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Stable Matchings for the Room-mates Problem

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Stable Matchings for the Room-mates Problem

Summary

We show that, given two matchings for a room-mates problem of which say the second is stable, and given a non-empty subset of agents S if (a) no agent in S prefers the first matching to the second, and (b) no agent in S and his room-mate in S under the second matching prefer each other to their respective room-mates in the first matching, then no room-mate of an agent in S prefers the second matching to the first. This result is a strengthening of a result originally due to Knuth (1976).

In a paper by Sasaki and Toda (1992) it is shown that if a marriage problem has more than one stable matchings, then given any one stable matching, it is possible to add agents and thereby obtain exactly one stable matching, whose restriction over the original set of agents, coincides with the given stable matching. We are able to extend this result here to the domain of room-mates problems.

We also extend a result due to Roth and Sotomayor (1990) originally established for two-sided matching problems in the following manner: If in a room-mates problem, the number of agents increases, then given any stable matching for the old problem and any stable matching for the new one, there is at least one agent who is acceptable to this new agent who prefers the new matching to the old one and his room-mate under the new matching prefers the old matching to the new one.

Sasaki and Toda (1992) shows that the solution correspondence which selects the set of all stable matchings, satisfies Pareto Optimality, Anonymity, Consistency and Converse Consistency on the domain of marriage problems. We show here that if a solution correspondence satisfying Consistency and Converse Consistency agrees with the solution correspondence comprising stable matchings for all room-mates problems involving four or fewer agents, then it must agree with the solution correspondence comprising stable matchings for all room-mates problems.

Keywords: Stable matchings, Room-mate problem

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1. Introduction :

A salient feature of many markets is to match one agent with another. This is particularly true, in the case of assigning tasks to individuals where each task is under the supervision of an individual, and where the set of supervisors and the set of workers are disjoint. Such markets are usually studied with the help of "two sided matching models" introduced by Gale and Shapley (1962) called the marriage problem. However, not all matching problems where disjoint pairs are required to form, is dichotomous. For instance in a doubles version of a tennis tournament, pairs are formed from a given pool of players, without any obvious dichotomy existing within the pool. In the case of "mixed doubles" however, a man and a woman need to form a pair, as in the case of a two-sided matching market. The problem of forming disjoint pairs out of a given set of agents is what Gale and Shapley(1962) called a room-mates problem. The marriage problem is indeed a special case of their room-mates problem.

The solution concept proposed by Gale and Shapley (1962), called a stable matching, requires that there should not exist two agents, who prefer each other, to the individual they have been paired with. It was shown in Gale and Shapley (1962), in a framework where every agent has preference defined by a linear order over the entire set of agents, that a room-mates problem may not admit any stable matching although a marriage problem always does. Indeed, given a marriage problem, there is always a stable matching which no man considers inferior to any other stable matching, and there is always a stable matching that no woman considers inferior to any other stable matching. The first is called an M – optimal stable matching (i.e. stable matching optimal for men) and the second one a W – optimal stable matching (i.e. stable matching optimal for women). An overview of the considerable literature on marriage problems that has evolved out of the work of Gale and Shapley (1962), is available in Roth and Sotomayor (1990). Lahiri (2002) contains alternative simpler proofs of some existing results and some new conclusions for two-sided matching problems.

Tan (1991) obtained a necessary and sufficient condition for the existence of a stable matching for a room-mates problem. Chung (2000), generalized a result of Roth and Vande Vate (1990) originally established in the context of the marriage

