The Design of Agency Relations: Four Essays on Contract Theory, Applications, and Experimentation

Thesis by

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I am confident that I could not have produced a dissertation of this scope and content at another institution. The combination of research on Venetian contracting practices and experimental research might seem eclectic, but the motivations for both bodies of research were complementary. One of the great features of my experience at Caltech was that I was able to vigorously pursue both bodies of research without hindrance. Indeed, Caltech provided both the material and intellectual support that I needed and, indeed, confidently expected.

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Abstract

The first part of the thesis takes up a contracting problem in which a venture capitalist (VC) finances agents to conduct risky projects in which the VC can neither observe the agents' actions nor verify the agents' actions *ex post*. The central issue is how to keep agent from cheating the VC by skimming profits. Theoretical results developed in the first chapter are applied in successive chapters to data sets of maritime contracts that pertain to the financing of Venetian trade in the years 1190-1220 and 1303-1351.

The contract data indicate that risk-sharing between contracting parties would less likely obtain in the conduct of the most risk-laden ventures whereas contracting parties tended to share commercial risk in the conduct of those ventures that were least subject to both commercial and physical hazards. Such patterns in the contract data may, at first sight, seem counter-intuitive, but they line up with qualitative predictions of the theoretical framework. The central theoretical finding is that under general conditions debt contracts – contracts in which agents effectively buy the right to conduct a venture from the VC -- dominate contracts in which the VC and agent share commercial risk. An exercise in dynamic optimization indicates that while there might be some scope for risk-sharing between the contracting parties, debt contracts neutralize

informational rents an investor must otherwise yield to his agent to induce truthful reporting of outcomes the investor can neither observe nor verify.

The second part of the thesis takes up an experimental examination of contracting. The experimental design involves a market in which agents buy and sell rights to participate in a follow-on stage of strategic interaction. The central question posed is how the game and the market, two different types of processes, interact. The results demonstrate that outcomes in the game are systematically linked to outcomes in the market. The game outcomes can be characterized by traditional game-theoretic solution concepts. Moreover, the market converges to a competitive equilibrium consistent with the Nash equilibrium that obtains in the game.

Keywords: Venture Capital, Mechanism Design, Implementation Theory, Experimentation, Economic History, Contract Theory, Principal-Agent Theory, Venice

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Chapter 1:

Stopping Agents from Cheating and Venture Capital Contracting

Through the Middle Ages and into the 17th century the wealth of Northern Italian city states derived from maritime trade within and beyond the Mediterranean world, and coming into the 15th century the organization of the trade came to be dominated by trade "firms" – commercial entities that monopolized the services of trading agents via long-term employment contracts. Over most of the millenium preceding the emergence of trade firms, however, maritime trade was organized almost exclusively through pair-wise contracts that would match an investor and a trading agent in a single trade venture. Within the terms of a contract, an investor typically advanced funding or other resources to an agent, and the agent would travel to foreign ports to conduct trades on the investor's behalf. The agent would return with goods such as spices, grain, and alum for re-export to European markets, and the proceeds generated by the round-trip venture would be distributed according to a sharing rule. Most contracts were either fixed-rate loans, known in Venice as *prestitti marittimi* or "sea loans," or were profit-sharing agreements, known in Venice as *colleganza* contracts and recognized outside of the literature of Venetian commercial practices as *commenda* contracts. Sea loans specify fixed returns to the principal, and most typically they are distinguished from normal loans by requiring the agent to make payment contingent on the safe return of the vessel on which the agent ventured. *Colleganza* contracts specified non-degenerate linear sharing rules by which the investor and agent shared profits contingent, again, on the safe return of the vessel. Investors never secured agents' services by wage contracts.

Curiously, the data indicate that investors tended to contract agents' services for the conduct of the most risk-laden ventures by debt contracts ("loans") while at the same time they secured agents' services via profit-sharing contracts for the conduct of the most secure ventures. In traditional models, the alignment of incentives depends on the (costless) *ex post* observability and verifiability of agents' outputs. Incentive alignment, however, implicates the flows of information supporting compensation schemes. In some contracting problems such as the one examined here, however, investors can neither observe nor verify agents' outputs, and yet there is abundant data to indicate that the contracting of agency services by means of pair-wise contracts constituted the dominant of organizing trade and mobilizing financial resources in the Mediterranean for the larger part of a millenium.

The paper rationalizes patterns in the data by establishing a few simple observations. First, the chief strategic feature of "sea loans" is that they yielded to investors payoffs that were independent of agents' reports of transactions –

the same transactions that the investor could neither observe nor verify. While loans required the investor to consider the prospect of an agent's default, they neutralized any losses an agent could impose on the investor by misrepresenting the results of transactions conducted on the investor's behalf. Loan contracts simply relieved investors of having to know all the details of complex transactions. Contracts such as *colleganza*, however, specified payoffs to investors that depended entirely on agents' reports. One might not be too surprised, then, to find that investors were more likely to have secured the services of agents in the trade of commonly traded commodities along commonly traveled routes. The annual trade in pepper from Egypt, for example, provided a context in which *colleganza* contracting dominated. The Egyptian pepper trade involved two informational advantages: 1) the trade involved an homogeneous good, and so the price of pepper constituted a means by which an agent's report could be measured; and 2) the Egyptian trade was well-attended by other agents thereby providing investors with much public information about pepper prices. An agent could then have expected his investors would compare his reports of transactions to the reports of other agents. Investors could easily detect inferior reports and impose sanctions such as, say, not hiring the agent in the succeeding year's pepper trade.

The basic idea is that the strategic viability of contracts featuring non-degenerate sharing-rules such as *colleganza* had to rigged-up by embedding them in larger mechanisms that permitted investors to extract information. In contrast, the strategic viability of loan contracts could be established without implicating some larger game. The "larger mechanism" involved a game between agents by which agents' reports would be compared. Inferior reports would invite sanction, and without too much fine-tuning investors could structure sanctions such that truthful reporting by every agent would emerge as a Nash equilibrium of the game.

The basic apparatus presented here includes features that show up in such things as models of non-linear pricing or models of regulation and procurement. A seemingly eclectic range of models work out of the "differential approach" that has been popularized by, among others, Laffont and Tirole in their various publications including, but not limited to, *A Theory of Incentives in Procurement and Regulation* (1993), *Fundamentals of Public Economics* (1988), and "Creating Competition Through Interconnection" (1996). The various models that work out of the "differential approach" share mathematically similar features even though the models that have been developed pertain to a broad array of otherwise diverse problems. Indeed, as Jean Tirole observes in *The Theory of Industrial Organization* (1990, pg. 153), the techniques "can be applied to a variety of problems in economics, including topics relevant to industrial organization, such as the theories of optimal regulation and optimal auctions." To Professor

Tirole's list I would like to add the more specialized item "optimal (medieval maritime) agency contracts."

