Bargaining on Networks: An Experiment^

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Abstract: While markets are often decentralized, in many other cases agents in one role can only negotiate with a proper subset of the agents in the complementary role. There may be proximity issues or restricted communication flows. For example, information may be transmitted only through word-of-mouth, as is often the case for job openings, business opportunities, and confidential transactions. Bargaining can be considered to occur over a *network* that summarizes the structure of linkages among people. We conduct an alternating-offer bargaining experiment using separate simple networks, which are then joined during the session by an additional link. The results diverge sharply depending on how this connection is made. Payoffs can be systematically affected even for agents who are not connected by the new link. We use a graph-theoretic analysis to show that any two-sided network can be decomposed into simple networks of three types, so that our result can be generalized to more complex bargaining environments. Participants appear to grasp the essential characteristics of the networks and we observe a rather consistently high level of bargaining efficiency.

Introduction

In many social and economic situations, agents are in contact only with a relatively small subset of other agents. Communication is possible only through a structure that is seldom complete, regardless of whether this structure is implicit or explicit, or whether it is endogenous or imposed exogenously. In this sense one can talk about a *network*, which summarizes the structure of linkages among people; this is a concept of location effects in differentiated markets. We can analyze networks using the tools of graph theory, which provide a method for decomposing an arbitrary number of buyers and sellers into relatively simple subgraphs, plus some extra links.

A network can be seen to represent an intermediate case between bilateral bargaining and matching in a large centralized market such as the double auction (e.g., Smith 1962, 1964). Roth, Prasnikar, Okuno-Fujiwara, and Zamir (1991) demonstrate convincingly that results are very different for an ultimatum game, with one-to-one matching, and a "market game," where a single agent on one side can agree to a proposal from any of nine agents on the other side. While in some environments each agent is potentially able to interact with all other agents, many important economic interactions can be effectively characterized using bilateral networks. Information may be transmitted only through word-of-mouth, as is often the case for job openings, business opportunities, and confidential transactions. Networks thus have economic implications for a wide range of situations that feature a limited number of agents and connections.

Both intuitively and theoretically, some connections are more important than others. An added link in a local network may or may not change the "balance of power" among a number of agents. Since we may be able to add or delete links in markets (endogenous network choice), it is useful to study the effect of such changes in the trading regime. Kranton and Minehart (2000) show that "buyers and sellers, acting strategically in their own self-interest, can form network structures that maximize overall welfare." If the nature of a link is important, we can also gauge its value both theoretically and empirically. Corominas-Bosch (1999) presents a model in which sellers and buyers are connected through a fixed network. The objective of the model is to identify the conditions on the network that determine the realized prices in equilibrium.

The results depend on the properties of the graph that are induced by the network. More precisely, it is shown that there exists a method of decomposing *any* bipartite graph (with an arbitrary number of agents on either side) into subgraphs of three different types. The analysis studies a subgame-perfect equilibrium in which agents split the surplus evenly if either buyers and sellers are equally prevalent or if one of the sides is larger and the smaller side is not "well-connected". However, if one side is larger and the smaller side *is* well-connected, agents on this smaller side receive all of the surplus in equilibrium. Thus, the analysis succeeds in telling us which connections are important and which are irrelevant.

Our focus is on studying the effect of different "types" of links to networks. The experimental setup is that of a two-sided market, with two types of agents (e.g., buyers and sellers) who have identical preferences and who engage in sequential bargaining – alternating offers over a shrinking pie, with multiple possible rounds. All proposals and acceptances are anonymous, but are nevertheless public information. The agents are differentiated only by their positions in the network; indeed, the position of an agent determines her bargaining power relative to the others.

We test whether bargaining behavior differs according to the nature of the link that is added, and whether the predictions of this theory are borne out in the laboratory. Consider the simple networks shown in Figure 1:

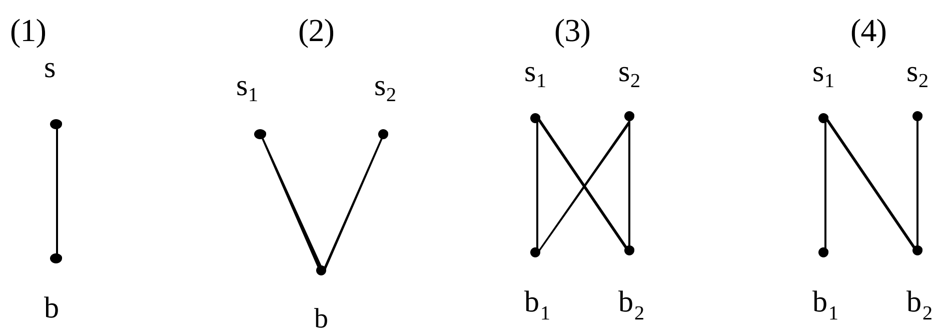


Figure 1

Network (1) depicts a bilateral bargaining game, as in the classic ultimatum game (Güth, Schmittberger, and Schwarze 1982). Network (2) is analogous to the Roth *et al.* (1991) market game, but with only two responders (instead of nine) for each proposer. In both networks (3) and (4), there are two buyers and two sellers; in network (3) each buyer is connected to each seller, while in network (4) there is no link between b_1 and s_2.

We wished to maintain as much simplicity as possible in our design, while still modeling a situation featuring two different ways to link small networks and correspondingly different theoretical predictions about the effects of adding such links. We introduce a connection either between network (2) and network (3) or between network (2) and network (4). This new connection links either the bottom of network (2) to the top of the other network, or the top of network (2) to the bottom of the other network. As shall be seen, this new link should not theoretically affect the bargaining results in the first case, while in the second case it should make a big difference. Our theory also predicts that there should be no difference in bargaining behavior for networks (3) and (4), either by themselves or when linked to network (2). In our experimental design, we use alternating-offer bargaining (the top and bottom sides of the network alternate) with a shrinking pie and an uncertain time horizon. Players who do not reach an agreement receive a small reservation payoff.

Figure 2 shows the 7-person networks that are created by the new link between network (2) and network (3):

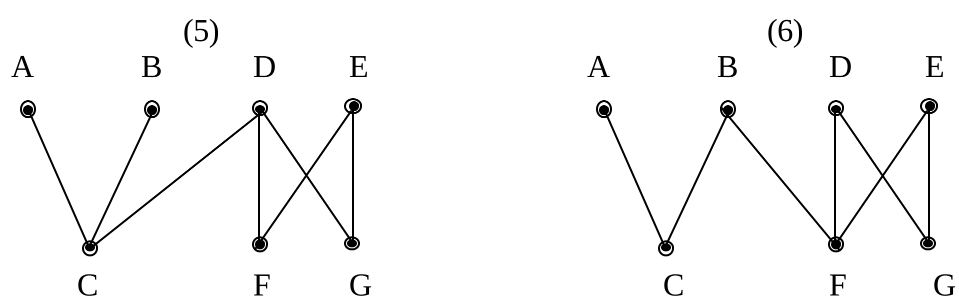


Figure 2

It may be helpful to provide some intuition for the theoretically-predicted differences between these two networks. In network (6) we see that the added BF link serves as a propagation mechanism. We know that one of A, B, D, or E must receive 0 (or the reservation payoff). Assume it is A (we can start with B, D, or E and get the same result), then B must also receive 0, or else A could propose receiving ε and C would accept the proposal. Thus, since B would accept any positive sum, F would not contract with D or E unless one of them accepts 0. This leaves G in a position to also extract surplus. Essentially, C, F, and G are jointly able to exploit the players on the other side; C, F, and G receive full shares and A, B, D, and E receive only the reservation payoffs. On the other hand, there is no propagation across the CD link in network (5). D knows that either A or B must get 0, so that C will expect to get a full share. D eliminates C from his bargaining plans, and the (D,E,F,G) network can be considered in isolation.

Thus, very small changes in the network (visually small, differing by only one connection) may strongly alter the situation. A new connection can affect players who are not directly involved. On the other hand, some new connections do not matter at all theoretically. We also wished to see whether adding such an irrelevant connection would affect actual network bargaining.

Graph-theoretic Analysis

Let us examine how to determine the subgame-perfect equilibrium payoffs (SPE). We consider a general bilateral network where all buyers are identical and all sellers are identical. There is alternating-offer bargaining, a shrinking pie, a public display of (non-targeted) offers, and targeted acceptances. A complete description of the game played is presented in the next section. Our analysis begins with the study of the simplest possible networks: Networks with at most 2 sellers and 2 buyers. We start from the network shown in Figure 2, characterizing the unique SPE when starting the game at period t_0 and finishing at an uncertain period.[1]

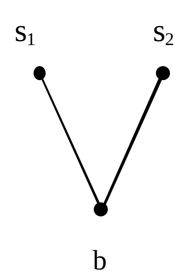


Figure 2

[1] In our design, if two or more linked agents are still unmatched after period 4, a coin is then tossed to determine whether period 5 or period 6 will be the final period.

The top of the network (i.e., s_1 and s_2) makes proposals in odd-numbered periods, while the bottom side (b) makes proposals in even-numbered periods. For convenience, we will call the people at top of the network "sellers" and those at the bottom will be "buyers." All proposals (x_1, x_2) will refer to (Proposer, Responder) payoffs.

Proposition 1 (all propositions and proofs are given in Appendix B) gives the SPE of our game, on the assumption that money is the only argument in the utility function. The result is intuitively clear: Competition is so strong that the agents on the long side are forced to yield all surplus to the agent alone on the short side. In this respect, it is worth noting that competition is much stronger than the ultimatum effect given by the last period. Even if it is the turn of s_1 and s_2 to propose in the last period, they are forced to yield all surplus to agent b. It is easy to show that the analogous result holds if the network has two buyers and one seller.

Now consider Figure 3. Proposition 2 establishes that here the agents will split the surplus nearly evenly, with the first proposer having a small advantage:

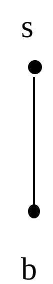


Figure 3

Proposition 3 extends this results to the two possible networks we can construct with 2 sellers and 2 buyers:

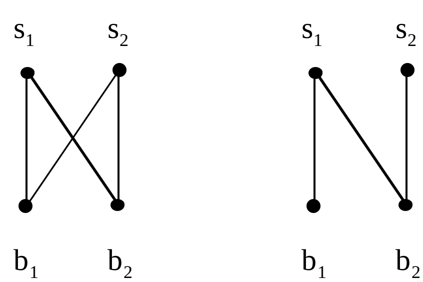


Figure 4 Figure 5

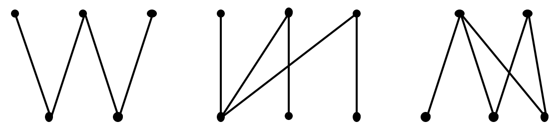
Interestingly, according to this theory there is no difference between Figure 4 and Figure 5. One might initially suppose that the equilibrium should favor the agents having more connections, but a closer look tells us that the extra connection in Figure 4 is actually irrelevant. Suppose s_1 offers a small share to (b_1,b_2). Clearly b_2 will reject such a proposal, since he has s_2 all to himself. If b_1 also rejects the proposal, s_1 will be forced to offer a larger share. This process continues until b_1, b_2, s_1, and s_2 receive equal shares (subject to the slight inequality present from the asymmetric timing of offers).