model, to show that the satisfaction of a "no odd rings" condition was sufficient for a room-mates problem to admit a stable matching. This result was shown to hold even when preferences were not necessarily strict. Diamantoudi, Miyagawa and Xue (2002), were able to show that a process of "myopic blocking" would necessarily converge to the set of stable matchings of a room-mates problem with strict preferences, provided the required set was non-empty. However, while the body of literature on existence of stable matchings for room-mates problems is quite enormous, there has been very little investigation of the properties of such matchings, if and when they do exist. This paper attempts to fill this gap by analyzing the co-operative theory of stable matchings for room-mates problems. The first significant result that we present here is a strengthening of a result originally due to Knuth (1976). The original result said that given any two stable matchings for a marriage problem, if no man prefers the first matching to the second, then no woman prefers the second matching to the first. In Lahiri (2002) we show that, given two matchings for a marriage problem of which say the second is stable, if (a) no man prefers the first matching to the second, and (b) no man and the woman he is paired with under the second matching prefer each other to their respective assignments in the first matching, then no woman prefers the second matching to the first. In this paper we are able to extend the above result to the domain of all room-mates problems in the following manner: Given two matchings for a room-mates problem of which say the second is stable, and given a non-empty subset of agents S if (a) no agent in S prefers the first matching to the second, and (b) no agent in S and his room-mate in S under the second matching prefer each other to their respective room-mates in the first matching, then no room-mate of an agent in S prefers the second matching to the first. As a consequence, we obtain an extension of a result in Lahiri (2002) from the domain of marriage problems to the domain of room-mates problems. The earlier result, which was a generalization of the Strong Stability Theorem of Demange, Gale and Sotomayor (1987) for a particular case, says that if an unstable matching for a marriage problem is no better for any man compared to a given stable matching, then there is a pair under the stable matching who block the unstable matching. Our result here says that if for a subset of agents it is the case that an unstable matching is no better than a given stable matching, and if all blocking pairs of the unstable matching comprise an agent from the set and an agent from the set of room-mates of the given set, then there is a pair of room-mates in the stable matching who block the unstable matching.

In a paper by Sasaki and Toda (1992) it is shown that if a marriage problem has more than one stable matchings, then given any one stable matching, it is possible to add agents and thereby obtain exactly one stable matching, whose restriction over the original set of agents, coincides with the given stable matching. We are able to extend this result here to the domain of room-mates problems.

A theorem due to Roth and Sotomayor (1990), says that if in a marriage problem, the number of women increases, then there is a non-empty subset of men and the set of women they are assigned to under the M – optimal stable matching, such that given any stable matching for the old marriage problem and any stable matching for the new one, every man in the set prefers the new matching to the

old one and every woman in the set prefers the old matching to the new one. This result requires the use of a theorem due to Gale and Sotomayor (1985), which says that with more women around, men prefer the new optimal stable matchings to the corresponding ones of the old marriage problem, while the opposite is true for woman. However, the starting point of the above result due to Roth and Sotomayor (1990) is the following: If in a marriage problem, the number of women increases by one, then given any stable matching for the old marriage problem and any stable matching for the new marriage problem, there is a non-empty subset of men and the set of women they are paired with under the new stable matching, such that every man in the set prefers the new matching to the old one and every woman in the set prefers the old matching to the new one. In this paper we extend this latter result to the domain of all room-mates problems in the following manner: If in a room-mates problem, the number of agents increases, then given any stable matching for the old problem and any stable matching for the new one, there is at least one agent who is acceptable to this new agent who prefers the new matching to the old one and his room-mate under the new matching prefers the old matching to the new one.

Sasaki and Toda (1992) shows that the solution correspondence which selects the set of all stable matchings, satisfies Pareto Optimality, Anonymity, Consistency and Converse Consistency on the domain of marriage problems. The observation that a similar result is true on the domain of all room-mates problems is quite immediate. However, the solution correspondence comprising matchings which resemble a kind of serial dictatorship is always non-empty valued on the domain of all room-mates problems and also satisfies the above mentioned properties. We show here that if a solution correspondence satisfying Consistency and Converse Consistency agrees with the solution correspondence comprising stable matchings for all room-mates problems involving four or fewer agents, then it must agree with the solution correspondence comprising stable matchings for all room-mates problems.

2. The Model :

Let X be a non-empty finite subset of \mathbb{N} (the set of natural numbers), denoting the set of participating agents. Each agent $a \in X$ has preferences over X represented by a linear order R_a (: a binary relation R on X is said to be a linear order if it is reflexive, complete, anti-symmetric and transitive). Given a binary relation R on X and a non-empty subset S of X , let $R|_S = R \cap (S \times S)$ and let $P(R) = \{ (x,y) \in R / (y,x) \notin R \}$ denote the asymmetric part of R .

A room-mates problem G is an array $\langle X, (R_a)_{a \in X} \rangle$. Given a room-mates problem $G = \langle X, (R_a)_{a \in X} \rangle$ and $a \in X$, the acceptable set for a , denoted $A(a) = \{b \in X / (b,a) \in R_a\}$.

Given $G = \langle X, (R_a)_{a \in X} \rangle$ and $a, b, c \in X$, we denote $(b,c) \in R_x$ by $b R_x a$, $P(R_a)$ by P_a and $(b,c) \in P_a$ by $y P_x z$.