A distinguishing feature of models that work out of the "differential approach" is that they incorporate agents' incentives as a problem of motivating self-selection among "types." In the context examined here, for example, agents realize returns from contracted ventures. The returns determine their types, and the investor (the "principal") designs a compensation schedule that induces high-value type agents -- agents who have realized high returns -- to distinguish themselves from agents who have realized low returns. That is, the principal designs compensation schemes that induce agents to truthfully report their "types" or, the same thing, to report the returns that obtained to the contracted venture.

The remainder of the chapter proceeds in four parts. The first part presents a simple model from which loan contracts generally emerge as the optimal mode of contracting, the second part develops a model that applies to contracting in a context involving multiple agents, and the third part outlines the qualitative predictions that emerge from the two modeling exercises. The final part concludes.

I The basic framework

Modeling the problem of designing a contract featuring risk-sharing will demonstrate that under a standard set of assumptions 1) contracts featuring some non-degenerate degree of risk-sharing can be designed without implicating some larger mechanism, yet 2) loan contracts can nonetheless emerge from the modeling process as the optimal contracts. In the model that follows the investor (or principal) assumes the role of contract designer. The investor engages the services of an agent to conduct a venture that will generate a risky return on the investor's investment. The "venture" is a production technology that requires both the inputs of the investor and agent. The investor's problem is to impose on the agent at the time of contracting (before the realization of the return) a "sharing rule" that assigns payoffs to the prospective agent as a function of the agent's *ex post* report of the return. Under very general conditions on the agent's risk preferences, the investor can tailor a sharing-rule that induces the agent to reveal the realized return. To jointly achieve revelation and some non-degenerate degree of risk-sharing, the contract designer needs to have exacting knowledge of the agent's preferences. That is a lot of information that contract designers perhaps do not ordinarily have. A useful feature of loan contracts, however, is that designing them does not require extensive knowledge of agents' preferences. They are simple to implement.

Strategic interaction between the principal and the agent unfold over the course of a three stage process. In the first stage, the agent posts a bond, and both the principal and agent commit to terms of contract. The bond mitigates or neutralizes losses to the principal that would obtain in the event the agent were to fail to remit payment according to the terms of contract at the termination of the venture. The risk of default, however, does not implicate the sharing rule, and so is not the focus of the paper. In the second stage, the agent realizes the outcome that obtains to the venture. In the third and last stage, the agent reports an outcome to the principal – and he may very well lie – and the principal and agent distribute payoffs according to the terms of contract.

The structure of strategic interaction is outlined below.

<u>Stage of interaction</u>	
1) Contracting	The contracting parties commit to terms of contract, and the agent posts a bond.
2) Realization	The agent realizes the outcome of the venture. The principal cannot observe the outcome.
3) *Ex post* Accounting	Commercial and physical hazards are bygone. The agent reports an outcome, and the principal and agent distribute payoffs according to the terms of contract. The principal cannot verify the outcome.

The model constitutes a partial equilibrium treatment of the problem of contracting agency services in that the principal is invested with all bargaining power. The principal imposes a "take-it-or-leave-it" offer on the agent, an offer that renders to the agent expected payoffs that match the utility of the second-best application of the agent's inputs.

The partial equilibrium treatment will correspond closely to a general equilibrium analysis in a broad range of environments, because the shape of the sharing rule, i.e., the marginal compensation the agent receives for every marginal change in the realized return, should remain invariant across environments. The shape of the sharing-rule structures the agent's incentives to report returns truthfully whereas the absolute scale of the sharing rule bears upon the agent's decision to participate in a venture or to reject a contract offer.

As conceptualized here, a general equilibrium treatment would examine the types of contracts that emerge market-wide in a bilateral market in which candidate parties for contracting bargain over the exchange of venture capital for agency services. In such a market investors and agents bargain not so much over the price of agency services (or venture capital) as over vectors of items that constitute the terms of contract. In a market featuring a large number of agents and a scarce supply of investment resources, agents may very well offer competitive bids – where bids are vectors of candidate terms of contract – for contracts with investors. Nonetheless, the modeling exercise that follows suggests that the terms of contract that emerge in equilibrium should remain qualitatively the same even in a market featuring an abundance of investment resources chasing after a scarce supply of agents. The relative scarcity of agents does not change the incentive alignment problem facing investors; competition for agency services does not change agent's incentives to report outcomes truthfully once an investor and agent have signed a contract. Rather, relative scarcity might improve agents' options outside of the candidate contract with the investor, in which case investors could expect to compensate agents more generously for their services by "pushing up" the entire sharing rule.

A simple model

The principal will induce an agent to reveal realized returns by presenting the agent with the prospect of being retained for service in succeeding trade ventures. While the idea of being "retained" involves repeated interaction, all of the apparatus and results that follow can immediately be recovered by alternatively interpreting the prospect of being retained simply as the prospect of receiving a one-time prize.

The model involves a three-stage process whereby 1) the agent and principal determine the terms by which the principal secures the agent's services, 2) the agent realizes the outcome of the venture, and 3) the agent reports an outcome and receives a payoff as a function of the reported outcome. The analysis also proceeds in three stages. First we characterize the incentives facing the agent at the time at which the agent reports the realized return to the principal. Second we establish how the agent responds to his incentives, and, lastly, we factor the agent's response into the principal's selection of contracts. At the time of reporting, all risks are bygone, and the only action that remains is to distribute payoffs as a function of the agent's report. The issue facing the principal is to identify at the time of contracting modes of contracting (if any) that would induce the agent to reveal the realization of the return. Among these modes the principal determines which contracts would generate the highest expected payoff to himself.

Conducting a "venture" involves making a draw of a random variable x, a real number indicating the "rate of return" on each unit of the principal's investment $I \geq 0$. The principal requires the agent's "service" in conducting the draw, and the agent requires the investor's input I. Further, the agent is afforded the opportunity to draw in one of two possible states: "no disaster" and "disaster." "Disaster" ("shipwreck," say) constitutes a state in which the agent bears some personal disutility and in which no return is recoverable from the venture. The random variable x has support $[\underline{x}, \bar{x}]$. We impose the following assumptions:

(A1) Let f(x), a continuously differentiable probability mass distribution with $f(x)>0$ over the support, characterize the common subjective probability assessment of the investor and agent.

(A2) Let the agent's and principal's risk preferences be characterized by twice differentiable von Neumann-Morgenstern utility functions $V(\cdot)$ and $U(\cdot)$

over income. For now assume the contracting parties are risk-averse, that is, $V' > 0$, $V'' < 0$, $U' > 0$ and $U'' < 0$.