We now wish to characterize a SPE that will exist in any network. The idea is the following. We have observed above that some networks are "competitive" (Figure 2), having a unique SPE in which the short side of the market receives all surplus. On the other hand, other networks (Figures 3, 4 and 5) are "even" (neither of the sides is stronger), and have a unique SPE in which agents split the payoffs nearly evenly. This structure generalizes to any network. Indeed, we will be able to decompose any network into a union of smaller networks, each one being either a "competitive" or an "even" network, plus some extra links.

Our derivation closely follows Corominas-Bosch (1999). We adapt the analysis of the infinite horizon game treated therein to our finite-horizon game. For a basic discussion of notation and results in graph theory, we refer the interested reader to Appendix C.

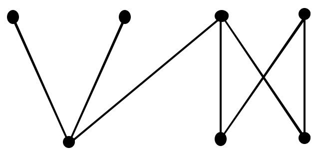
We will now define three types of particular graphs (G^S, G^E, and G^B) (the formal definition can be found in Appendix C). Let graphs G^S be those with more sellers than buyers, such that any set of sellers can be "jointly matched" with buyers if the number of sellers in this set does not exceed the number of buyers.[2] In the following figure, G_1 is of type G^S since it has more sellers than buyers (3 versus 2), and since we can find a jont matching involving any set of 1 or 2 sellers. Graphs G^B are the complement, substituting sellers for buyers and *vice versa*. Finally, graphs G^E have as many sellers and buyers and are such that there exists a joint matching involving all of them.

[2] Intuitively, a set of sellers can be jointly matched if there exists a collection of pairs of linked members such that each agent belongs to at most one pair. See Appendix C for more detail.

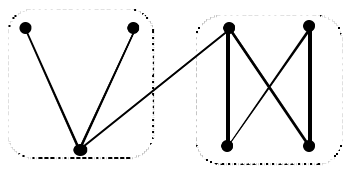


G_1: type G^S G_2: type G^E G_3: type G^B

Not every graph is one of these three types, as is illustrated by the following graph:



Nevertheless, we can decompose this graph into two subgraphs, one of type G^S and one of type G^E, plus an extra link.



G^S G^E

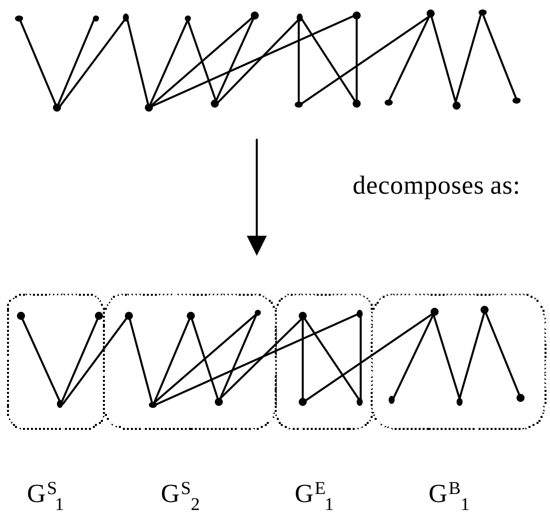
We now show that any graph decomposes as a union of subgraphs which are of one of these three types, plus some extra links which will never connect a buyer in a subgraph G^B with a seller in a subgraph G^S. Moreover, the property of belonging to a subgraph of a given type is exclusive:

Theorem 1

1) Every graph G can be decomposed into a number of connected subgraphs G^S_1 ,..., G^S_{nS} (of the G^S type), G^B_1 ,..., G^B_{nB} (of the G^B type), G^E_1 ,..., G^E_{nE} (of the G^S type), such that: a) each node of G belongs to one of the subgraphs and only to one and b) the links which connect in G a node in a subgraph with a node in another subgraph do not link a seller in a G^S_i with a buyer in a G^B_j, with $i\in\{1,...,n_S\}$ and $j\in\{1,..., n_B\}$.
2) A given node always belongs to the same type of subgraph for any such decomposition.

Proof: See Appendix B. ■

The following is an example of a decomposition: the graph in the figure below decomposes into two subgraphs of type G^S, one of type G^E and one of type G^B.



The decomposition we have defined above directly allows us to characterize an equilibrium that applies to any graph. This SPE will give all the surplus to the short side in the subgraphs that are G^S or G^B ("competitive" networks), while the surplus will be split relatively evenly (taking into account the first mover advantage) in G^E subgraphs ("even" networks).

Theorem 2: Take any graph G (starting at t_0) and decompose it as a union of G^S, G^E and G^B. Then, there exists a SPE[3] in which:

Sellers in G^S receive 200, buyers in G^S receive $\Pi\ t_0$–200.
Sellers in G^B receive $\Pi\ t_0$–200, buyers in G^B receive 200.
Sellers in G^E receive:
If t_0 is odd: $\Pi_5/2 + 100(5- t_0)/2+50$
If t_0 is even: t_0 is 6: 200, otherwise $\Pi_5/2 + 100(5- t_0)/2$
Buyers in G^E receive:
If t_0 is odd: $\Pi_5/2 +100(5- t_0)/2-50$
If t_0 is even: t_0 is 6: Π_6-200, otherwise $(\Pi_5/2 +100(5- t_0)/2)$

Proof: See Appendix B.

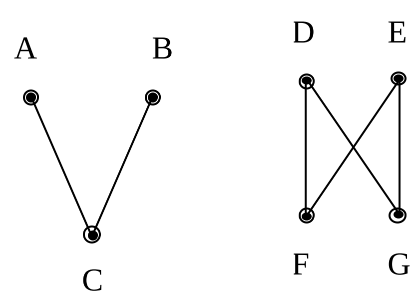
[3] In our game a pair of connected agents may reach a agreement at any point in time, while unmatched agents keep playing. An agent who does not reach an agreement receives a reservation payoff of 200. Thus, to describe the subgame-perfect equilibria of the game, we need to know the equilibrium in any possible network that results as a consequence of the deletion of some of the links in the initial network.

Note that all of the equilibria are efficient, since agreements are reached in the first period.

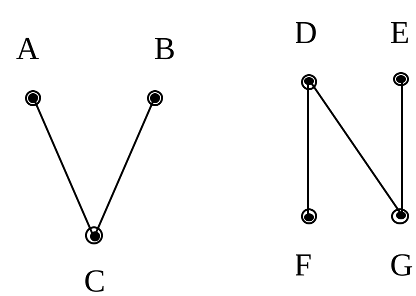
Experimental design

This experiment was conducted in May and June of 1999, at the Universitat Pompeu Fabra in Barcelona, Spain. Participants were recruited by posting notices at campus locations. A total of 105 people participated in our study (each person could only participate in one session). Most of these were students in economics or business, with a smaller percentage of students in the humanities. Session lasted about 100 minutes and average earnings were approximately 1600 Spanish *pesetas* (at the time, $1 = 140 pesetas), including a show-up fee of 500 pesetas.

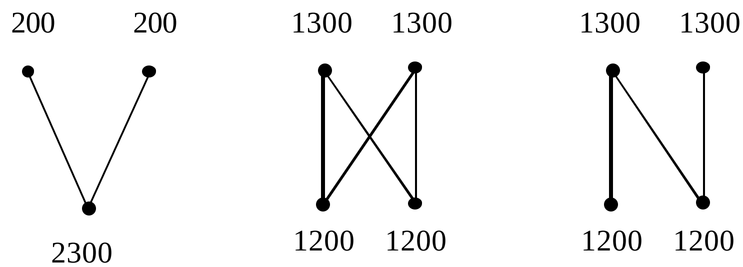
Participants were given written instructions (an English translation of the instructions is presented in Appendix A) and these were read aloud. We used a three-person network and one of two types of four-person networks in the initial phase of our experimental sessions. Thus, there were seven agents in each experimental session. These are the networks we used in the initial phase:



or



We can adapt the theory presented in the previous section to the particular networks used in our design: The equilibrium payoffs (shown below) for our networks are determined by the appropriate (according to Theorem 1) decomposition into subgraphs of type G^S, G^E and G^B. Applying Theorem 2 leads to the (unique, by Proposition 4) SPE payoffs. Note that these networks do not decompose into subgraphs, but are simply type G^S ("competitive", the first one) or G^E ("even", the other two).



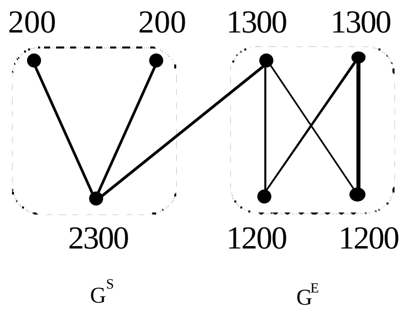
We conducted 15 sessions. There were 4 sessions for each type of network, except for Treatment 1, as one session was canceled due to an insufficient number of participants. Each session consisted of 10 separate bargaining interactions or "periods." Every participant received a sheet of paper that stated his or her letter assignment in the period. Each period was comprised of up to 5 or 6 bargaining rounds,[4] with the total amount to be divided shrinking after each unsuccessful bargaining round.[5] In the first half of the first round, agents A, B, D, and E made proposals (on a sheet of paper) to divide 2500, specifying any pair of (Self, Other) payoffs that summed to this amount. Blank sheets were simultaneously collected from players C, F, and G, so that anonymity with respect to role was preserved.[6]

After period 4, we added a link between the three-person and the four-person networks, to form a seven-person network. The new link either connected player C to player D or player B to player F. We now write the SPE payoffs (again, unique by

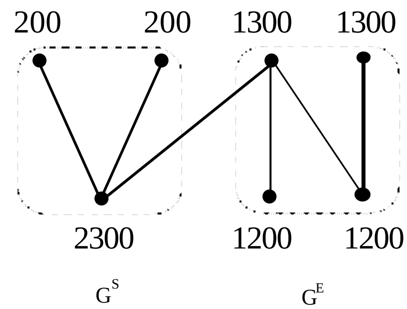
[4] If no agreement was reached at the end of round 4, a coin was tossed to determine whether round 5 would be the last one, or whether there would potentially be a round 6. We introduced this uncertainty in order to prevent unraveling effects, at least prior to round 5.
[5] Vince Crawford points out that it would also be interesting to use an unstructured bargaining protocol, as alternating-offers models may make idiosyncratic predictions about the effects of outside options in bilateral bargaining and this could carry over to the network structure in the design.
[6] We continued to collect sheets from all players in all cases.