A room-mates problem $G = \langle X, (R_a)_{a \in X} \rangle$ is called a marriage problem if there exists two non-empty disjoint subsets M and W of X , such that (i) $M \cup W = X$; (ii) for all $a, b, c \in X$: [$a, b \in M, c \in W$ with $a \neq b$ implies $a P_a b$ and $c P_a b$]; (iii) for all $a, b, c \in X$: [$a, b \in W, c \in M$ with $a \neq b$ implies $a P_a b$ and $c P_a b$]. We denote a marriage

problem as $\langle (M, W), (R_x)_{x \in M \cup W} \rangle$. M is called the set of men and W the set of women.

Given a room-mates problem $G = \langle X, (R_a)_{a \in X} \rangle$, a matching for G is a bijection μ from X to itself such that for all $a \in X$: (i) $\mu(a) \in A(a)$; (ii) $\mu(\mu(a)) = a$.

Since the identity function on X is a matching every room-mates problem admits at least one matching.

Given a matching μ for a room-mates problem $G = \langle X, (R_a)_{a \in X} \rangle$, a pair $(a, b) \in X \times X$ is said to block μ , if $b P_a \mu(a)$ and $a P_b \mu(b)$. The matching μ is said to be stable if it does not admit any blocking pair.

Given two matchings μ, μ' for $G = \langle X, (R_a)_{a \in X} \rangle$ and a non-empty subset S of X , we write:

- (i) $\mu \geq_S \mu'$ if $\mu(a) R_a \mu'(a)$ for all $a \in S$;
- (ii) $\mu >_S \mu'$ if $\mu \geq_S \mu'$ but $\mu \neq \mu'$;
- (iii) $\mu \gg_S \mu'$ if $\mu(a) P_a \mu'(a)$ for all $a \in S$

In the case where S is a singleton, $S = \{a\}$, we write $\mu R_a \mu'$ to denote $\mu \geq_{\{a\}} \mu'$ and $\mu P_a \mu'$ to denote $\mu >_{\{a\}} \mu'$.

Let E be the class of all room-mates. Given $G \in E$, let $F(G)$ be the set of all matchings for G . Let $F = \bigcup_{G \in E} F(G)$. Let 2^F , denote the power set of F (i.e. the set of

all subsets of F). A solution on E is a function $\varphi: E \rightarrow 2^F$, such that for all $G \in E$, $\varphi(G) \subset F(G)$.

The stable matching solution on E , denoted St is the solution on E , such that for all $G \in E$: $St(G) = \{\mu \in F(G) / \mu \text{ is a stable matching for } G\}$.

The following example due to Gale and Shapley (1962) shows that a room-mates problem need not admit any stable matching.

Example 1 (Gale Shapley (1962)) : Let $X = \{1, 2, 3, 4\}$. Suppose the preferences of the agents are defined as follows:

Agent 1: $2 P_1 3 P_1 4 P_1 1$;

Agent 2: $3 P_2 1 P_2 4 P_2 2$;

Agent 3: $1 P_3 2 P_3 4 P_3 3$;

Agent 4: $1 P_4 2 P_4 3 P_4 4$.

Suppose the matching μ is such that $\mu(4) \neq 4$. If $A\mu(4) = 3$, then $\{2, 3\}$ blocks μ ; if $\mu(4) = 2$, then $\{1, 2\}$ blocks μ ; if $\mu(4) = 1$, then $\{1, 3\}$ blocks μ . Hence if μ were a stable matching it should be the case that $\mu(4) = 4$. If $\mu(1) = 1$, then both $(3, 1)$ and $(4, 1)$ are blocking pairs. If $\mu(2) = 2$, then both $(1, 2)$ and $(4, 2)$ are blocking pairs. If $\mu(3) = 3$, then both $(2, 3)$ and $(4, 3)$ are blocking pairs. Thus, the given room-mates problem does not admit a stable matching.

Hence we cannot claim that St is non-empty valued.

Given $G = \langle X, (R_a)_{a \in X} \rangle \in E$, a matching $\mu \in F(G)$ is said to be Pareto Optimal if there does not exist $\mu' \in F(G)$, such that $\mu'(a) R_a \mu(a)$ for all $a \in X$ and $\mu'(a) P_a \mu(a)$ for some $a \in X$.

3. Properties of Stable Matchings for Room-mates Problems:

Lemma 1: Let μ and $\bar{\mu}$ be stable matchings for a room-mates problem G . Let $a \in X$ and $b = \mu(a) \neq a$. If, $\mu(a) P_a \bar{\mu}(a)$, then $\bar{\mu}(b) P_b \mu(b)$.