(A3) The binary distribution over the states "no disaster" and "disaster" is characterized by $\phi \in [0, 1]$ where ϕ = Prob("no disaster").

The principal's design problem entails choosing a sharing-rule, a function $s: [\underline{x}, \overline{x}] \rightarrow [0,1]$, that specifies the portion the principal yields to the agent of the return $\hat{x}I$ the agent reports after the realization of x. That is, given a report $\hat{x}$ the agent receives a payoff $s(\hat{x})I$. The principal can neither observe nor verify the realization x. The principal also chooses a retaining-rule, a function $R: [\underline{x}, \overline{x}] \rightarrow [0,1]$, that determines the probability with which the agent receives a secondary payoff or "prize." As interpreted here, this secondary payoff will be comprised of the expected utility the agent enjoys from being retained for service in a succeeding commercial venture net of the utility the agent enjoys from forgoing employment in a succeeding round of interaction. Without loss of generality, this secondary payoff could be interpreted as a one-shot payoff such as a lump-sum payment, but under either interpretation the prospect of receiving a secondary payoff introduces a tension that the principal can use to induce the agent to truthfully report the realized return x. The agent trades off under-reporting the return x – and expropriating the sum $(x - \hat{x})I$ – against receiving with some fine-tuned probability a secondary prize.

In evaluating one-shot deviations from truth-telling, we appeal to the notion of Markhov perfect equilibrium (MPE). The concept of MPE is employed implicitly in the Shapiro and Stiglitz (1984) model of efficiency wages and is explicitly articulated in the Maskin and Tirole (1988) model of dynamic oligopoly. The idea is to restrict our attention to equilibria in which truth-telling emerges in every period of interaction rather than to consider equilibria that involve some period-to-period stream of mis-representations. To do this, we examine the prospects for current-period deviations given agents reveal outcomes truthfully in future stages of interaction.

We proceed here with the interpretation of the prize as the present value of successive re-employment net of the value of the second-best application of the agent's inputs. The value of the second-best is exogenously determined as $\overline{V}$. One can think of $\overline{V}$ as the value to the agent of "working in the fields" and forgoing employment as a trading agent. Let the value of being employed V_E before the realization of an outcome x be comprised of 1) the expected utility to the agent of the venture for which he has been currently retained and 2) the value of being variously retained or excused from service in an infinite sequence of succeeding rounds of interaction or "trading seasons." Assume that the agent's utility is additively separable over time and that the agent exhibits some degree of impatience. That is, the agent discounts future payoffs by a discount factor $\delta < 1$.

We assume being retained entails conducting ventures that are identically characterized by $f(\cdot)$ and by the level of investment I and that the continuation value of being currently unemployed is some bounded number V_U. Finally, without loss of generality, we assume that the agent reverts to employed status in the following trading season in the event he experiences disaster in the current trading season. Given the agent always reveals realizations drawn from $f(\cdot)$, the continuation value of being employed V_E is bounded and stationary and can be expressed as

$$V_E = \phi\left\{\int_{\underline{x}}^{\overline{x}} V(s(z)I)dF(z) + \delta\left[\int_{\underline{x}}^{\overline{x}} R(z)dF(z)\right]V_E + \delta\left[\int_{\underline{x}}^{\overline{x}} [1-R(z)]dF(z)\right]V_U\right\} + (1-\phi)\{\delta V_E - y\} \tag{1}$$

where

$\int_{\underline{x}}^{\overline{x}} V(s(z)I)dF(z)$ = the agent's expected utility from the current venture,

$\int_{\underline{x}}^{\overline{x}} R(z)dF(z)$ = the probability with which the agent is retained in the succeeding trading season, and

$\int_{\underline{x}}^{\overline{x}} [1-R(z)]dF(z)$ = the probability with which the agent is subsequently excused from service and reverts to unemployed status.

The idea expressed in equation (1) is that at the outset of a venture (before a return has been realized) an agent faces a probabilistic stream of payoffs characterized by V_E. Because V_E is stationary, being retained in a succeeding trading season restores the agent to a stream that again is characterized by V_E. Upon being excused from service the agent faces a probabilistic stream of payoffs characterized by V_U.

The continuation value of being unemployed V_U can also be expressed as a stationary process. We assume there exists some technology by which currently unemployed agents are employed with some probability (possibly zero) in successive trading seasons. Without loss of generality assume there exists a pool of (n+k) agents, that in any given trading season k agents are retained, that all of them experience the same draw from f(·), that all of them reveal x, and, finally, that at the close of the trading season all k agents are retained for service in the next trading season with probability R(x). Under these assumptions, the following characterization of V_U emerges:

$$V_U = \overline{V} + \phi\left\{\delta\left[\int_{\underline{x}}^{\overline{x}} \tfrac{k}{n}[1-R(z)]dF(z)\right]V_E + \delta\left[\int_{\underline{x}}^{\overline{x}}[1-\tfrac{k}{n}[1-R(z)]]dF(z)\right]V_U\right\} + (1-\phi)\delta V_U \tag{2}$$

where

$\int_{\underline{x}}^{\overline{x}} \frac{k}{n}[1 - R(z)]dF(z)$ = the probability with which an unemployed agent is hired in the succeeding trading season, and

$\int_{\underline{x}}^{\overline{x}} [1 - \frac{k}{n}[1 - R(z)]]dF(z)$ = the probability with which an unemployed agent remains unemployed in the succeeding trading season.

To simplify the notation, let

$$EV = \int_{\underline{x}}^{\overline{x}} V(s(z)I)dF(z), \text{ and}$$

$$ER = \int_{\underline{x}}^{\overline{x}} R(z)dF(z).$$

Finally, we are in a position to express the "prize" the agent receives by being retained. Here the prize is identified as (V_E - V_U), the continuation value of employment net of the value of unemployment, i.e., the second-best application of the agent's inputs. Solving equations (1) and (2) for V_E and V_U permit the following means of expressing the "prize" where the "prize" constitutes the value to the agent of truthfully reporting in all periods of future and current interaction:

$$(V_E - V_U) = \frac{\phi(EV - \overline{V}) - (1-\phi)(y + \overline{V})}{(1-\delta) + \delta\left(\frac{n+k}{n}\right)[1 - ER]}. \tag{3}$$

The agent's maximization problem

We are now in a position to characterize the incentives facing the agent at the time the agent renders a report $\hat{x}$ given a realization x. At the time of contracting the parties commit to a contract that is characterized by a triple {s(x), R(x), I}. At the time of reporting, both commercial and physical risks are bygone. The agent has simply to determine whether or not to report the true realization of the return on the investment. He may very well cheat the investor, but the payoff the agent enjoys from cheating will depend on the sharing rule $s(\hat{x})$ and the retaining rule $R(\hat{x})$.