Proposition 4). Note that the two seven-person networks with a link from the top of the three-person group to the bottom of the four-person group do not decompose into subgraphs, but are simply "competitive". The four possible seven-person networks are:

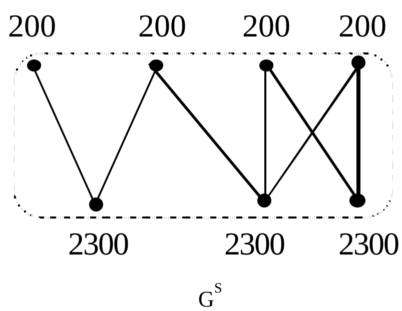
Treatment 1



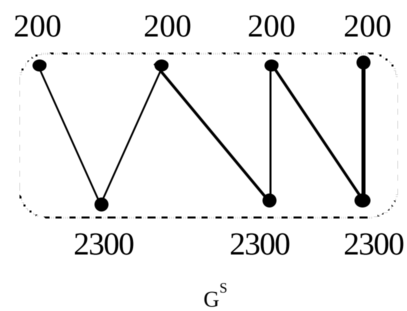
Treatment 2



Treatment 3



Treatment 4



A quick examination of the network types shows that the added link in networks 3 and 4 does not change the equilibrium predictions for the base networks, while the added link in networks 5 and 6 dramatically changes the predictions for the players in the original four-person network. The equilibrium outcomes do not differ between networks 3 and 4, or between networks 5 and 6.

The networks were drawn on the board and each proposal was written next to the player's letter. In the second half of the first round, players C, F, and G indicated which one (if any) of the outstanding proposals they wished to accept; one could only accept a proposal from an agent to whom one was connected.[7] Acceptances and rejections were indicated on the board and an ellipse was drawn around links between those agents who had reached agreements, removing them from the network.

If there still remained any agents who could potentially reach an agreement, we proceeded to round 2. Now, agents C, F, and G (if they were unmatched) made proposals to divide 2400. These proposals were written on the board and agents A, B, D, and E responded to the proposals made. If a 3rd round was necessary, the remaining players on the top of the network made proposals to divide 2300 and the remaining players on the bottom of the network responded. This process continued either until no further match could be made or until the end of round 5 (or 6); any player(s) who did not reach an agreement received a payoff of 200.

The session then proceeded to the next period. Letter assignments were changed in each period, subject to the constraint that each person remained in their original 3- or 4-person network.[8] People were told that one of the 10 periods would be chosen at random for implementation of actual monetary payoffs. We played four periods before adding a link between the two networks and six periods after the link was added. The number of periods to be played either before or after the link was added was not divulged to the participants, although they were told that there would be a change in the network at some point in time. At the end of the experiment, a 10-sided die was rolled to determine the period chosen for payment. Participants were then paid individually and privately.

Experimental Results

We first present the bargaining results separately for each of the four treatments. In treatments 1 and 2 we add a link from the bottom of the network resembling a V to the top of networks resembling an |X| and an N, respectively. In treatments 3 and 4, we add

[7] If two people accepted a proposal from the same person, a coin toss determined which acceptance went through. The unmatched player was sent on to the next network bargaining round.
[8] It may seem more natural to keep the same letter assignments throughout the session. Indeed, we suspect that this might accelerate a learning process. However, this approach would raise issues of reputation. In addition, role rotation allows for "smoothing" of the heterogeneity of individuals and minimizes arbitrary performance by a participant unhappy at being stuck in a disadvantageous role throughout the session.

the link from the top of the V to the bottom of the |X| and the N we start with networks resembling a V and an N. In all treatments a link is added after period 4.

How well do the observed payoffs conform to the theoretical predictions? Table 1 summarizes the average payoffs in each treatment, both before and after the introduction of the additional link. The average payoffs over time are presented as Tables 7-10 in Appendix D.

Table 1 – Average Payoffs by Network Position

		Network Position						
Treatment	Period	A	B	C	D	E	F	G
1	1-4	546	496	1575	1200	1221	1192	1121
V / |X|	5-10	415	307	1956	1236	1208	1194	1158
2	1-4	818	434	1447	1294	1003	1059	1312
V / N	5-10	400	386	1914	1192	1233	1096	1254
3	1-4	538	753	1403	1172	1203	1178	1216
V \ |X|	5-10	916	768	1484	858	851	1376	1284
4	1-4	425	650	1612	1219	1130	1147	1248
V \ N	5-10	789	734	1657	609	639	1595	1450

Some patterns are immediately apparent from the data. A link added to the top of the four-person network (treatments 1 and 2) doesn't affect the payoffs of players F and G relative to those of players D and E. However, when the link is instead added to the bottom of the four-person network, the payoffs of players F and G improve substantially relative to those of players D and E. Also, when an extra connection is given to player C, her payoffs increase substantially. On the other hand, when the extra connection is given to player B, the payoffs for player C do not seem to be affected.

The average (A,B) payoff in periods 1-4 is fairly similar across the four treatments (521, 626, 646, 538), as we would expect since all treatments are identical to this point. Note that payoffs are affected in a consistent manner by the nature of the added link. In both treatments (3 and 4) where the link connects C and D, payoffs for A and B decline, payoffs for C increase, and payoffs for D, E, F, and G are essentially unchanged. In the two treatments where the added link connects B and F, payoffs for A and B increase, payoffs for C change little, payoffs for D and E decrease sharply, and payoffs for F and G increase sharply.

Table 1 shows that player A receives higher average payoffs than player B in periods 5-10 in all treatments. This seems surprising where the added BF link would at least superficially appear to favor B. It seems that this added link encourages B to be a bit more aggressive (or less pessimistic). The average 1st-round proposal by B (for B payoffs) decreases by 460 from the periods 1-4 to periods 5-10 with a CD link, compared to a negligible decrease of 4 with a BF link. The change is smaller in each of the 7 sessions with the CD link than in each of the 8 sessions with the BF link, and so the difference in behavior is significant at p = .0002 by the Wilcoxon test.[9] Yet our theory does not consider that B has greater bargaining power and B's optimism is not rewarded.

Bargaining efficiency is consistently rather high with this particular bargaining institution. Full efficiency would mean that three agreements were reached in the first bargaining round, thereby dividing 2500 in each case, or 7500 in total for the 6 matched players. The worst possible efficiency would mean that no agreements were reached, so that these same 6 players would receive 200 apiece, or 1200 in total. We therefore define bargaining efficiency as follows: Add the total payoffs for all 7 players, then exclude the 200 payoff for an unmatched player. Efficiency ≡ (Total – 1200)/6300. Table 2 shows the resulting levels of bargaining efficiency:

Table 2 – Bargaining Efficiency

Period	Treatment 1	Treatment 2	Treatment 3	Treatment 4
1-4	94.8%	96.2%	94.7%	95.7%
5-10	96.6%	97.4%	96.4%	96.4%

Three pairs reached an agreement in 139 of the 149 periods played and 437 of 447 possible matches were made.[10] On average, participants received 96.2% of the possible surplus. Although there were scattered instances of stubborn behavior, people

[9] In fact, we see a significant difference immediately, from period 4 to period 5; the Wilcoxon test gives Z = 2.66, p < .01.

[10] Non-agreements occurred in periods 1 and 7 of session 3, period 6 of session 5, period 4 of session 6, periods 4, 8, and 9 of session 8, period 4 of session 11, period 5 of session 12, and period 1 of session 13. The disagreements in session 11 and session 13 were the result of players D and G reaching an agreement, thereby leaving players E and F isolated. Thus, only 8 disagreements reflect failed bilateral bargaining.

generally were able to bargain effectively. We conjecture that the public display of proposals and responses was useful for bargaining efficiency. Bargaining efficiency does not vary greatly across treatments or time (see Table 5 in Appendix E. Table 3 shows the distribution of the number of rounds needed to reach agreement in each session:

Table 3 - Distribution of Agreements by Round

	# of Agreements Reached (Round)						
Treatment	1	2	3	4	5	6	None
1	64	19	3	0	2	0	2
2	93	19	2	3	1	0	2
3	99	14	1	1	1	0	4
4	79	24	5	6	1	0	2
Total	**335**	**76**	**11**	**10**	**5**	**0**	**10**

Three-quarters of all agreements occurred in the first round, while another 17% of all agreements are reached in the second round. Only 15 bargaining sessions go beyond round 4, and two-thirds of these never become agreements.[11]

Figures 1-3 illustrate how payoffs change over time:

Figure 1 - C Earnings Over Time

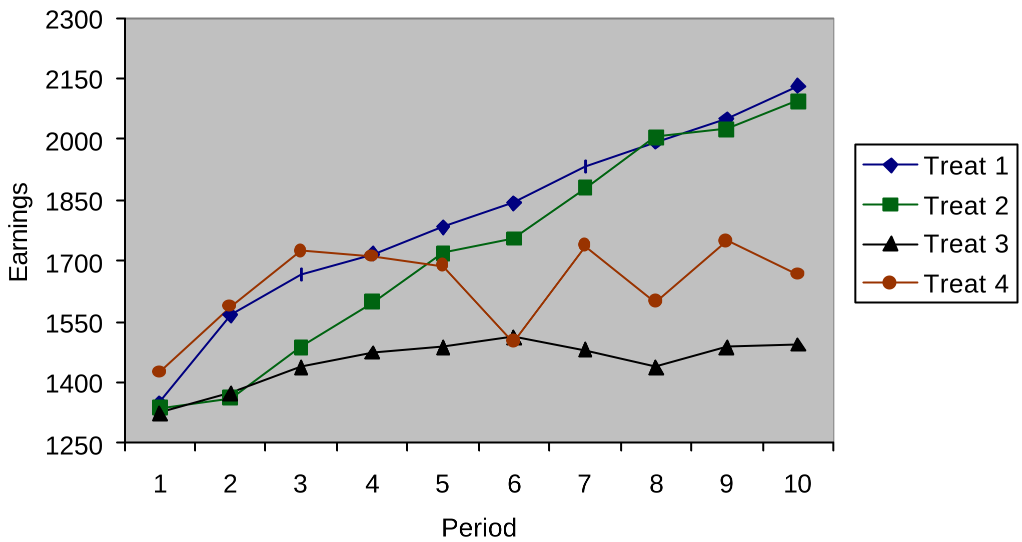


Figure 1 shows that player C's earnings increase in all treatments prior to the addition of a link. When the new link connects C and D, C's earnings continue to increase steadily. However, when the new link connects B and F, C's earnings do not increase after period 4.