Proof : Suppose $\mu, \bar{\mu}, a$ and b are as above. If $b = \mu(a) P_a \bar{\mu}(a)$, then $\bar{\mu}(a) \neq b$. Thus stability of $\bar{\mu}$ requires, $\bar{\mu}(b) P_b a = \mu(b)$. Q.E.D.

The following lemma extends one due to Knuth (1976) and Lahiri (2002):

Lemma 2: Let G be a room-mates problem, for which $\bar{\mu}$ is a stable matching. Let S be a non-empty subset of X . Suppose that μ is a matching such that $\bar{\mu} \geq_S \mu$. If there does not exist $a \in S$, such that $(a, \bar{\mu}(a))$ blocks μ , then $\mu(b) R_b \bar{\mu}(b)$ for all $b \in \bar{\mu}(S)$.

Proof : Towards a contradiction suppose that $a = \bar{\mu}(b) P_b \mu(b)$, for some $a \in S$.

Since $(a, \bar{\mu}(a)) = (a, b)$ does not block μ , and since $\mu(a) \neq b$, it must be the case that $\mu(a) >_a b = \bar{\mu}(a)$. This contradicts the hypothesis $\bar{\mu} \geq_S \mu$, and proves the lemma. Q.E.D.

Hence, if in Lemma 2, μ is a stable matching, then, $\bar{\mu} \geq_S \mu$ if and only if $[\mu(b) R_b \bar{\mu}(b) \text{ for all } b \in \bar{\mu}(S)]$.

As a consequence of Lemma 2 we obtain the following stronger version of the Strong Stability Theorem due to Demange, Gale and Sotomayor (1987) extended from the domain of marriage problems to the domain of room-mates problems, which is valid for a special case.

Corollary of Lemma 2 : Let G be a room-mates problem and suppose μ is an unstable matching, such that $\mu^* >_S \mu$ for some stable matching μ^* and some non-empty subset S of X . Suppose that if (a, b) is a blocking pair for μ , then both $\{a, b\} \cap \mu^*(S) \neq \emptyset$ and $\{a, b\} \cap \mu(S) \neq \emptyset$. Then there exists $a \in S$, such that $(a, \mu^*(a))$ blocks μ .

Proof : Suppose towards a contradiction, that there does not exist a pair $(a, \mu^*(a))$ with $a \in S$ which blocks μ .

Suppose that for some $b \in \mu^*(S)$, we have $a = \mu^*(b) P_b \mu(b)$. Hence $\mu(a) P_a b = \mu^*(a)$. This contradicts $\mu^* >_S \mu$. Thus, $\mu(b) R_b \mu^*(b)$ for all $b \in \mu^*(S)$.

Since μ is unstable there exists a pair (a,b) which blocks μ . Thus, $bP_a\mu(a)$ and $aP_b\mu(b)$. Suppose $a \in S$. Let $b \in \mu^*(S)$. If we can show $\mu^*(a) R_a b$, then we are done. Towards a contradiction suppose $b P_a \mu^*(a)$. Since μ^* is stable, $\mu^*(b) >_b a$. Thus $\mu^*(b) >_b \mu(b)$. This contradicts, $\mu(b) R_b \mu^*(b)$ for all $b \in \mu^*(S)$. Thus there exists $a \in S$, such that $(a, \mu^*(a))$ blocks μ . Q.E.D.

The following lemma is worth noting:

Lemma 3: Let G be a room-mates problem for which μ is a stable matching. Let S be any non empty proper subset of X and let $Y = S \cup \mu(S)$ or $Y = X \setminus (S \cup \mu(S))$. Suppose $Y \neq \emptyset$. and let $G' = \langle Y, (R'_a)_{a \in Y} \rangle$, where $R'_a = R_x \upharpoonright Y$. Let μ' denote the restriction of μ to Y . Then μ' is a stable matching for G' .

Proof: Stability of μ' is easy to establish. Q.E.D.

Lemma 4: Let μ be a stable matching for a room-mates problem $G = \langle X, (R_a)_{a \in X} \rangle$. Then μ is Pareto Optimal for G .

Proof: Towards a contradiction suppose there is a matching $\mu' \in F(G)$ such that $\mu'(a) R_a \mu(a)$ for all $a \in X$ and $\mu'(a) P_a \mu(a)$ for at least one $a \in X$. Suppose $c = \mu'(b) P_b \mu(b)$. Thus $\mu'(c) = b \neq \mu(c)$ and $\mu'(c) R_c \mu(c)$ implies $\mu'(c) P_c \mu(c)$. Thus, (b,c) is a blocking pair for μ , contradicting its stability. Thus μ is Pareto Optimal. Q.E.D.