According to his contract with the principal the agent receives a payoff $s(\hat{x})I$. Additionally, misrepresenting the realization x renders to the agent an additional payoff $(x-\hat{x})I$. Finally, reporting $\hat{x}$ secures re-employment in the succeeding trading season with probability $R(\hat{x})$, and he reverts to unemployed status with probability $1-R(\hat{x})$. Taken all together the agent's maximand is

$$\pi(\hat{x};x) \quad = \quad V\big(s(\hat{x})I+(x-\hat{x})I\big) \quad + \quad \delta R(\hat{x})V_E \quad + \quad \delta[1-R(\hat{x})]V_U\,.$$

With the slightest rewriting the agent's maximand is easier to interpret.

$$\pi(\hat{x};x) \quad = \quad V\big(s(\hat{x})I+(x-\hat{x})I\big) \quad + \quad \delta R(\hat{x})(V_E - V_U) \quad + \quad \delta V_U \qquad (4)$$

In equation (4) $R(\hat{x})$ is plainly the probability with which the agent secures the "prize" (V_E - V_U).

The agent's first-order condition yields

$$\frac{\partial \pi(\hat{x};x)}{\partial \hat{x}} = V'\big(s(\hat{x})I + (x-\hat{x})I\big)\big(s'(\hat{x})-1\big)I \quad + \quad \delta R'(\hat{x})(V_E - V_U) \;=\; 0 .$$

Rearranging yields a more instructive expression:

$$s'(\hat{x}) \;=\; 1 \;-\; \frac{\delta R'(\hat{x})(V_E - V_U)}{V'\big(s(\hat{x})I + (x-\hat{x})I\big)I} \tag{5}$$

Equation (5) contains all the information the principal needs in order to craft a sharing rule s(x) that will induce the agent to reveal realized outcomes. Equation (5) characterizes the agent's response function $\hat{x}(x)$, and, indeed, implicit differentiation of (5) and successive integration would permit us to generate a complex expression for $\hat{x}(x)$. We can avoid this exercise simply by observing that the principal wants to choose the shape of the sharing rule such that $\hat{x}(x) = x$, i.e., such that the agent reveals x when x is realized. Sharing rules satisfying the following condition achieve the result:

$$s'(\hat{x}) \;=\; 1 \;-\; \frac{\delta R'(\hat{x})(V_E - V_U)}{V'\big(s(\hat{x})I\big)I} \tag{6}$$

To see this, substitute the left-hand side of (5) with the right-hand side of (6), and observe that the response function $\hat{x}(x) = x$ satisfies the resulting equation. What equation (6) says is that unless 1) the agent's prospect of being retained is increasing in the agent's report, and 2) the value of being employed exceeds the value of forgoing employment, the only way the principal can induce the agent to reveal x is to render to the agent all payoffs on the margin. That is, only contracts satisfying $s'(\hat{x}) = 1$ would induce truthful reporting.

The forgoing discussion establishes the first result.

Proposition 1: Given $V' > 0$, $V'' < 0$, and $s'<1$, compensation schemes $s(\hat{x})$ that conform to the condition $s'(\hat{x}) = 1 - \frac{\delta R'(\hat{x})(V_E - V_U)}{V'(s(\hat{x})I)I}$ induce truthful reporting. That is $\hat{x}(x) = x$.

Proof: Apply total differentiation to $\pi(\hat{x}(x);x)$. The Envelope Theorem identifies terms that together identically equal zero for each x in $[\underline{x}, \overline{x}]$. Collecting these terms and rearranging yields equation (6).

A parallel but weaker result can be achieved when the agent is risk-neutral (V'' = 0). Under risk-neutrality equation (6) becomes

$$s'(\hat{x}) = 1 - \frac{\delta R'(\hat{x})(V_E - V_U)}{I}. \quad (6')$$

While truthful reporting is consistent with (6′), reporting any outcome is also consistent. Again, the agent's best response is characterized by the correspondence $\hat{x}(x) = [\underline{x}, \overline{x}]$. The risk-neutral agent is indifferent between revealing the realized outcome and reporting a different outcome, because a risk-neutral agent assigns equal weight to current payoffs and to future (discounted) payoffs. In the case of the risk-averse agent, the concavity of the function $V(\cdot)$ permits us to recover a response function $\hat{x}(x)$, and as we have demonstrated special conditions on the sharing rule and retaining rule permit us to recover the particular response function $\hat{x}(x) = x$.

The condition $s'(\hat{x}) = 1 \; \forall \hat{x} \in [0,1]$ identifies the class of contracts whereby the agent guarantees to the principal a fixed payoff. Under such contracts, the agent bears all risk. Non-degenerate risk-bearing obtains only where $0 < s'(\hat{x}) < 1$.

Substituting equation (6) into the agent's second-order condition yields

$$\left.\frac{\partial^2 \pi(\hat{x};x)}{\partial \hat{x}^2}\right|_{\hat{x}=x} = V''(s(x)I)[1 - s'(x)]I^2 .$$

The second-order condition holds so long as $s'(x) \leq 1$. Observe that the condition $s'(x) = 1$ constitutes something of a singularity. At $s'(x) = 1$ the payoff to the principal does not depend on the agent's report, and it is not possible to find a function $\hat{x}(x)$ by inverting the agent's first-order conditions. Rather, the agent's best response is characterized not by a function but by the correspondence $\hat{x}(x) = [\underline{x}, \overline{x}]$.

The principal's program

Assuming again that the agent is risk-averse ($V'' < 0$), equation (6) and the second-order condition $s'(x) < 1$ induce the response function $\hat{x}(x) = x$. The principal factors the two conditions into his own utility maximization problem. Specifically, the principal maximizes his expected utility by choosing a sharing rule s(x) and a retaining rule R(x) that jointly satisfy (6) and $s'(x) < 1$. Moreover, we impose on the principal the condition that he choose rules that render to the agent payoffs such that $EV - \overline{V} \geq \left(\frac{1-\phi}{\phi}\right)(y + \overline{V})$, a constant. We term the conditions that induce truthful reporting as "incentive compatibility" constraints or "ICs," because they establish the conditions under which truthful reporting is, indeed, compatible with the agent's incentives. We term the condition $EV - \overline{V} \geq \left(\frac{1-\phi}{\phi}\right)(y + \overline{V})$ a "voluntary participation" constraint or "VP."