Figure 2 - (A+B)/2 Earnings Over Time

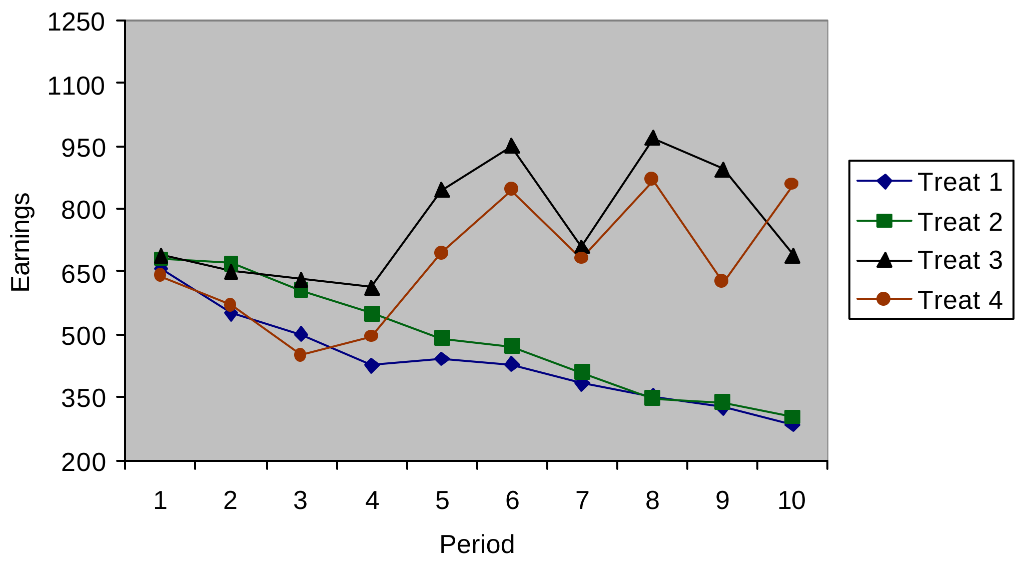


Figure 2 shows that the average earnings for players A and B decline in all treatments prior to the addition of the new link. This trend continues when the new link connects C and D; however, when the new link connects B and F, the average earnings increase somewhat.

[11] Although the numbers here are quite small, a similar result in time-decay bargaining (with an arbitration horizon) is found in Charness (1996). Once people have shown a persistent willingness to sacrifice money, even a relatively large financial disincentive in the last period may not induce an agreement.

Figure 3 - Average (F, G) - (D, E) Over Time

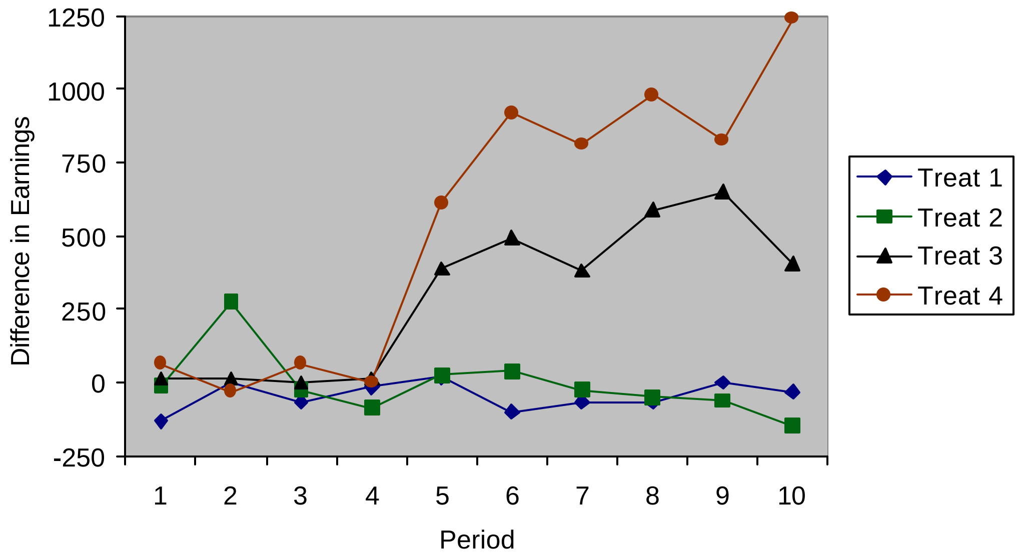


Figure 3 shows that, in the first 4 periods, there is very little difference between the average payoffs for F and G and the average payoffs for D and E. However, behavior after the new link is added is very sensitive to whether the link connects C and D or B and F. In the first case there is no change, but in the second case F and G payoffs increase dramatically.

We perform some simple OLS regressions to confirm the visual pattern. First, consider player C's earnings over time.

Periods 1-4

$$C = \underset{(32.6)}{1372} + \underset{(2.42)}{88.67}*Period$$

Periods 5-10

$$C = \underset{(24.1)}{1552} - \underset{(1.22)}{114.2}*CD + \underset{(0.26)}{4.45}*Period + \underset{(2.93)}{71.19}*CD*Period$$

"CD" is a dummy whose value is 1 if and only if the treatment has a link introduced from C to D. "Period" means the number of elapsed periods from the beginning of the time span in the regression. In the early periods, there is a significant upward trend in C's payoffs and, as expected, there is no significant difference between treatments prior to addition of the new link. In the later periods, there is virtually no change in C's payoffs when the link connects B to F, but the significant positive trend continues with a CD link.

Next, consider the difference over time between the average payoffs for players F and G and the average payoffs for players D and E.

Periods 1-4

$$\frac{(F + G) - (D + E)}{2} = \underset{(0.69)}{24.67} - \underset{(-0.58)}{11.17}\text{*Period}$$

Periods 5-10

$$\frac{(F + G) - (D + E)}{2} = \underset{(5.33)}{503.5} - \underset{(-3.46)}{476.4}\text{*CD} + \underset{(2.02)}{49.82}\text{*Period} - \underset{(-1.93)}{68.80}\text{*CD*Period}$$

In the early periods, there is no difference between the average payoffs and there is no difference across treatments. However, a new link from B to F immediately increases the (F,G) payoffs relative to the (D,E) payoffs and this difference increases over time as well. There is essentially no difference in (F,G) and (D,E) payoffs after a link is added from C to D.

Discussion

It seems clear that bargaining behavior is systematically affected by the addition of a new link. How well do the data conform to the theoretical predictions?

First, we can compare the data from the first 4 periods for all treatments. Perhaps not surprisingly, the (200,200,2300) division predicted for (A,B,C) is never observed. Player C always receives significantly more than half of the pie and the trend is clearly positive; 4th period average C payoffs ranged from 1475 to 1717 across treatments. The (D,E,F,G) allocations are almost the same across treatments and are quite close to the nearly even division predicted.

When the new link is added, we see dramatic changes in some cases and no changes in others. The CD link does not change (D,E,F,G) payoffs at all; perhaps few expect D will try to undercut A and B. On the other hand, the introduction of a BF link causes immediate 5th period jumps in the difference between (F,G) and (D,E) payoffs, as well as a significant upward trend in this difference thereafter. The (200,200,2300,2300) division predicted does not materialize, but the difference between (F,G) and (D,E) payoffs is quite large by the end of the sessions with an N network (Treatment 4).

In contrast to the predictions, there is a difference in (A,B,C) allocations depending on the type of new link. The rate of increase for player C's payoff declines when a BF link is added, but it remains steady when a CD link is added. (A,B) payoffs tend to be a bit higher after a BF link is added, but continue their earlier decline when a CD link is added. Yet it seems premature to conclude that, after a BF link is added, C payoffs would not eventually resume their upward climb or (A,B) payoffs would not eventually diminish. Participants' initial intuition about the effect of a BF link on the relative bargaining power of players A, B, and C may be meeting some resistance.

Table 4 shows the payoff changes for role combinations in each session:

Table 4 – Payoff Changes by Session

Nature of link	Session	$\Delta\frac{(A+B)}{2}$	ΔC	$\Delta\frac{(F+G)-(D+E)}{2}$
Bottom of V to top of |X|	1	-63	226	154
	2	-302	604	-25
	3	-127	312	-92
Average for Treatment 1		**-164**	**381**	**12**
Bottom of V to top of N	4	-256	512	-192
	5	-242	483	21
	6	-304	608	-62
	7	-131	262	-67
Average for Treatment 2		**-233**	**466**	**-75**
Top of V to bottom of |X|	8	240	104	617
	9	208	162	523
	10	208	33	425
	11	131	21	300

Average for Treatment 3		**197**	**80**	**466**
Top of V to bottom of N	12	285	-220	901
	13	483	-42	733
	14	-15	204	633
	15	119	221	1179
Average for Treatment 4		**218**	**41**	**862**

In a strict sense, each session is only one observation, since all choices made after the first round of the first period of a session are interdependent to some degree. We can perform the nonparametric Wilcoxon-Mann-Whitney rank-sum test (see Siegel and Castellan, [1988]) on the change in payoffs for each of the 15 sessions to conservatively check for differences across the nature of the link, as well as across individual treatments.

When we test for differences induced by different links, we see that the changes in payoffs line up in perfect order for each of the three role combinations. The changes in average (A,B) payoffs and the average difference in (F,G) and (D,E) payoffs is always highest when a link is added from the top of the V; this reverses for player C's payoffs. In each case, the rank-sum test indicates that differences according to the placement of the added link are significant at p = .0002.[12] It is quite clear that the added link has a systematic effect on bargaining behavior.

We can also make 6 comparisons for payoff changes across the |X| and the N networks. Recall that our theory (non-intuitively) predicts no differences in this case. Only one of these comparisons shows a difference significant at p = .10 (using the Wilcoxon test), so that there does not appear to be a systematic difference in bargaining behavior between the |X| and the N networks. There is also no significant difference in the results across these cases in periods 1-4, according to the Wilcoxon test on the (D,E,F,G) payoffs in these periods.[13]

We believe that the public display of all information helped to accelerate the learning process and minimize disagreements. Perhaps this additional information

[12] We generally have a directional hypothesis, so p-values reflect one-tailed tests, except where otherwise indicated.
[13] The test statistic is Z = 1.36. However, if we eliminate the case where D and G, the doubly-connected members of the N network, reached a 1st-round agreement (making it impossible for E and F to get more than 200), this is reduced to Z = 0.53.

facilitates a common perception of the active social norm. Blume, DeJong, Kim, and Sprinkle (1998) find that providing a population history leads to an increase in the proportion of separating outcomes achieved in a sender-receiver game. We suspect that more revelation generally tends to support more effective coordination where such coordination is feasible and mutually beneficial. [14]

Disagreement Rates

We observe very few failures (only 2.2%) to reach bargaining settlements and a consequently high bargaining efficiency, which is fairly consistent over time. Most previous bargaining experiments have much higher disagreement rates, but these are typically one-round bargaining games between two players. Multi-period bargaining games with discounting between periods and very low final disagreement payoffs generally have similarly low terminal disagreement rates. In Binmore *et al.* a 100 pence cake is reduced to 25 pence in the 2nd round; only 3 of 22 initial demands between 63 and 77 are rejected (final-round rejection rates are not reported). When game theory would predict a very lopsided division, Güth and Tietz (1988) observe that 14% (12 of 84) of bilateral negotiations end in disagreement. Neelin, Sonnenschein, and Spiegel (1988) find that 12% fail to reach agreement, while less than 3% do not reach agreement in their three-period and five-period studies.[15] Ochs and Roth (1989) observe very few final disagreements in either their two-period or three-period games, around 3% in each.[16] In Bolton (1991), this rate was around 8% for the standard direct-money split treatment and less than 3% with the more competitive tournament payoffs.