As a consequence of Lemma 3, we obtain the following version of a result originally due to Sasaki and Toda (1992).

Lemma 5: Let μ, μ' with $\mu \neq \mu'$ be stable matchings for a room mates problem $G = \langle X, (R_a)_{a \in X} \rangle$. Then there exists a room-mates problem $G' = \langle Y, (R'_a)_{a \in Y} \rangle$ and a stable matching μ^1 for G' such that (i) $Y \setminus X$ is a singleton say 'n'; (ii) $R'_a \upharpoonright X = R_a$ for all $a \in X$; (iii) $\mu^1 \upharpoonright X = \mu$ (iv) there does not exist any stable matching μ^2 for G' such that $\mu^2 \upharpoonright X = \mu'$.

Proof: By Lemma 4, μ is Pareto Optimal. Since $\mu \neq \mu'$, there exists $b \in X$ such that $\mu(b) P_b \mu'(b)$.

For $a, c \in X \setminus \{b\}$, let R'_a be the linear order such that (i) $a P_a c$ implies $a P'_a n P'_a c$; and (ii) $R'_a \upharpoonright X = R_a$.

Let R'_b be the linear order such that $R'_b \upharpoonright X = R_b$ and for all $a \in X \setminus \{b\}$, $a P_b \mu'(b)$ implies $a P'_b n P'_b \mu'(b)$.

Let R'_n be any linear order such that for all $a \in X \setminus \{b\}$: $b P'_n n P'_n a$.

Let μ^2 be any matching such that $\mu^2 \upharpoonright X = \mu'$. Hence, $\mu^2(n) = n$. Thus, $n P'_b \mu'(b)$ and $b P'_n n P'_n a$ for all $a \in X \setminus \{b\}$ implies (b,n) is a blocking pair for μ^2 .

Now, $\mu(b) P_b \mu'(b)$ implies $\mu(b) P'_b n$. Let μ^1 be any matching such that $\mu^1 \upharpoonright X = \mu$.

Thus, $\mu^1(n) = n$. Thus, (b,n) is not a blocking pair for μ^1 . Further, $n P'_a a$ for all $a \in X \setminus \{b\}$, implies that (a,n) cannot be a blocking pair if $a \in X \setminus \{b\}$. Since $\mu^1 \upharpoonright X = \mu$

and μ is stable for G , there can thus be no other blocking pair for μ^1 . Thus, μ^1 is stable for G' . Q.E.D.

Corollary of Lemma 5: Let $G = \langle X, (R_a)_{a \in X} \rangle$ be a room-mates problem with $\#St(G) > 1$. Let $\mu \in St(G)$. Then there exists a room-mates problem $G' = \langle Y, (R'_a)_{a \in Y} \rangle$ with $X \subset Y$, $\#Y - \#X = St(G) - 1$, and a stable matching μ^1 for G' such that (i) $R'_a|X = R_a$ for all $a \in X$; (ii) $\mu^1|X = \mu$ (iv) $St(G') = \{\mu^1\}$.

The final theorem of this section is an extension of a similar theorem due to Roth and Sotomayor (1990) from the domain of marriage problems to the domain of room-mates problems. This result says that if a new participant is added to a room-mates problem, then given any stable matching for the earlier problem and any stable matching for the new one where the new entrant is paired off with another agent, there is at least one agent on the new arrival's admissible set, who is better off at the second stable matching. Further, the room-mate of this particular beneficiary of the second stable matching, is now worse off than before.

Theorem 1: Let $G = \langle X, (R_a)_{a \in X} \rangle$ and $G' = \langle Y, (R'_a)_{a \in Y} \rangle$, where $Y = X \cup \{a_0\}$, for some $a_0 \notin X$. Let $R_a = R'_a|X$, for all $a \in X$. Let μ be a stable matching for G and let μ' be a stable matching for G' . If $\mu'(a_0) \neq a_0$, then there exists $b \in T = \{a \in X / a P_{a_0} a_0\}$ such that $\mu'(b) P_b \mu(b)$ and $b \succ_{\{\mu'(b)\} \cap X} \mu'(\mu(b))$.