Condition (VP) indicates that although the principal can impose "take-it-or-leave-it" offers on the agent, the agent does indeed have the option of "leaving it" and enjoying a payoff $\overline{V}$. Lastly, we observe that while the condition $s'(x) = 1$ does not uniquely induce $\hat{x}(x) = x$, it is exactly when and only when $s'(x) = 1$ that the principal is unconcerned about achieving revelation. Taking all these conditions together we pose the principal's program as

(Problem P)

$$\underset{s(x),R(x)}{\text{Max}} \quad \phi\int_{\underline{x}}^{\overline{x}} U([z-s(z)]I)dF(z) \quad + \quad (1-\phi)U(-I)$$

$$\text{s.t.} \quad x = \arg\max_{\hat{x}} V(s(\hat{x})I + (x-\hat{x})I) + \delta R(\hat{x})V_E + \delta[1-R(\hat{x})]V_U \qquad \text{(IC)}$$

$$(V_E - V_U) = \frac{\phi(EV-\overline{V}) - (1-\phi)(y+\overline{V})}{(1-\delta)+\delta(\frac{n+k}{n})[1-ER]} \geq 0 \qquad \text{(VP)}$$

$$s'(x) \leq 1 \qquad \text{(SOC)}$$

where (IC) indicates the agent's "incentive compatibility" constraint, (VP) indicates the "voluntary participation" constraint, and (SOC) indicates the monotonicity restriction on the sharing rule by which the agent's second-order condition holds for all realizations x.

If we ignore all but the participation constraint and assign a LaGrange multiplier μ to condition (VP), then pointwise optimization generates the following "first-best" solution to the principal's program:

$$s(x) \text{ solves } \mu = \frac{U'((x-s(x))I)}{V'(s(x)I)}, \text{ constant} \qquad (7)$$

Differentiating the first-order condition (7) with respect to x yields the following characterization of the first-best sharing rule:

$$s'(x) \quad = \quad \frac{U''V'}{U''V' + U'V''} \qquad (8)$$

Equation (8) yields well-known results. When both parties to contracting – the principal and the agent – are risk-averse then the contract yielding first-best risk sharing will, in general, be non-linear. When the principal is risk-neutral ($U'' = 0$) and the agent is risk-averse, then the first-best contract conforms to $s'(x) = 0$. That is, the principal renders to the agent a payoff that relieves the agent of any stochastic variation in his payoffs. The principal offers the agent a fixed wage and the principal bears all the risk. Conversely, when agent is risk-neutral ($V'' = 0$) and principal is risk-averse, then the first-best contract conforms to $s'(x) = 1$. The agent bears all the risk by rendering to the principal a fixed payoff.

So much for first-best. Imposing incentive compatibility restricts the set of available sharing rules. To see this, observe that (6) can be rearranged to yield

$$\frac{V'(1-s')}{R'} = \frac{\delta(V_E - V_U)}{I} = \text{constant}.$$

Differentiating this expression yields an identity

$$\left(\frac{V''}{V'}\right)s'(1-s')I - s'' - \left(\frac{R''}{R'}\right)(1-s') = 0. \tag{9}$$

Equation (9) yields some immediate qualitative results. First, contracts conforming to $s' = 1$ satisfy (9) given any form of risk-preferences and under any retaining rule R(x). More generally, any linear sharing rule with $s' = \sigma$ must satisfy

$$(1-\sigma)[V''R'I\sigma - V'R''] = 0$$

or

$$\sigma = \begin{cases} 0 & R'(x) \text{ constant} \\ \left(\frac{V'}{V''}\right)\left(\frac{R''}{R'}\right)\frac{1}{I} & R(x) = \left[\frac{(1-\sigma)}{\delta\sigma(V_E - V_U)}\right]V. \\ 1 & R(x) \text{ indeterminate} \end{cases}$$

In general, when we impose incentive compatibility, the sharing rule $s'(x) = 1$ corresponds to the optimal contract. Equation (6) and (VP) reveal that the participation constraint and the incentive compatibility constraint both bind only if $s'(x) = 1$. That is, if the value of being employed does not dominate the value of forgoing employment, then the principal has no means by which to encourage the agent to truthfully report outcomes. Given he cannot induce the agent to reveal x, the best he can do is to secure a fixed payoff. The principal imposes a contract of the form $s(x) = x - \alpha$ where α solves $(V_E - V_U) = 0$.

A question remains if maintaining a non-degenerate "prize" $(V_E - V_U) > 0$ would agree with the optimal contract. If $(V_E - V_U) > 0$ then the principal will impose $R'(x) > 0$. Under these two conditions incentive compatibility holds only if $s'(x) < 1$. An application of the calculus of variations to the principal's program establishes that under modest conditions $s'(x) = 1$ conforms to the optimal contract. At the optimum, the participation constraint binds, and R(x) is indeterminate.

To establish the result, we begin by fixing a retaining rule R(x) that satisfies the following:

(A4) R(x) is continuously differentiable with $R' > 0$, $R \geq 0$, and $R \leq 1$ $\forall x$.

Equation (6) indicates that if $R'<0$ then $s'>1$. However, we require $s' \leq 1$. At the same time, equation (6) indicates that the condition $R'=0$ imposes $s'=1$. Accordingly, we restrict our attention to retaining rules that satisfy (A4).

Rearranging, integrating, and taking expectations of equation (6), the incentive compatibility constraint, yields

$$\int_{\underline{x}}^{\overline{x}} \left[\int_{\underline{x}}^{x} V'I(1-s')dz \right] f(x)dx = \delta(ER - R(\underline{x}))(V_E - V_U).$$

Applying integration by parts to the first term, substituting $(V_E - V_U)$ with the right-hand side of (3), and rearranging yields

$$EV = \overline{V} + k\int_{\underline{x}}^{\overline{x}} V'I(1-s')(1-F)dx + \frac{(1-\phi)}{\phi}(y + \overline{V}) \qquad (10)$$

$$\text{where } k = \left(\frac{(1-\delta)+\phi\delta(1-ER)}{\phi\delta(ER-R(\underline{x}))}\right) > 0.$$

The second term on the right-hand side of equation (10) indicates the **expected informational rent** the principal must surrender to the agent under a contract {s(x), R(x), I}. If s′=1 for all x, then this rent is zero. We will revisit the informational rent when we examine the transversality conditions of the attending dynamic optimization problem. The last term on the right-hand side of equation (IC′) indicates the fixed **premium** the principal must surrender to the agent for the disutility imposed on him in the event of "disaster."