Several experiments have two-sided bargaining with one player alone on one side linked to multiple players on the other. These studies also feature a trend toward the advantaged side getting all surplus and only rarely is there no agreement reached. Prasnikar and Roth (1992) and Roth *et al.* (1991) link nine buyers submitting bids for a good with one seller, who can accept the highest bid or refuse all offers and receive

[14] However, providing information about individual choices does not appear to lead to increased contributions or a reduction of the group variance in experiments on the voluntary contribution mechanism. See Sell and Wilson (1991) and Croson (1997).
[15] Discounting was held "constant" across treatments, so that the pie in the last decision period was always one-quarter the original size.
[16] Ochs and Roth (1989) only reports final disagreement rates for rounds 1 and 10.

nothing. This process results in the seller receiving virtually all surplus, and so there are rarely (if ever) any final disagreements. Perhaps more parallel is Grosskopf (1998), where the network changes in the middle of the session, going either from a two-person network to one with one seller with 3 buyers, or *vice versa*. There is a single round in which the single seller specifies a proposed allocation of the pie and the buyer(s) then respond(s). Interestingly, the disagreement rate is about 30% in the two-person network, but only 1-4% in the four-person network. The average share proposed for the single seller goes up to 90% by the 6th (and last period), compared to 72.5% in the first period, in the treatment where a single seller is initially linked with three buyers.[17]

However, note that in all of these studies with multiple players, the preponderance of the participants remain unmatched and receive reservation payoffs of 0. In our experiment, all but 10 cases of 147 resulted in six players (of seven) eventually being matched in three pairs.

A higher disagreement rate is generally observed in bargaining studies featuring a long single-period of unstructured bargaining. Forsythe, Kennan, and Sopher (1991) use a 30-minute bargaining period, one-sided private information about the size of the pie, and handwritten offers and responses transmitted across rooms. Disagreement rates ranged were about 39% for small stakes, but only about 5% for larger stakes. Ashenfelter, Currie, Farber, and Spiegel (1992) allow 5 minutes of unstructured bargaining over computer terminals, either with or without an "arbitrator" to choose final allocations in the event of disagreement. Their disagreement rates ranged from 28-43%. Charness (1996) adapts this design, allowing 10 minutes for each bargaining session and introducing a "bargaining cost" structure where payoffs were discounted (up to a maximum of 40%) at intervals as time elapsed.[18] Final disagreement rates ranged from 9%-16% over three treatments in this hybrid of single- and multi-period designs.

[17] However, when the order is reversed the average demand only reaches 80% in the 6th round of the four-person network after six separate periods with two-person networks, each with average demands of about 70%. There seems to be some reluctance or hesitancy to exploit one's advantage after a relatively stable and long-term standard.

[18] Participants bargained over a "settlement amount." Any settlement reached was reduced by 4% if more than 100 seconds were needed, by 8% if more than 200 seconds were needed, etc. If no agreement was reached at the end of 600 seconds, a further discount of 20% was applied to the arbitrated settlement, bringing the total discount to 40%.

It appears that disagreements are more frequent with discrete multiple periods. In one sense this is expected, since more formal rejections are needed for a final disagreement to occur. On the other hand, since bargaining pairs could exchange a large number of proposals during a long bargaining period,[19] we might expect a countervailing tendency. Analogizing to the field, perhaps breaking potential negotiations into multiple sessions or meetings is similarly more effective than is a single long session. It also seems that the rate of final disagreement is sensitive to the pattern and degree of payoff discounting, so that there may be some optimal discounting strategy.

Related Work and Applications

Jackson and Wolinsky (1996) point out that "the formal network through which relevant information is shared among employees may have an important effect on … productivity. The place of an agent in the network may affect … his or her bargaining position relative to others and this might be reflected in the design of such organizations." They define and discuss the equilibrium concept of pairwise stability, and use cooperative game theory to examine issues such as how networks form among agents, and which networks fulfill stability or efficiency properties.[20] Jackson and Watts (1998) and Bala and Goyal (1998) also address the dynamics of non-cooperative network formation. Kranton and Minehart (1998) study why bilateral networks arise and whether they are efficient. They conclude that networks can enable agents to pool uncertainty in demand and that efficient networks are an equilibrium of their network formation game.

Job search and labor market issues seem appropriate for network analysis, since workers frequently find jobs through personal contacts; Topa (1999) finds that the actual spatial distribution of unemployment in the Chicago area is consistent with a model of local interactions and information spillovers. Boorman (1975) models the structure of social relationships as a graph with undirected ties connecting individuals. Montgomery (1991) studies the effect of social networks on labor market outcomes. Calvó-Armengol

[19] As many as 40 in Charness (1996), for example.

[20] The network in Corominas-Bosch (1999) can be considered to represent an assignment game in the sense of Shapley and Shubik (1972), where buyers value the goods of sellers at either 0 (if they are not connected) or 1 (if they are connected). When our experimental setup is transformed into a cooperative

(2000) establishes a relationship between the social structure of bilateral contacts and the job-search process. Network structure also plays a critical role in matching markets (e.g., Gale and Shapley 1962, Kelso and Crawford 1982, Roth 1984, Crawford and Rochford 1986, Roth and Sotomayor 1989), and in systems compatibility and the optimization of communication and transportation grids.[21]

If we permit endogenous links, a network analysis may be relevant to understanding economic issues such as "contestable markets." Here the issue is the effect of potential market entrants on an incumbent monopolist's pricing; a contestable market can only be in equilibrium if the prices of the incumbent firm are sustainable. Suppose the monopolist can first make a pricing decision in a network framework, but that a second firm can choose to add itself to the network (at a cost) if there was no deal in period 1. The nature of the available links would be crucial to the result. Perhaps this would address the Holt (1995) comment that future experimental work "should make more effort to distinguish the predictions of noncooperative game theory from those of contestable markets theory" (p. 386).

There have not been many economics experiments studying the effect of specific network structure on the behavior of agents. Kirchsteiger, Niederle, and Potters (1998) study a market where the trading institution is endogenous - traders can choose the subset of traders they wish to inform about their offers - and find that traders express clear preferences about the trading institution. Knez and Camerer (1995) merged experimental groups in the course of some sessions, and Roth and Schoumaker (1983) paired subjects in various combinations after training that induced different expectations. Yet these studies do not address the asymmetrical nature of many networks or the value of different links.

Research using network analysis spans some interdisciplinary gaps. There is a large sociology literature that considers social capital in a network structure, with measures for what it means to be "better connected." Burt (2000) presents a detailed survey of the field and argues that social capital is the contextual complement to human

game, it is interesting to note that the unique SPE of the networks analyzed lies in the core of the assignment game

[21] Chwe (1999) shows that "low-dimensional" networks can be better for coordination even though they have fewer links than "high-dimensional" networks.

capital. Instead of having better skills, a person may be somehow better connected. One can consider that "in the absence of unambiguous information, people use network structure as the best available information" (p. 5). If there are only sparse connections between two groups, those people with links to both groups have a competitive advantage. Lovaglia, Skvoretz, Willer, and Markovsky (1995) and Willer, Lovaglia, and Markovsky (1997) use network exchange theory (Markovsky, Willer, and Patton 1988) and a "graph-theoretic power index" to predict power (which relates to exclusion from exchange) and profit rankings in social exchange networks.[22]

The closest experimental studies to our project are social exchange network experiments, such as Markovsky, Skvoretz, Willer, Lovaglia, and Erger (1993) and Lovaglia, Skvoretz, Willer, and Markovsky (1995).[23] In the latter study, people attempt to allocate a pool of resources, and make offers via a computer network that makes matches using an algorithm. They find differences in outcomes depending on whether a network has full information or restricted information; generally, outcomes favor people with exchange relations with otherwise disconnected people. Their empirical results suggest that "equity concerns are not inextricably woven into social exchange network settings, but rather that equity is a distinct process which may or may not be activated in a given social context … [depending] upon whether certain conditions are satisfied."

Conclusion

In many markets, a buyer is connected to only a small subset of all sellers, and *vice versa*. Some of these connections are better than others. Such an interaction can be modeled as a network, and graph theory tells us that we can decompose an arbitrary number of buyers and sellers into relatively simple subgraphs (plus some extra links). This institution can be seen to represent an intermediate case between bilateral bargaining and matching in a large decentralized market. If we consider that it may be

[22] This index is calculated by counting paths from a position in a network; advantageous links ("odd-length paths") are added to the index and disadvantageous links ("even-length paths") are subtracted. Calvó-Armengol (1999) presents a measure in which one's bargaining power is inversely related to the number of people one's neighbors can reach.

[23] See Willer (1999) for a review of sociology experiments with small-group exchange networks.

possible to add or subtract links in markets, we can predict the effect of such changes in the trading regime.

The experimental results show that a small change in the overall network leads to very different effects on individual outcomes, even for bargainers not directly involved with the new link. We see that one's location in the network affects one's bargaining power. The allocations chosen diverge sharply depending on how the connection is added. The graph-theoretic result that all bilateral networks can be decomposed into relatively simple ones permits an application of our experimental findings to general bilateral networks.

We observe a high degree of bargaining efficiency, in that the total payoffs received are about 95% of the maximum possible. The public display of all bids and acceptances may accelerate learning with respect to both bargaining power and group norms about appropriate division. While there are only 10 separate bargaining interactions for each individual in an experimental session, there is strong evidence of substantial changes in bargaining behavior even over this limited period of time.

There are many potential applications for this approach and our results have implications for network formation and design. We suspect that the network framework may be a useful metaphor for many market environments. As network theory is still evolving and general solutions are often unobtainable, experimental study seems a very natural complement in this emerging area.

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Appendix A - Instructions

Thank you for participating in this experiment. You will receive 500 pesetas for attending the session and appearing on time. In addition, you will make decisions for which you will receive an amount of money; the amount depends on the choices made in the experiment. You will receive a subject number that we will use to identify you during the experiment. Please hold on to this number, as we will need it in order to pay you.

In this experiment, you will be in a group of 7 persons who will engage in anonymous bargaining sessions. As explained below, people will make proposals to divide a sum of money between them. In each session, every person will be *connected* to one or more other persons. You can only bargain with those people with whom you are connected. An individual can only reach an agreement with at most one other person in a bargaining session.

An example of a diagram of a *network* (the overall set of possible connections between people) is shown on the board. A network has two *sides*, a top and a bottom.

Your connection(s) will be constant throughout a bargaining session; however, there will be multiple bargaining sessions and your location on the network may change from one session to the next. The network itself will remain constant for some number of bargaining sessions, but the network will change at some point in the experiment. You will be informed when this occurs and a diagram of the new network will be displayed on the board.

Each bargaining session will consist of up to 5 or 6 *rounds*, each of which consists of two parts. In the 1st part of the 1st round, each member of the top side of the network will make a *proposal* for dividing a sum of money with anyone on the bottom side of the network with whom he or she is connected. A proposal is a suggestion of how much money you would receive and how much money a person accepting the proposal would receive. In the 2nd part of the 1st round, individuals on the bottom side of the network respond to the proposals made by those individuals with whom they are connected. One may choose to accept one of these proposals or choose to reject all available proposals. If a proposal is accepted, there is a *match* and both parties to the match are removed from the network for the remainder of that bargaining session. If there are no more possible matches that can be made, the bargaining session has been completed.

