadaver kidneys, several countries have launched, or are considering, national kidney exchange programs involving live donors [1,4,7,11]. Patients can enter such a program together with a member of their family or friend who is willing to donate them a kidney but cannot due to incompatibility. National kidney exchange programs aim to implement exchanges between two compatible patient–donor pairs u and v so that the donor of pair u donates her kidney to the patient of pair v and vice versa. This requires four simultaneous operations. More complicated exchanges involving more than two donor–patient pairs are also possible; however, we focus on pairwise exchanges since they are easier to perform in practice.

Donor–patient pairs approach a hospital in order to enroll into the national kidney exchange programs. In an ideal scenario, each hospital reports its donor–patient pairs to the program and a central authority runs an algorithm that decides which pairwise kidney exchanges will take place. In practice, strategic issues immediately arise. A hospital may prefer to not enroll some easy-to-match donor–patient pairs to the program and instead match them and perform the kidney exchange operations internally. This may have an impact on patients of other hospitals who could have benefited if the hospital

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truthfully reported all its donor–patient pairs to the program. The current paper follows the line of research that seeks to design algorithms (or mechanisms) that discourage hospitals from behaving untruthfully. The main objective is to perform as many kidney exchanges as possible under this constraint. This is a *mechanism design* [5] problem, and in particular—because paying for organs is illegal in almost all countries—it falls within the scope of approximate mechanism design without money [6].

We can model the problem as a matching problem in graphs. The input consists of a graph in which the nodes represent donor–patient pairs and an edge connects two nodes u and v when the donor of pair u and the patient of pair v are compatible, and the donor of pair v and the patient of pair u are compatible. Each node of the graph is controlled by exactly one self-interested agent (a hospital). A *mechanism* takes the graph as input and returns a matching, i.e., a disjoint pair of edges indicating which pairwise kidney exchanges will take place. The *gain* of an agent is the number of nodes under her control that are matched. Clearly, an optimal solution is easy to find by a maximum matching computation. Unfortunately, a mechanism that returns such a solution may incentivize hospitals to behave untruthfully in the following sense. A hospital could hide some of its nodes from (i.e., not enroll them into) the system so that the mechanism is essentially applied on a graph that contains neither the hidden nodes nor the edges incident to them. Then, the gain of the hospital is the number of its nodes that are matched by the mechanism plus the number of nodes it managed to match internally. Such behavior can lead to fewer matched nodes compared to the best possible solution, i.e., fewer patients who receive kidneys. So, we seek mechanisms that guarantee that no agent has any incentive to deviate from truth-telling. Our goal is to design such mechanisms that also return matchings of high cardinality, i.e., high total gain.

The mechanisms can be deterministic or randomized. Given an instance of the problem, a deterministic mechanism returns a simple matching. A randomized mechanism returns a probability distribution over matchings. In the latter case, we distinguish between *universally truthful* mechanisms and mechanisms that are *truthful in expectation*. The former are induced by a probability distribution over truthful deterministic mechanisms, whereas the latter guarantee that no agent can deviate from truth-telling in order to increase her expected gain. The efficiency of truthful mechanisms is assessed through their *approximation ratio*, i.e., the maximum ratio over all possible instances of the problem of the size of the maximum cardinality matching over the expected size of the matching returned by the mechanism.

Related work Early work on kidney exchange problems in Economics [8–10] has considered the incentives of incompatible donor–patient pairs. However, as national kidney exchange programs emerged, it has become apparent that such incentives are less important compared to the incentives of the hospitals [3]. The model considered in the current paper has also been studied in [2,3,12,13]. The fact that the maximum cardinality matching mechanism is not truthful was first observed by Sönmez and Ünver [12] (see also [3]). Ashlagi et al. [2] present a universally truthful randomized 2-approximation mechanism (called MIX-AND-MATCH) for arbitrarily many agents. MIX-AND-MATCH is based on a simple deterministic truthful 2-approximation mechanism for two agents, henceforth called MATCH. MATCH returns a matching that contains the maximum number of *internal edges* (where the nodes on both sides are controlled by the same agent), breaking ties in favor of the matching with maximum cardinality. A nice property of MATCH is *inclusion-maximality*; this translates to the requirement that a donor–patient pair does not participate in any kidney exchange only when all its compatible donor–patient pairs participate in some pairwise kidney exchange. A randomized mechanism has this property when it returns a probability distribution over inclusion-maximal matchings. On the negative side, there are lower bounds of 2 and 8/7 for deterministic truthful mechanisms and randomized mechanisms that are truthful in expectation, respectively [2,3]. Ashlagi et al. [2] also propose the mechanism FLIP-AND-MATCH for two agents. FLIP-AND-MATCH equiprobably selects among the outcome of MATCH and a maximum cardinality matching. They prove that this mechanism has approximation ratio 4/3 and leave open the question of whether it is truthful in expectation. Ashlagi and Roth [3] and Toulis and Parkes [13] consider weaker notions of truthfulness in random graph models that reflect the compatibility frequency among donors and patients from the human population. As in [2], no such information is required in our setting.

Our results In an attempt to better understand the potential and limitations of randomized mechanisms, we consider the case of two agents. This case is of special interest because efficient mechanisms can enable cooperation between pairs of hospitals on an *ad-hoc* basis, in countries where a national kidney exchange program is not yet in place. Our main result is a randomized mechanism called WEIGHT-AND-MATCH for 2-agent pairwise kidney exchange that is truthful in expectation and has a tight approximation ratio of 3/2. This establishes, for the first time, a separation between the power of randomized mechanisms and deterministic mechanisms (for which there is a lower bound of 2).

WEIGHT-AND-MATCH is inspired by the mechanism FLIP-AND-MATCH proposed in [2]. Unfortunately, it turns out that FLIP-AND-MATCH is not truthful due to its use of maximum cardinality matchings. This observation is our starting point for the definition of the new mechanism. WEIGHT-AND-MATCH first assigns weights to the edges of the input graph and then selects equiprobably among two maximum-weight matchings: one with minimum cardinality (the particular weights assigned to the edges guarantee that this matching is identical to the one returned by MATCH) and one with maximum cardinality (which replaces the second matching used by FLIP-AND-MATCH). Informally, this definition guarantees that the bad incentives created by the second matching are canceled out by the outcome of MATCH.

We complement this result with new lower bounds on the approximation ratio of randomized mechanisms that are truthful in expectation or universally truthful, distinguishing between mechanisms that are inclusion-maximal and those that are not. Here we use the same 2-agent instance as in previous work [2,3,12] but our stronger analysis leads to im-

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