Proof: Let $X = \{a_1, \dots, a_K\}$ and $Y = X \cup \{a_0\}$. Let R_i denote R_{a_i} and P_i denote P_{a_i} for $i = 0, 1, \dots, K$. Since $\mu'(a_0) \neq a_0$, $\mu'(a_0) \in T$. Let $\mu'(a_0) = a_1$. If $a_0 P_1 \mu(a_1)$, then take $b = a_1$. Thus, $\mu'(b) P_b \mu(b)$ and $b \succ_{\{\mu'(b)\} \cap X} \mu'(\mu(b))$, the latter being vacuously true. Hence, suppose, $a_2 = \mu(a_1) P_1 a_0 = \mu'(a_1)$. Since μ' is stable, it must be the case that $\mu'(a_2) P_2 a_1 = \mu(a_2)$. If $a_2 \in T$, then we can take $b = a_2$ and obtain $\mu'(b) P_b \mu(b)$ and $b \succ_{\{\mu'(b)\} \cap X} \mu'(\mu(b))$.

Having obtained a_n , $n \geq 2$, by the above procedure, where (i) [$a_n = \mu(a_{n-1})$, $a_n \notin T$, $a_n = \mu(a_{n-1}) P_{n-1} a_n = \mu'(a_{n-1})$, if n is even]; (ii) [$a_n = \mu'(a_{n-1})$, $a_n = \mu'(a_{n-1}) P_{n-1} a_n = \mu(a_{n-1})$, if n is odd], let $a_{n+1} = \mu(a_n)$, if n is odd, and $a_{n+1} = \mu'(a_{n-1})$, if n is even. Suppose there exists $0 \leq j < t \leq K$, such that $a_{2j} = a_{2t}$, a_{2j} and a_{2t} are obtained by the above procedure and $a_{2j}, a_{2t} \notin T$. Without loss of generality suppose k is the first such t . If $j \geq 1$, Then, $a_{2j-1} = a_{2k-1}$ and $a_{2j-2} = a_{2k-2}$, leading to a contradiction. Thus, suppose $j = 0$. Thus, $a_0 = a_{2k} = \mu(a_{2k-1})$, which is not possible, since $a_0 \notin X$. Hence, there does not exist $0 \leq j < t \leq K$, such that $a_{2j} = a_{2t}$, a_{2j} and a_{2t} are obtained by the above procedure and $a_{2j}, a_{2t} \notin T$.

Since X is finite, there exists a smallest k such that $a_{2k} \in T$. Let $b = a_{2k}$. Thus, $\mu'(b) P_b \mu(b)$ and $b \succ_{\{\mu'(b)\} \cap X} \mu'(\mu(b))$. Q.E.D.

4. Some Consequences for the Marriage Problem:

A stable matching μ_M for a marriage problem G is said to be M - optimal (i.e. optimal for men) if $\mu_M \geq_M \mu$, whenever μ is any stable matching for G .

A stable matching μ_w for a marriage problem G is said to be W - optimal (i.e. optimal for women) if $\mu_w \geq_w \mu$, whenever μ is any stable matching for G .

Theorem 2 (Gale and Shapley (1962), Roth and Sotomayor (1990)) : Every marriage problem admits an M -optimal and a W - optimal stable matching.

It is proved in Lahiri (2002), that a direct consequence of Lemma 2 and the deferred acceptance procedure with men proposing used by Gale and Shapley (1962) and Roth and Sotomayor to establish Theorem 2, is the following theorem due to Gale and Sotomayor (1985 a,b).

Theorem 3 (Gale and Sotomayor (1985 a,b)) : Let $G = \langle M, W, (R_x)_{x \in M \cup W} \rangle$ and $G' = \langle M, W', (R'_x)_{x \in X} \rangle$ be marriage problems, where $W \subset W'$, $X = M \cup W'$ and $R_x = R'_x \upharpoonright M \cup W$ for all $x \in M \cup W$.

Let μ_M and μ_w be the M – optimal and W – optimal stable matchings for G . Let μ'_M and μ'_w be the M – optimal and W – optimal stable matchings for G' . Then,
 (i) $\mu_M \geq_w \mu'_M$, $\mu_w \geq_w \mu'_w$; (ii) $\mu'_w \geq_M \mu_w$, $\mu'_M \geq_M \mu_M$.