If there are still possible matches, we continue to a 2nd round. In the 1st part of the 2nd round, all persons on the bottom side of the network who have not become matched will make proposals to divide a (smaller) sum of money with connected persons on the top side of the network. In the 2nd part of the 2nd round, each unmatched individual on the top side of the network will choose either to accept one of the proposals made by people with whom he or she is connected or to reject all available proposals. Matches are determined and displayed. Once again, if there are no more possible matches to be made, the bargaining session is over. If there are still potential further matches, the bargaining session will continue to a 3rd round, in which the top side of the network will make proposals to divide a (still smaller) sum of money. A 4th round, where the bottom side of the network would make proposals, would follow if necessary.

If we reach a 5th round of a bargaining session, we will flip a coin to see if a 6th round will be permitted (if necessary) or if the bargaining session ends after the 5th round.

The amount of money to be divided will diminish over the course of a bargaining session, in the following manner:

A proposal made in the 1st round suggests a division of 2500 pesetas
A proposal made in the 2nd round suggests a division of 2400 pesetas
A proposal made in the 3rd round suggests a division of 2300 pesetas
A proposal made in the 4th round suggests a division of 2200 pesetas
A proposal made in the 5th round suggests a division of 2100 pesetas
A proposal made in the 6th round suggests a division of 2000 pesetas

Any individual who remains unmatched at the end of a bargaining session would receive a payoff of 200 pesetas for that session.

Mechanics: A diagram of the network in use will be shown on the board at all times. We designate positions on the network with the letters A-G. When proposals are made, we will indicate all of the proposals on this diagram. The choice of each responder to either accept or reject proposals will subsequently be displayed. If a match has been made, the connection between the two matched parties will be circled.

At the beginning of each bargaining session, you will receive a sheet of paper with a drawing of the network; your location on the network will be circled. You have been given a stack of small pieces of paper with your subject number on them. When you are making a proposal or when you are rejecting or accepting proposals, please do so on one of the small pieces of paper and also fill in your assigned letter in the space provided.

As it may be possible that a responder could respond to more than one proposal, if you choose to accept a proposal you must indicate the letter of the person making this proposal.

In the event of more than one person accepting the same proposal, we will randomly determine which responder becomes matched. If you have accepted a proposal but do not become matched, you must proceed to the next round.

We wish to preserve anonymity throughout the experiment. We therefore ask that you turn in one of the small pieces of paper in each part of each round played, even if you are already matched or if it is not your turn to propose or respond. If this procedure were not followed, other participants might be able to deduce the identity of the person at a location on the network. If it is your turn to propose or respond, please do so. If it is not your turn, we ask that you write “Not my turn” on one of the small pieces of paper.

Payment: Although there will be a number of bargaining sessions, at the end of the experiment we will randomly select (using a die) the results from one of these bargaining sessions for actual payment.

If you have any questions, please ask them now or by raising your hand during the course of the experiment. Communication between participants is strictly forbidden. Are there any questions?

Appendix B – Propositions and Proofs

For simplicity, in the propositions and theorems below, we denote by Π_t the amount that can be split among any two agents at round *t*. That is, $\Pi_t = 2500-(t-1)*100$, for $1 \leq t \leq 6$.

Proposition 1: Suppose that the initial network is given by Figure 2 in the text and suppose that the game starts at round t_0, with $1 \leq t_0 \leq 6$. Then the unique subgame-perfect equilibrium payoff gives 200 to each of agents s_1 and s_2, and agent b gets Π_{t0} - 200.

Proof: First note that if two agents reach agreement the game is immediately finished, since there is no possibility of a second agreement among another pair of agents. Suppose now that we are in the 6th round, when agent b has to propose a division of Π_6. If s_1 or s_2 reject, they do not reach an agreement and so they receive a payoff of 200. Therefore the game reduces to an ultimatum game, and the only equilibrium is the one in which b proposes (Π_6-200, 200) and the proposal is accepted.

Now, suppose that we are in the 5th round. Interestingly, whether this is the last round of the bargaining session or not, the only equilibrium is the one in which both s_1 and s_2 propose (200, Π_5-200) and b accepts. To see why, suppose w.l.o.g that agent s_1 receives an agreement proposing a share of (p, Π_5-p) with p>200. It must be the case that b accepts the offer from s_1 at round 5, which means that s_2 is excluded, receiving a payoff of 200. But then, s_2 could undercut and instead propose (in round 5) the division (200+ε, Π_5-200-ε) which b should accept, since $\Pi_5-200-\varepsilon > \Pi_5-p$ and since the most b can get in the next round is Π_6-200, which is smaller than Π_5-200-ε. With similar arguments we can determine the SPE from round t_0 on. The precise strategies would be the following:

- If t_0 is odd:

    At round t= t_0+2n, with n Î {0,1,…, min(3, (5- t_0)/2}.

    Agents s_1 and s_2 both propose (200, Π_t-200). Agent b accepts a proposal iff the share offered is greater than or equal to Π_t-200. (In case of ties, b accepts the proposal by s_1.) Otherwise, b rejects.

    At round t= t_0+(2n+1), n Î {0,1,…, min(3, (5- t_0)/2}

    Agent b proposes (Π_t-200, 200). Agents s_1 and s_2 both accept iff the share offered is greater than 200. Otherwise, they reject.

- If t_0 is even:

    At round t=t_0+2n, n Î {0,1,…, min(3, (5- t_0)/2)}.

    Agent b accepts a proposal iff the share offered is greater than or equal to Π_t-200. (In case of ties, he accepts the proposal by s_1.) Otherwise, he rejects.
    Agents s_1 and s_2 both propose (200, Π_t-200).

    At round t= t_0+(2n+1), n Î {0,1,…, min(3, (5- t_0)/2)}.

    Agents s_1 and s_2 both accept iff the share offered is greater than 200. Otherwise, they reject.

Agent b proposes (Π_t-200, 200). ■

Proposition 2: Suppose that the initial network is given by Figure 3 in the text and suppose that the game starts at round t_0, with $1 \leq t_0 \leq 6$. Then, the unique subgame-perfect equilibrium payoff gives agents a payoff of:

If t_0 is odd:	s receives $\Pi_5/2 + 100(5- t_0)/2+50$, b receives $\Pi_5/2 +100(5- t_0)/2-50$
If t_0 is even:	If t_0 is 6, s receives 200, b receives Π6-200
	If t_0 is 2 or 4, s receives $\Pi_5/2 + 100(5- t_0)/2$, b receives $\Pi_5/2 +100(5- t_0)/2$

Proof: Suppose that we are in the 6th round. The equilibrium will then be agent b proposing (Π_6-200, 200) and agent s accepting. Now, suppose that we are in the 5th round. With probability 1/2, this is the last round (so the only equilibrium tells s to propose (Π_5-200,200)), and with probability 1/2 it is not. If it is not the last round, we know that in the next round b will receive Π_6-200 and s will receive 200. Therefore, in the only equilibrium, s proposes (Π_5-(Π_6-200), Π_6-200) and leave the responder indifferent between accepting or rejecting. In expected terms, the payoff agent s receives in the 5th round is (Π_5-200+Π_5-(Π_6-200)) = (Π_5-200+300) = Π_5/2+50 and the payoff agent b receives is (200+Π_6-200) = Π_6/2. In this manner, we can calculate all the proposals in equilibrium, since from standard bargaining results (see Rubinstein 1982) we know that proposals will leave the responder indifferent between accepting or rejecting.■

Proposition 3: Suppose that the initial network is given by Figure 4 or in Figure 5 above and suppose that the game starts at round t_0, with $1 \le t_0 \le 6$. Then, the unique subgame-perfect equilibrium gives payoff will be:

If t_0 is odd: s_1 and s_2 receive $\Pi_5/2 + 100(5- t_0)/2+50$, b_1 and b_2 receive $\Pi_5/2 +100(5- t_0)/2-50$

If t_0 is even: If t_0 is 6, s_1 and s_2 receive 200, b_1 and b_2 receive Π6-200

If t_0 is 2 or 4, s_1 and s_2 receive $\Pi_5/2 + 100(5- t_0)/2$, b_1 and b_2 receive $\Pi_5/2 +100(5- t_0)/2$

Proof: Suppose that we are in the 6th round. If there is only a pair left, we know the equilibrium by the previous proposition and we are done. Alternatively, suppose that all four agents are still in the market. If a responder (seller) rejects, he or she receives a payoff of 200, so should clearly accept any proposal that is greater than or equal to it. Moreover, it is also clear that two pairs will reach agreement. If this were not true, at least one of the two buyers would be unmatched and would receive only 200. Thus, a profitable deviation would be proposing a share of (200+ε, Π_6-200-ε), since any such proposal will be accepted by at least one of the sellers. The equilibrium then will be both agents b_1 and b_2 proposing (Π_6-200, 200) and both sellers accepting from different buyers. Any proposal that would give less to sellers would be rejected, and any proposal that would give more could be tendered by the proposer and still be accepted. Once we deduce the payoffs for round 6, we can proceed as before by using induction, since they will always leave the responder indifferent between accepting or rejecting.■

Algorithm for Theorem 1:

The graph decomposition.

An outline of the algorithm: We first remove the subgraphs that have a set of sellers of size t collectively linked to less than t buyers. We do so starting with the subgraphs in which multiple sellers are collectively linked to only one buyer. Then we remove the subgraphs in which more than 2 sellers are collectively linked to only 2 buyers. When we have exhausted all the possibilities we then remove the subgraphs that have a set of buyers of size t, collectively linked to less than t sellers. The subgraphs removed in the first case, will be type G^S_i, the ones removed in the 2nd case will be type G^B_i and the remaining subgraphs will be type G^E_i.

Starting from a graph G_t, with the initial graph being G_1= G

Part 1)

Step s1)

Step s1.1} Start from G_t=< $S_t \cup B_t$, L_t>, with the initial graph being G_1= G. All agents have a subindex; this is a permanent number. Examine every subset $\tilde{S}$ of S_t such that $|\tilde{S}|$=2, starting from the subsets that contain s_1 in the order {s_1, s_2}, {s_1, s_3}, ..., {s_1, s_n}, then with the ones that contain s_2 in the order {s_2, s_3}, {s_2,

s_4}, ..., {$s_{2,}$ s_n} and so on. That is, the order for looking at the subsets is {$s_{k,}$ s_t}, t=k+1,k+2,...,n , starting from k=1, k=2 up to k=n (in short, lexicographic ordering).