Observe that (VP) holds if s′≤1. Substituting (VP) with s′≤1 and substituting (IC) with (10) transforms the program that is readily amenable to some method of dynamic optimization. The program becomes

(Problem P′)

$$\underset{s(x)}{\text{Max}} \int_{\underline{x}}^{\overline{x}} U([x-s(x)]I)f(x)dx$$

s.t.

$$EV - k\int_{\underline{x}}^{\overline{x}} V'I(1-s')(1-F)dx = \overline{V} + \frac{(1-\phi)}{\phi}(y+\overline{V}) \qquad \text{(IC′)}$$

$$s' \leq 1 \qquad \text{(VP′)}.$$

The constraint (IC′) is a global constraint and therefore is less restrictive than the pointwise incentive compatibility constraint (6). Nonetheless, Problem P′ will yield a sufficient condition under which the condition $s'=1$ will emerge globally.

The program yields the following functional equation with μ corresponding to the Lagrange multiplier on the constraint (IC′) and the function $\gamma(x)$ corresponding to the continuum of multipliers corresponding to constraint $s'(x) \leq 1$ for each x:

$$V(s) = \int_{\underline{x}}^{\overline{x}} \{Uf + \mu Vf - \mu k V'I(1-s')(1-F) + \gamma(x)(1-s')\} dx \qquad (11)$$

The Euler equation, transversality conditions, complementary slackness condition, and non-negativity conditions corresponding to the principal's program are

$$\gamma' = U'If - \mu(1+k)V'If + \mu k V''I^2(1-F),$$

$$\gamma(\underline{x}) = \mu k V'(s(\underline{x})I)I > 0,$$

$$\gamma(\overline{x}) = 0,$$

$$\gamma(x)(1-s'(x)) = 0,$$

$$\gamma(x) \geq 0, \text{ and}$$

$$\mu \geq 0.$$

These conditions yield instructive expressions:

$$\gamma(x) \;=\; \int_{\underline{x}}^{x} (U' - \mu V')If dz \;+\; \mu k V'I(1-F) \tag{12}$$

$$\mu \;=\; \left(\frac{\int_{\underline{x}}^{\overline{x}} U'((sx)I)dF(x)}{\int_{\underline{x}}^{\overline{x}} V'((x - s(x))I)dF(x)} \right) \;=\; \frac{E[U']}{E[V']}$$

The conditions indicate that the constraint $s' \leq 1$ binds at $\underline{x}$ and that it does not bind at $\overline{x}$. The constraint will bind everywhere in the interior $(\underline{x},\overline{x})$ if $\gamma(x)>0$ everywhere in the interior.

Equation (12) identifies two opposing effects that bear upon the imposition of loan contracts. The second term on the right-hand side of equation (12) constitutes the marginal informational rent the principal must deliver to the agent when the agent reports a realization x. It's presence in $\gamma(x)$ indicates that, other things equal, the principal would impose $s'=1$ to neutralize any informational rent at any x, although the marginal rent dissipates at the highest realization $x=\overline{x}$. The marginal informational rent is always non-negative, because the agent requires an inducement to report outcomes truthfully, but it dissipates, because at the highest realization $x=\overline{x}$ no further (costly) inducements are necessary to induce even higher reports.

Equation (12) further indicates that if any risk-sharing occurs, it occurs at the highest realizations, because it is at these realizations that the marginal informational rents are smallest. This result changes somewhat when we impose the pointwise constraint represented by equation (6) in place of the integral constraint (IC′). Equation (6) indicates that if any risk-sharing obtains then some sharing obtains at each $x \in [\underline{x}, \overline{x}]$ where $R'(x) > 0$.

The first term of the right-hand side of (12) implicates (normalized) differentials in the principal's and agent's valuations of their payoffs on the margin. When we impose s′=1 over $(\underline{x}, \overline{x})$, this term will be negative. To see this, observe that the condition s′=1 indicates that the agent yields to the principal a fixed payoff that we will denote by αI. Accordingly, the principal's marginal utility U′(αI) is constant. The second term simplifies to

$$U'1\left[F(x) - \frac{\int_{\underline{x}}^{x} V' f dx}{E[V']}\right].$$

Because V′ is positive and decreasing over $(\underline{x}, \overline{x})$, the expression in brackets is negative in $(\underline{x}, \overline{x})$.

The second term of the right-hand side of (12) will dominate the first term over $(\underline{x}, \overline{x})$ if $\delta \leq \frac{V'|_{x=\overline{x}}}{E[V']}$. That is, if the agent is not too impatient then γ(x) will be strictly positive over $(\underline{x},\overline{x})$ indicating, in turn, that no risk-sharing will obtain at any interval on $(\underline{x},\overline{x})$.

The result is presented in the following proposition:

Proposition 2: Given assumptions (A1), (A2), and (A4), and the condition $\delta \le \frac{V'((\overline{x}-\alpha)I)}{E[V'((x-\alpha)I)]}$ where α solves $(V_E - V_U) = 0$, the solution to the principal's dynamic program includes a sharing rule that conforms to s′=1 $\forall x$ in $[\underline{x},\overline{x})$. For a given investment I, the optimal contract {s(x), R(x), I} corresponding to the principal's dynamic program includes the sharing rule s(x) = x - α. R(x) is indeterminate.

Proof: By (A4), we choose some retaining rule $R(\cdot)$ that is strictly increasing and differentiable over $[\underline{x},\overline{x}]$. In the solution to Problem P′, the condition $\delta \le \frac{V'((\overline{x}-\alpha)I)}{E[V'((x-\alpha)I)]}$ imposes $\gamma'(\overline{x}) = U'If - \mu(1+k)V'If \le 0$ which in turn imposes $\gamma' \le 0 \;\; \forall x \in [\underline{x},\overline{x}]$. $\gamma(x) = \int_{\underline{x}}^{x}(U' - \mu V')Ifdz + \mu kV'I(1-F)$ is continuous over the interval $[\underline{x},\overline{x}]$, and the transversality conditions yield $\gamma(\underline{x}) > 0$ and $\gamma(\overline{x}) = 0$. These conditions and the continuity of $\gamma(\cdot)$ yield $\gamma(x) > 0 \; \forall x \in [\underline{x},\overline{x})$. In turn, the complementary slackness condition

$\gamma(x)(1 - s'(x)) = 0$ indicates that constraint $s' \leq 1$ binds in the half-open interval $[\underline{x}, \overline{x})$.

To see the power of the transversality conditions, we evaluate the principal's program in the absence of the constraints $s'(x) \leq 1$ (set $\gamma(x) = 0$) and the transversality conditions. The corresponding Euler equation yields the following characterization of the optimal sharing rule.

$$s' = \frac{U'' + \mu k V'' \frac{d}{dx}\left(\frac{1-F}{f}\right)}{U'' + \mu V'' + \mu k V'' - \mu k V'''\left(\frac{1-F}{f}\right)} \qquad (13)$$

Were we to ignore the terms in equation (13) that feature k, then (13) would conform to (8), the condition under which first-best risk-sharing obtains. Imposing incentive compatibility, however, imposes the terms featuring k, indicating that the optimal sharing rule deviates from first-best risk-sharing.