As a consequence of Theorems 1 and 3, we get the following theorem:

Theorem 4 : (Roth and Sotomayor (1990)) : Let $G = \langle M, W, (R_x)_{x \in M \cup W} \rangle$ and $G' = \langle M, W', (R'_x)_{x \in X} \rangle$ be marriage problems, where $W \subset W'$, $X = M \cup W'$ and $R_x = R'_x \upharpoonright M \cup W$ for all $x \in M \cup W$. Let μ_M be the M – optimal stable matching for G , and let μ'_w be the W – optimal stable matching for G' . If there exists $w_0 \in W' \setminus W$, such that $\mu'_w(w_0) \in M$, then there exists $m \in M$ and $w \in W'$, such that $w = \mu'_w(m)$ and $\mu(w) P'_m \mu(m)$ and $\mu(w) P'_w \mu'(w)$, whenever μ is a stable matching for G and μ' is a stable matching for G' .

Proof : Let $G^0 = \langle M, W^0, (R^0_x)_{x \in Y} \rangle$, where $W^0 = W \cup \{w_0\}$ and $Y = M \cup W^0$. By Theorem 3, $\mu^0_w \geq_{w^0} \mu'_w$. Thus, w_0 is not single under μ'_w implies w_0 is not single under μ^0_w . By Theorem 1, $m \in M$ and $w \in W'$, such that $w = \mu^0_w(m) >_m \mu_M(w)$ and $\mu_M(w) >_w \mu^0_w(w)$. By Theorem 3, $\mu'_w \geq_M \mu^0_w$ and $\mu^0_M \geq_{w^0} \mu'_M$. Thus, $\mu'_w(m) >_m \mu_M(m)$ and $\mu_M(w) >_{\mu_M(S) \cap W^0} \mu'_w(w)$. This proves the theorem. Q.E.D.

5. Axiomatic Characterization of Stable matchings for Room-mates Problems:

Let PO be the solution on E , such that for all $G \in E$: $PO(G) = \{\mu \in F(G) / \mu \text{ is Pareto Optimal for } G\}$.

A solution ϕ on E is said to satisfy Pareto Optimality if for all $G \in E$, $\phi(G) \subset PO(G)$.

It follows from Lemma 4, that St satisfies Pareto Optimality.

A solution φ on E is said to satisfy Consistency (CONS) if for any $G = \langle X, (R_a)_{a \in X} \rangle \in E$, $\mu \in \varphi(G)$ and non-empty subset Y of X satisfying $\mu(Y) = Y$, $\mu|_Y \in \varphi(G')$ where $G' = \langle Y, (R_a|_Y)_{a \in Y} \rangle$.

It follows from Lemma 3, that St satisfies CONS.

A solution φ on E is said to satisfy Converse Consistency (COCONS) if for any $G = \langle X, (R_a)_{a \in X} \rangle \in E$ and $\mu \in F(G)$: [$\mu|_Y \in \varphi(G')$ for all $G' = \langle Y, (R_a|_Y)_{a \in Y} \rangle$ where $Y = \{a, b, \mu(a), \mu(b)\}$ for two distinct elements a, b in X] implies [$\mu \in \varphi(G)$].

Since $\mu \in F(G) \setminus St(G)$ implies that there exists a blocking pair (a, b) so that $\mu|_Y \notin St(G')$ where $G' = \langle Y, (R_a|_Y)_{a \in Y} \rangle$ with $Y = \{a, b, \mu(a), \mu(b)\}$, clearly, St satisfies COCONS.

Proposition 1: Let φ be a solution on E satisfying CONS and COCONS. If $\varphi(G) = St(G)$ for all $G = \langle X, (R_a)_{a \in X} \rangle \in E$ with $\#X \leq 4$, then $\varphi = St$.

Proof: Let $G = \langle X, (R_a)_{a \in X} \rangle \in E$ and $\mu \in \varphi(G)$. Since φ satisfies CONS, $\mu|_Y \in \varphi(G')$ for all $G' = \langle Y, (R_a|_Y)_{a \in Y} \rangle$ where $Y = \{a, b, \mu(a), \mu(b)\}$ for two distinct elements a, b in X . As a consequence of our assumption in the proposition, requiring equality of φ and St for all room-mates problems with at most four agents, $\mu|_Y \in St(G')$ for all $G' = \langle Y, (R_a|_Y)_{a \in Y} \rangle$ where $Y = \{a, b, \mu(a), \mu(b)\}$ for two distinct elements a, b in X . Since St satisfies COCONS, $\mu \in St(G)$. Thus, $\varphi(G) \subset St(G)$. By a similar argument we can show that $St(G) \subset \varphi(G)$. Thus, $St(G) = \varphi(G)$. Q.E.D.