Once you find one $\tilde{S} \subseteq S_t$ with $|\tilde{S}|$=2 such that $|N(\tilde{S})| = 1$, stop. For every seller $s^i \notin \tilde{S}$ (here again we will follow the ordering given by the subindices), if it is true that $N(\tilde{S} \cup s^i) = N(\tilde{S})$, then relabel $\tilde{S} := \tilde{S} \cup s^i$

Call G_t^1 (superindex 1 stands for "Part 1") the subgraph in G_t induced by the set of sellers $\tilde{S}$ and the set of buyers $N(\tilde{S})$

If we run Step s1.1) and we found G_t^1, then call $\bigcup_{j=t+1}^{k_t} G_j := G_t - G_t^1$, i.e., the connected subgraphs that we get when we remove G_t^1 from G_t, and again run Step s1) for each G_j with j>t.

If we run Step s1.1) without finding any G_t^1, then go to Step s2).

...

Step sk)

Step sk.1) Start from G_t.. Examine every subset $\tilde{S}$ of S_t such that $|\tilde{S}| = k+1$ following the lexicographic ordering.

Once you find one $\tilde{S} \subseteq S_t$ with $|\tilde{S}| = k+1$ such that $|N(\tilde{S})| = k$, stop. For every seller $s^i \notin \tilde{S}$ (here again we will follow the ordering given by the subindices), if it is true that $N(\tilde{S} \cup s^i) = N(\tilde{S})$, then relabel $\tilde{S} := \tilde{S} \cup s^i$

Call G_t^1 the subgraph in G_t induced by the set of sellers $\tilde{S}$ and the set of buyers $N(\tilde{S})$

Step sk.2) If we run Step sk.1) and we found a G_t^1, then call $\bigcup_{j=t+1}^{k_t} G_j := G_t - G_t^1$, i.e., the connected subgraphs that we get when we remove G_t^1 from G_t, and again go to Step s1) with each G_j with j>t.

If we run Step sk.1) without finding any G_t^1, then go to Step sk+1).

.....

Step sm)

Step sm.1) Start from G_t. Examine every subset $\tilde{S}$ of S_t such $|\tilde{S}| = m+1$, following the same ordering as before.

Once you find one $\tilde{S} \subseteq S_t$ with $|\tilde{S}| = m+1$ such that $|N(\tilde{S})| = m$, stop. For every seller $s^i \notin \tilde{S}$ (here again we will follow the ordering given by the subindices), if it is true that $N(\tilde{S} \cup s^i) = N(\tilde{S})$, then relabel $\tilde{S} := \tilde{S} \cup s^i$

Call G_t^1 the subgraph in G_t induced by the set of sellers $\tilde{S}$ and the set of buyers $N(\tilde{S})$

Step sm.2) If we run Step sm.1) and we found a G_t^1, then call $\bigcup_{j=t+1}^{k_t} G_j := G_t - G_t^1$,, i.e., the connected subgraphs that we get when we remove G_t^1 from G_t, and go again to Step s1) with each G_j with j>t.
If we run Step sm.1) without finding any G_1^1, then end Part 1).

Once we are finished with Part 1), we go to Part 2).

Part 2) Part 2 is completely symmetric to Part 1). The roles of buyers and sellers get reversed. The steps go from Step b1) to Step bn). We start Part 2) with the G_t that come from the last iteration in Part 1).

End of the algorithm.
....
This decomposition is a refinement of the canonical structure theorem due independently to T. Gallai and J. Edmonds (see Gallai [1963,1964], Edmonds [1965] and Lovasz and Plummer [1986, ch. 3] for a good survey). It can be shown that the algorithm above runs the decomposition described in Theorem 2. See Corominas-Bosch (1999) for details.

Theorem 2: Take any graph G (starting at t_0) and decompose it as a union of G^S, G^E and G^B. Then, there exists a SPE[24] in which:

Sellers in G^S receive 200, buyers in G^S receive $\Pi\ t_0$–200.
Sellers in G^B receive $\Pi\ t_0$–200, buyers in G^B receive 200.
Sellers in G^E receive:
If t_0 is odd: $\Pi_5/2 + 100(5- t_0)/2+50$
If t_0 is even: t_0 is 6: 200, otherwise $\Pi_5/2 + 100(5- t_0)/2$
Buyers in G^E receive:
If t_0 is odd: $\Pi_5/2 +100(5- t_0)/2-50$
If t_0 is even: t_0 is 6: Π_6-200, otherwise $(\Pi_5/2 +100(5- t_0)/2)$

We will show the result using induction. Let's first show the result for a number of sellers ≤ t, and a number of buyers ≤ t, with t=2.

Step 0) t=2
Only four different graphs are possible. These are the graphs analyzed in the previous section (figure 4 and 5), in which the above statement is true.

Step 1) t=k

[24] In our game a pair of connected agents may reach a agreement at any point in time, while unmatched agents keep playing. An agent who does not reach an agreement receives a reservation payoff of 200. Thus, to describe the subgame-perfect equilibria of the game, we need to know the equilibrium in any possible network that results as a consequence of the deletion of some of the links in the initial network.

Suppose that the result is true for graphs of sizes $n \leq k-1$, $m \leq k-1$. For the graph G and for any subgraph G_i of G that results from removing a set of pairs of nodes from G, the strategies must specify prices for proposers to propose in any given subgraph G_i and responses for any given distribution of prices, in any given graph G_i.

• Strategies whenever the current graph is G_i, a strict subgraph of G (somebody has traded)
Call the current round t', with $t_0 \leq t' \leq 6$. By the induction step we know of the existence of an SPE in this subgame and the prescribed strategies for the agents.

• Strategies whenever the graph is G (nobody has traded)
Call the current round t', with $t_0 \leq t' \leq 6$.

Proposals: In G^S, proposals always give sellers a share of 200 and buyers a share of $\Pi_{t'}$-200 (the rest).
In G^B, proposals always give buyers a share of 200 and sellers $\Pi_{t'}$-200.
In G^E, proposals will be given by:
If t' is odd sellers propose: $\Pi 5/2 + 100(5-t')/2+50$ for themselves, $\Pi 5/2 + 100(5-t')/2-50$ for the buyer.
If t' is even buyers propose: if t'=6: $\Pi_{t'}$-200 for themselves, 200 for the seller. Otherwise, buyers propose $\Pi 5/2 + 100(5-t_0)/2$ for themselves, $\Pi 5/2 + 100(5-t_0)/2+50$ for the buyer.

Call this proposal P.
Responses: Relabel agents in each G^S_i as $\{s^S_1,\ldots,s^S_{n^S_i}\}$ and $\{b^S_1,\ldots,b^S_{m^S_i}\}$. Similarly, relabel agents in each G^B_i as $\{s^B_1,\ldots,s^B_{n^B_i}\}$ and $\{b^B_1,\ldots,b^B_{m^B_i}\}$. Then, relabel agents in each G^E_i as $\{s^E_1,\ldots,s^E_{n^E_i}\}$ and $\{b^E_1,\ldots,b^E_{m^E_i}\}$, in such a way that there exists a matching linking s^E_i with b^E_i
Then, if the proposal has been equal to P, all responders accept in the following way:

If t' is odd (sellers propose):
In G^S_i, buyer b^S_j accepts the proposal by seller s^S_j.
In G^E_i, buyer b^E_j accepts the proposal by seller s^E_j
In G^B_i, buyer b^B_j for $j=1,\ldots,n^B i$ accepts the proposal by seller s^B_j and buyers b^B_j for $j=n^B i+1, \ldots, m^B i$ accept the proposal from seller $s^B_{n^B_i}$.
If t' is even (buyers propose): symmetric, with roles of buyers and sellers reversed.

We now write what agents do facing some of the possible unilateral deviations:

Members of G^S (odd round): If the distribution differs from P in one price only, then call s_i the seller that deviated in its proposal. There will exist a matching involving all the buyers and a number equal of sellers (not involving s_i). Then all buyers will accept the proposal made by their correspondent seller in the matching.

Members of G^B (even round): Symmetric as above.

Members of G^E (odd round): If the difference is with one price being higher (the one proposed by s_i), then the n-1 buyers different than b_i accept from the n-1 sellers that did not deviate and buyer b_i rejects.
(even round) If the difference is with one price being higher (the one proposed by b_i), then the n-1 sellers accept from the n-1 buyers that did not deviate and seller s_i rejects.

Now, let us check that what we have above is indeed a Nash Equilibrium. For instance, suppose that you are a seller at round t'. As a proposer: In a G^B, the share you obtain in equilibrium equals $\Pi_{t'}$-200, which is the most you can ever obtain. In a G^S, you are proposing to receive 200 for yourself and to give $\Pi_{t'}$-200 for the others. If you deviate and try to get a bigger share, you will not be accepted and will be left isolated (since all other buyers in a G^S will reach agreement), receiving a payoff of 200. In a G^E, if proposing, by proposing a bigger share you will not be accepted, and next round you will receive even less. If responding, by rejecting you will receive in the same round exactly the same share you are being offered.

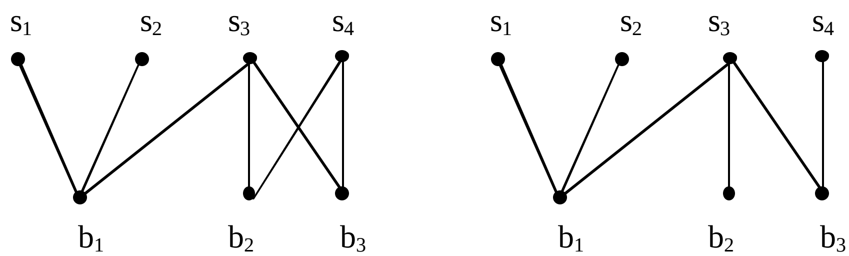
To define a subgame-perfect equilibrium, we must also state what strategies specify off the equilibrium path.

We now explain how strategies can be constructed so that the strategies above conform to a subgame perfect equilibrium. For any distribution of prices, agents have a finite set of actions that consist of either accepting one of the proposals or rejecting all. If less than the maximum possible number of pairs form, then by the induction step we know that there exists a SPE in the resulting subgraph (since this will be a subgraph that has a number of agents strictly smaller than k_i). We define strategies so that if less than the maximum possible number of pairs form, then strategies follow the SPE of the resulting subgraph (which we know exists by the induction step). If all agents reject, then the strategies will prescribe for proposers to propose price distribution P and for responders to accept. Therefore we can conclude that given an action for all responders, the payoffs are immediately determined. This must have at least one NE. We will define the strategies as follows: for any distribution of prices, strategies will tell responders to play according to this NE. However, note though that there may be multiple NE. If this is the case, strategies must specify which of the several NE will be played. Any specification would suffice. ■

Proposition 4

The SPE payoffs given by Theorem 2 are unique for the networks in our design.