Risk-sharing obtains if $s'<1$. Observe that the condition $s'<1$ requires

$$\frac{d}{dx}\left(\frac{1-F}{f}\right) < \frac{(1-\delta)+\phi\delta(1-\delta R(\underline{x}))}{(1-\delta)+\phi\delta(1-\delta ER)} - \left(\frac{V'''}{V''}\right)\left(\frac{1-F}{f}\right). \qquad (14)$$

One might have thought that the condition $s'<1$ would have implicated the principal's risk preferences, but inequality (14) indicates that the shape of the density function f(x) and the risk-preferences of the agent determine whether or not any degree of risk-sharing will obtain.

The following observation indicates a sufficient condition by which the condition $s'<1$ is consistent with a class of "reasonable" distributions and a class of "reasonable" utility functions. Specifically, if we restrict attention to log-concave probability distributions (see Bagnoli and Bergstrom, 1989), and if we assume that the Pratt measure of the agent's absolute risk-aversion is decreasing in income, then we can establish the inequality in (14).

Observation: Let V be three-times continuously differentiable with $V'>0$ and $V''<0$, and let f be continuously differentiable with $f>0$ over the support $[\underline{x},\overline{x}]$. These conditions, the condition $\frac{d}{dz}\left(\frac{-V''(z)}{V'(z)}\right)<0 \;\; \forall x$, and the log-concavity of the density function f(x) over $[\underline{x},\overline{x}]$ are consistent with the condition $s'<1$ for any x.

Proof: The first term on the right-hand side of inequality (14) is positive. The condition $\frac{d}{dz}\left(\frac{-V''(z)}{V'(z)}\right)<0$ implies $V'''>0$, indicating, in turn, that the second term on the right-hand side is also positive. The log-concavity of f(x) implies the log-concavity of (1-F). (See Theorem 2 in Bagnoli and Bergstrom, 1989.) The log-concavity of (1-F) implies $-\left(\frac{f}{1-F}\right)^2 - \frac{f'}{(1-F)} < 0$.

Multiplying through by $\left(\frac{1-F}{f}\right)^2$ yields $-1-\left(\frac{1-F}{f}\right)\frac{f'}{f} = \frac{d}{dz}\left(\frac{1-F(z)}{f(z)}\right) < 0$.

Accordingly, the left-hand side of (14) negative. Taken together, the right-hand side is greater than the left-hand side, indicating, in turn, that s′<1 for any x.

The observation indicates some prospect for risk-sharing, but the transversality conditions indicate that offering risk-sharing is costly to the principal. Loan contracts emerge as the optimal contracts.

I An implication for reputation mechanisms

Some reputation mechanisms such as the one articulated in Greif (1989) depend on principals offering agents' premiums to induce ruthful reporting outcomes. The basic framework presented here asks why parties to contracting would ever offer premiums, because premiums are costly. Proposition 2 indicates, for example, a context in which a principal will in general impose on an agent a contract that features no premium, although the apparatus could used to determine the premium the principal would have to offer an agent under a wage scheme or any other profit-sharing scheme that deviated from a loan contract.

The power of the mechanism articulated in Greif (1989) derives from 1) the differential between the payoff an agent receives from participating in the mechanism and the payoff an agent receives from engaging his inputs in activities external to the mechanism, and 2) the prospects for repeated interaction between contracting parties. In this framework, the principal offers an a contract that renders to the agent a premium, such as a wage premium, that exceeds the payoff the agent can secure outside of the candidate contract with the principal.[1] Principals employ a particular "trigger strategy" – they deny agents access to further business with them in the event agents render inferior reports of outcomes. The economic problem, then, is to determine how large the premium must be to secure truthful reporting. The agent weighs the lifetime stream of payoffs the agent secures from always revealing outcomes against the payoffs that include 1) the one-time payoff the agent secures by cheating his investor and 2) the future payoffs that obtain after having been fired.

The crucial assumption in such a framework is that the stream of payoffs an agent secures from telling the truth dominates the stream of payoffs that would obtain were the agent to "cheat." The basic framework presented here, however, endogenizes these payoffs, using a contracting party's reservation payoff as a

[1] Greif indicates that "the merchant must create a gap between the expected lifetime utility of an agent employed by him and the agent's best alternative elsewhere. To do so the merchant has to provide the agent a premium; for example, he can pay him a wage premium. (pg. 867)

benchmark. The meaning of this is that the basic framework effectively asks why any contracting party should offer any other a "premium."

To see this, consider the premium the principal would have to offer an agent in order to secure truth-telling under a wage contract. Given the principal guarantees to an agent a level of compensation ω (a fixed wage), the incentive compatibility condition identified in equation (6) of can be simplified to

$$(V_E - V_U) = \frac{V'(\omega)I}{\delta R} \qquad \text{where } R=R'\text{, a constant.}$$

At the same time, equation (3) of can be simplified to

$$(V_E - V_U) = \frac{\phi V(\omega) - \overline{V} - (1-\phi)y}{(1-\delta) + \delta\left(\frac{n+k}{n}\right)(1-ER)}.$$

To make the result plain, we take n "large" and $\phi=1$ so that

$$(V_E - V_U) = \frac{V(\omega) - \overline{V}}{1-\delta ER}.$$

Equating the first and third expressions and rearranging yields a differential equation

$$V'(\omega) - \frac{\delta R}{(1-\delta ER)I}V(\omega) = \frac{-\delta R\overline{V}}{(1-\delta ER)I},$$

the solution of which is

$$V(\omega) = \exp\left\{\frac{\delta R\omega}{(1-\delta ER)I}\right\} + \overline{V}. \qquad (17)$$

Equation (17) corresponds to the incentive compatibility constraint that obtains under a fixed-wage contract. In geometric terms, the right-hand side of (17) indicates a convex locus of points in V-ω space that must be tangent to the agent's (concave) utility function $V(\cdot)$ evaluated at some wage ω^*. The principal chooses R and I that uniquely determines a wage ω^* that achieves the result.

The second term on the right-hand side of (17), $\overline{V}$, is a benchmark. The first term on the right-hand side constitutes the **informational rent**. This rent is strictly positive, and it constitutes the premium the principal must yield to secure truthful reporting. As indicated by Proposition 2, however, it is not obvious that the principal will want to offer any premium given he can impose on the agent a loan contract that yields to the agent an expected payoff of $\overline{V}$.