Given $G = \langle X, (R_a)_{a \in X} \rangle \in E$ and a permutation π on X , let $G^\pi = \langle X, (R^\pi_a)_{a \in X} \rangle \in E$, where for all $a, b, c \in X$: [$\pi(b)R^\pi_{\pi(a)}\pi(c)$] if and only if [$bR_a c$].

If μ is a matching for G , then μ^π is the matching for G^π defined as follows: for all $a \in X$, $\mu^\pi(\pi(a)) = \mu(a)$.

A solution φ on E is said to satisfy Anonymity (AN) if for all $G = \langle X, (R_a)_{a \in X} \rangle \in E$ and all permutations π on X : [$\mu \in \varphi(G)$] implies [$\mu^\pi \in \varphi(G^\pi)$].

It is easily verified that St satisfies AN on E .

In view of the above we can state the following theorem.

Theorem 5: (i) St satisfies PO, CONS, COCONS and AN. (ii) Let φ be a solution on E satisfying CONS and COCONS. If $\varphi(G) = St(G)$ for all $G = \langle X, (R_a)_{a \in X} \rangle \in E$ with $\#X \leq 4$, then $\varphi = St$.

However St is not the solution on E to satisfy PO, CONS, COCONS, AN.

Given $G = \langle X, (R_a)_{a \in X} \rangle \in E$ and a one-to-one function $p: \{1, \dots, \#X\} \rightarrow X$, let $\mu^p(a) = a$ if $A(a) = \{a\}$. Let $Y = \{a \in X / A(a) \neq \{a\}\}$.

Let $a_{p(1)} \in Y$, be such that (i) $a_{p(1)}R_{p(1)}a$ for all $a \in Y$; (ii) $p(1) \in A(a_{p(1)})$.

Let $\mu^p(p(1)) = a_{p(1)}$ and $\mu^p(a_{p(1)}) = p(1)$. Let $Y^1 = Y \setminus \{p(1), a_{p(1)}\}$. If $Y^1 = \emptyset$, then the procedure stops. Suppose, $Y^1 \neq \emptyset$. Let $q(1) = p(1)$, $t_1 = \min \{t / p(t) \in Y^1\}$ and $q(2) = p(t_1)$. Clearly, $q(2) = p(2)$ if $a_{p(1)} \neq p(2)$ and $q(2) = p(3)$ if $a_{p(1)} = p(2)$. Further, $\mu^p(q(1)) = a_{q(1)}$ and $\mu^p(a_{q(1)}) = q(1)$. Having defined Y^k , $q(k)$, $q(k+1)$ for $k \geq 1$, let $a_{k+1} \in Y^k$ be such that (i) $a_{k+1} R_{q(k+1)} a$ for all $a \in Y^k$; (ii) $q(k+1) \in A(a_{q(k+1)})$. Let $Y^{k+1} = Y^k \setminus \{q(k+1), a_{q(k+1)}\}$. If $Y^{k+1} = \emptyset$, then the procedure stops. Suppose, $Y^{k+1} \neq \emptyset$. Let $t_{k+1} = \min \{t / p(t) \in Y^{k+1}\}$ and $q(k+2) = p(t_{k+1})$. Let $\mu^p(q(k+1)) = a_{q(k+1)}$ and $\mu^p(a_{q(k+1)}) = q(k+1)$.

Since, X is finite, there exists a smallest positive integer K , such that $Y^{K+1} = \emptyset$. At this stage, we would have obtained a matching μ^p for G . Call μ^p the p -serial dictatorship matching for G . Let $\text{Ser}(G) = \{\mu^p / p \text{ is a one-to-one function from } \{1, \dots, \#X\} \text{ to } X\}$.

The serial dictatorship solution on E denoted Ser , is the solution on E such that for all $G = \langle X, (R_a)_{a \in X} \rangle \in E$, $\text{Ser}(G) = \{\mu^p / p \text{ is a one-to-one function from } \{1, \dots, \#X\} \text{ to } X\}$.

The verification of the fact that Ser satisfies PO, CON, COCONS and AN, is tedious though routine.

Now consider the Gale-Shapley(1962) example of a room-mates as stated in Example 1. This problem does not admit any stable matching. However, it does admit the following serial dictatorship matchings: (a) 1 and 2 are room-mates; 3 and 4 are room-mates; (b) 2 and 3 are room-mates; 1 and 4 are room-mates; (c) 1 and 3 are room-mates; 2 and 4 are room-mates; (d) 1 and 4 are room-mates; 2 and 3 are room-mates. Hence $\text{Ser} \neq \text{St}$.

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