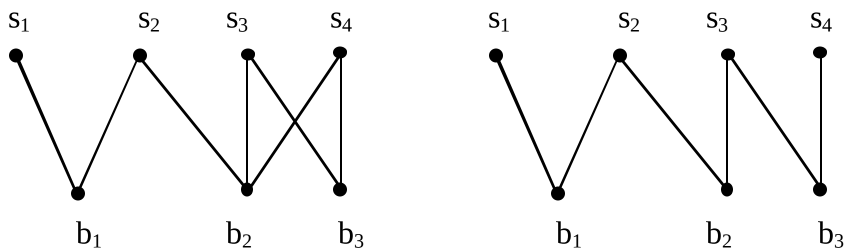
The uniqueness for network types 1 and 2 has already been shown.
We now show uniqueness for network types 3 and 4. Relabel sellers as s_1 to s_4, in the following way:



As a first step, we will show that in either case sellers s_1 and s_2 receive a payoff of 200 in equilibrium, while buyer b_1 receives 2300. Suppose to the contrary (w.l.o.g) that s_1 receives a payoff higher than 200. This cannot happen in an odd round, through s_1 proposing a partition that b_1 accepts, since s_2 would have undercut by proposing a lower share for himself (but one still higher than 200). Then, it should be the case that both s_1 and s_2 accepted from b_1 in an even round, each reaching agreement with the same probability, and otherwise receiving 200. But this cannot be an equilibrium either, as b_1 could propose a higher share for himself (and would still be accepted, since sellers in the following round would get 200). We can conclude then that s_1 and s_2 get 200 in equilibrium and b_1 gets the rest of the pie, starting in any subgame.

Now it is intuitive to see that agents s_3, s_4, b_2, and b_3 will play as in Figure 2 or 3, as if the link connecting b_1 and s_3 does not exist. Indeed, if all four agents are still in the market in the last round, we know that in equilibrium buyer b_1 will propose (Π_6-200, 200) and that this would be accepted by sellers s_1 and s_2. Clearly, if s_3 or s_4 rejects, he or she receives a payoff of 200, so should accept any proposal that is greater than or equal to it. Thus, we can apply the arguments of Proposition 3 here as well and conclude s_3 s_4, b_2, and b_3 will play as in Figure 2 or 3.

We now move to showing uniqueness for network types 5 and 6.



Note first that as four pairs will never form, at least one of the sellers must receive a payoff of 200 in equilibrium. Let us call this seller s_i. This seller must be linked to at least one buyer, call him b_i. Now, since s_i received 200 in equilibrium, this implies that he could not deviate in the first round and propose $200+\in$ for himself. This implies in turn that b_i could accept a share of 2300 from somebody else (since the network we are analyzing has a G^S structure, it follows that any buyer b_i is linked to at least 2 sellers), call him s_j. That is, this implies that seller s_j was proposing 200 for himself and was accepted. But again, if he could not deviate, this implies that all its linked buyers accept 2300 from other sellers. That is, the fact that a seller s_i received the reservation value in equilibrium implies that the sellers linked to b_i , with b_i being a buyer linked to s_i, also got the reservation value. Given the structure of the networks, in this case this implies that all sellers proposed the reservation value for themselves and were accepted.■

Appendix C – Graph Theory Notation and Results

All concepts are standard (excepting the def. of G^S , G^B and G^E) and can be found in any graph theory textbook (e.g., Gould [1988]).

A non-directed *bipartite graph* $G=<S \cup B,L>$ consists of a set of *nodes*, formed by n sellers $S=\{s_1,..., s_n\}$ and m buyers $B=\{b_1,..., b_m\}$, and a set of *links* L, each link joining a seller with a buyer. An element of L, say a link from s_i to b_j will be denoted as $s_i : b_j$.

A *subgraph* $G_0=<S_0 \cup B_0,L_0>$ of $G=<S \cup B,L>$ is a graph such that $S_0 \subseteq S$, $B_0 \subseteq B$, $L_0 \subseteq L$, and such that each link in L_0 connects a seller of S_0 with a buyer in B_0. When we speak of the *subgraph G_0 induced by the set of nodes $S_0 \cup B_0$ in G* we mean the subgraph formed by the nodes $S_0 \cup B_0$ and all the links that connect a seller in S_0 and a buyer in B_0 in G.

For each seller $s_j \in S$, let $N_G(s_j)$ be the set of buyers linked with s_j in $G=<S \cup B,L>$; for each buyer $b_j \in B$, let $N_G(b_i)$ be the set of sellers linked with b_i in G. Similarly, for a subset of sellers $S_0=\{s_1,..., s_t\}$ we will let $N_G(S_0)$ be the set of buyers *collectively linked* to S_0 in G (and analogously, for a set of buyers B_0). Formally, $N_G(S_0) = \cup^t_{j=1}(N_G(s_j))$.

In the graph $G=<S \cup B,L>$, consider a set of nodes $V \subseteq S$ or $V \subseteq B$ (either a subset of sellers or a subset of buyers). We will say that a set of nodes V is non-deficient if all its subsets of nodes are collectively linked to a set of at least the same number of members. Formally, a set of nodes V is *non-deficient* in $G=<S \cup B,L>$ if $|N_G(V_0)| \geq |V_0| \ \forall \ V_0 \subseteq V$.

A *matching* in a bipartite graph $G=<S \cup B,L>$ is a collection of pairs of linked members of B and S such that each agent in $S \cup B$ belongs to at most one pair. A matching *saturates all the nodes in V* if the set of pairs contains all members of V.

Hall's theorem (1935) gives us the necessary and sufficient conditions for a matching saturating a given set of nodes to exist:

Hall's Theorem: There exists a matching in G that saturates all the nodes in V $\leftrightarrow$ V is non-deficient.

We now write the formal definition for subgraphs G^S , G^B and G^E .

Definition 1: A graph $G=<S \cup B,L>$ with more sellers than buyers ($|S| = n>m= |B|$) is a G^S *graph* if any subset of sellers of size $\leq$ m is non-deficient (see Appendix C). Formally, for any subset $S_0 \subseteq S$ such that $|S_0| \leq m$, we have that $|N_G(S_0)| \geq |S_0|$. Symmetrically, a graph with more buyers than sellers (n<m) is a G^B *graph* if any subset of buyers up to size n is non-deficient. A graph with as many sellers and buyers (n=m) is a G^E *graph* if there exists a matching involving all its pairs.

Appendix D – Average Payoffs

Table 7 – Average Payoffs in Treatment 1

	Network Position						
Period	A	B	C	D	E	F	G
1	533	783	1350	1033	1217	1117	867
2	567	533	1567	1183	1233	1233	1183
3	533	467	1667	1317	1217	1183	1217
4	650	200	1717	1267	1217	1233	1217
Avg. 1-4	**546**	**496**	**1575**	**1200**	**1221**	**1192**	**1121**
5	683	200	1783	1183	1250	1217	1250
6	658	200	1842	1250	1250	1083	1217
7	267	500	1933	1283	933	1217	867
8	200	507	1993	1267	1283	1233	1183
9	450	200	2050	1217	1250	1233	1233
10	233	233	2133	1217	1233	1183	1200
Avg. 5-10	**415**	**307**	**1956**	**1236**	**1208**	**1194**	**1158**

Table 8 – Average Payoffs in Treatment 2

	Network Position						
Period	A	B	C	D	E	F	G
1	725	650	1325	1225	1225	1250	1225
2	200	1100	1375	1250	1212	1250	1238
3	425	838	1438	1225	1238	1225	1238
4	800	425	1475	988	1138	988	1162
Avg. 1-4	**538**	**753**	**1403**	**1172**	**1203**	**1178**	**1216**
5	1012	675	1488	1225	675	1325	1250
6	788	1112	1512	688	700	1338	1038
7	819	600	1481	875	1056	1400	1294
8	1062	875	1438	875	675	1362	1362
9	1012	775	1488	612	912	1438	1388
10	806	569	1494	875	1088	1394	1375
Avg. 5-10	**916**	**768**	**1484**	**858**	**851**	**1376**	**1284**

Table 9 – Average Payoffs in Treatment 3

	Network Position						
Period	A	B	C	D	E	F	G
1	450	913	1338	1212	1238	1212	1212
2	912	425	1362	1312	900	1188	1575
3	1012	200	1488	1300	1200	1175	1275
4	900	200	1600	1350	675	662	1188
Avg. 1-4	**818**	**434**	**1447**	**1294**	**1003**	**1059**	**1312**
5	400	581	1719	1250	1188	1200	1288
6	275	669	1756	1250	1162	1175	1312
7	619	200	1881	1238	1238	1162	1262
8	494	200	2006	1025	1262	950	1238
9	325	350	2025	1012	1288	962	1212
10	288	319	2094	1375	1262	1125	1212
Avg. 5-10	**400**	**386**	**1914**	**1192**	**1233**	**1096**	**1254**

Table 10 – Average Payoffs in Treatment 4

	Network Position						
Period	A	B	C	D	E	F	G
1	825	450	1425	1212	900	950	1288
2	200	938	1588	1300	1181	1200	1218
3	375	525	1725	1225	1200	1250	1300
4	300	688	1712	1138	1238	1188	1188
Avg. 1-4	**425**	**650**	**1612**	**1219**	**1130**	**1147**	**1248**
5	812	575	1688	538	875	1562	1075
6	925	762	1500	862	425	1512	1612
7	762	600	1738	512	850	1650	1338
8	875	862	1600	525	625	1588	1525
9	525	725	1750	650	825	1675	1450
10*	833	883	1667	567	233	1583	1700
Avg. 5-10	**789**	**734**	**1657**	**609**	**639**	**1595**	**1450**

*One of the four sessions did not have a period 10.

Appendix E – Bargaining Efficiency and Timing

Table 5 – Bargaining Efficiency

Period	Treatment 1	Treatment 2	Treatment 3	Treatment 4
1	88.2%	98.8%	98.0%	89.7%
2	96.8%	98.8%	99.6%	98.8%
3	98.4%	98.8%	98.4%	98.4%
4	96.8%	88.5%	82.5%	96.1%
Avg. 1-4	**95.0%**	**96.2%**	**94.6%**	**95.8%**
5	98.7%	99.2%	98.8%	90.9%
6	96.8%	91.7%	98.4%	98.4%
7	88.9%	97.2%	98.4%	96.0%
8	99.5%	99.2%	91.7%	98.4%
9	98.9%	98.8%	91.7%	98.4%
10	95.7%	98.4%	99.6%	96.3%
Avg. 5-10	**96.4%**	**97.4%**	**96.4%**	**96.4%**

Table 6 - Distribution of Agreements by Round

	# of Agreements Reached (Round)						
Session	1	2	3	4	5	6	Not
1	19	9	1	0	1	0	0
2	25	4	1	0	0	0	0
3	20	6	1	0	1	0	2
4	26	4	0	0	0	0	0
5	24	4	0	0	1	0	1
6	22	5	2	0	0	0	1
7	21	6	0	3	0	0	0
8	19	7	0	0	1	0	3
9	27	3	0	0	0	0	0
10	28	0	1	1	0	0	0
11	25	4	0	0	0	0	1
12	13	10	2	1	0	0	1
13	26	2	0	1	0	0	1
14	21	6	1	2	0	0	0
15	19	6	2	2	1	0	0
Total	**335**	**76**	**11**	**10**	**5**	**0**	**10**