II Contracting under parallel agency

When agents conduct ventures parallel to ventures conducted by other agents, investors have some prospect of engaging agents in a game between the agents out of which 1) truthful reporting emerges as a Nash equilibrium and even as a strong Nash equilibrium, and 2) risk-sharing obtains. In contrast, the basic framework engages only an investor and his agent in a game. The interesting feature of the basic framework is that it identifies a class of contracts by which an investor can extract from an agent a truthful report of the returns that obtains to a trade venture, and of this class of contracts debt contracts generally dominate.

They dominate, because they neutralize the rents an investor would have to yield to an agent to induce the agent to truthfully report outcomes under a sharing scheme that featured some degree of risk-sharing. Neutralizing rents, however, also entails neutralizing risk-sharing.

Under parallel agency, investors may coordinate contracts featuring non-degenerate degrees of risk-sharing such as *colleganze* in a manner that would permit them to compare agents' accounts *ex post*. In the event agents' reports are not mutually consistent, sanctions could be applied to agents reporting inferior returns. At the same time, rewards could be applied to agents providing superior reports. A combination of rewards and punishments could be used to impose an equilibrium in which all agents render identical reports and in which all agents' reports correspond to the truth.

It turns out that such a mechanism routinely emerges in the implementation theory branch of the mechanism design literature. (See, for example, Palfrey (1995).) The mechanism has two parts, the first of which is a generic "agreement mechanism." In the "agreement mechanism" agents conduct parallel ventures, learn the outcomes of their ventures, and then report outcomes to the principal(s). The principals apply sanctions when agents' reports do not agree. The real power of the mechanism, however, lies in the structure of sanctions and rewards not only in a truth-telling equilibrium but also "off the equilibrium path" when one or more agents lie. In particular, agents are rewarded when they report returns on investment superior to those reported by other agents, and agents who report inferior returns are sanctioned. It may be possible to structure payoffs and rewards so that collusion is untenable: the reward to defecting from a collusive arrangement and reporting a superior (and truthful) return outweighs the payoff to colluding.

The idea developed here is simple: agents are drawn into a game in which they seek to avoid reporting a return lower than any return reported by other agents. Agents are assumed – and this is a crucial assumption that will require some motivation – to be unable to report returns that exceed actual returns. A principal or a group of principals individually contract the services of k agents ($k \geq 2$). In conducting parallel ventures, each agent realizes the same draw of return x from a distribution F(x). For each agent i = 1, ..., k, a contract specifies a sharing rule $\sigma_i(\hat{\mathbf{x}})$, as a function of the element vector of k agents' reports $\hat{\mathbf{x}} = (\hat{x}_1, \ldots, \hat{x}_k)$ of the return that obtains to the k contracted ventures. In particular, we let $\sigma_i(\hat{\mathbf{x}}) = s_i(\hat{x})$ where $\hat{x}_i = \hat{x}$ for all i. We may permit $s_i(\hat{x})$ to conform to the first-best sharing rule characterized by equation (8), but in what follows all we will require is that $s_i' \geq 0$ for all $\hat{x} \in [\underline{x}, \overline{x}]$. Each contract also specifies a bond B_i that the agent may be required to forfeit partially or entirely in the event he reports a return that is inferior to returns reported by other agents.

In the framework, principals do not observe or verify outcomes, and this is, in fact, a feature common to mechanisms in the implementation theory literature. In the mechanism presented here, principals contract on unverifiable reports, and they induce agents to report honestly by 1) rewarding the agent or agents reporting the superior return in the event other agents report lesser returns, and 2) sanctioning those agents or agent who report inferior returns. In particular, if we let

$$\sigma_i(\hat{\mathbf{x}}) = s_i(\hat{x}_i) + (\hat{x}_i - \max(\hat{\mathbf{x}}_{-i})) \tag{15}$$

$$\text{where } \hat{\mathbf{x}}_{-i} = \{\hat{x}_1, \ldots, \hat{x}_k\} - \{\hat{x}_i\},$$

then reporting a superior return will dominate reporting an inferior return. To see this let $\pi_i(\hat{x}_i;\hat{\mathbf{x}}) = \sigma_i(\hat{\mathbf{x}})I + (x - \hat{x}_i)I$ denote the payoff agent i receives for reporting $\hat{x}_i$. The term $\sigma_i(\hat{\mathbf{x}})I$ constitutes the payoff specified in the contract, and the term $(x - \hat{x}_i)I$ is the payoff (possibly negative) that the agent extracts from misreporting the realization x. For example, if all agents report $\hat{x}$, then

$$\pi_i(\hat{x};\hat{\mathbf{x}}) = s_i(\hat{x})I + (x - \hat{x})I.$$

If agent i reports a return $\hat{x}_0$ that is inferior to $\hat{x}$ and, again, all other agents report $\hat{x}$, then agent i receives

$$\pi_i(\hat{x}_0;\hat{\mathbf{x}}) = s_i(\hat{x}_0)I + (x - \hat{x}_0)I + (\hat{x}_0 - \hat{x})I = s_i(\hat{x}_0)I + (x - \hat{x})I.$$

Finally, if agent i reports a return $\hat{x}_1$ that is superior to $\hat{x}$, then he receives

$$\pi_i(\hat{x}_1;\hat{x}) = s_i(\hat{x}_1)I + (x-\hat{x}_1)I + (\hat{x}_1-\hat{x})I = s_i(\hat{x}_1)I + (x-\hat{x})I .$$

If $s_i'(\hat{x}) > 0$, then clearly

$$\pi_i(\hat{x}_1;\hat{x})I \quad > \quad \pi_i(\hat{x};\hat{x})I \quad > \quad \pi_i(\hat{x}_0\ \hat{x})I . \tag{16}$$

The inequalities in (16) indicate that a system of sharing rules, rewards and punishments characterized by (15) does not impose a game between the agents in which truth-telling generally emerges as a Nash equilibrium. Given all other agents report $\hat{x}$ -- a report that may not correspond to the true realization x -- agent i extracts an inferior payoff by reporting a return inferior to $\hat{x}$. At the same time, however, agent i can secure a superior payoff by reporting a return that is superior to $\hat{x}$.

To secure a unique Nash equilibrium in which truth-telling obtains, we make a crucial assumption:

(A5) Agents are unable to report returns that exceed their actual returns.

The idea is that an investor would render to his agent resources which the agent was to expend completely in acquiring goods in foreign ports. Upon returning from trade ventures abroad, agents would transfer to their investors the commodities they had acquired. The investors would subsequently liquidate the merchandise and share the proceeds with their agents. Knowing the investment and inspecting the quantities the agent had acquired would permit investors to determine average price the agent had paid in foreign markets. Upon liquidating the merchandise, the investor could determine the return that obtained to the entire venture.

The Venetian Republic invested substantial resources in maintaining the integrity of reports of the quantity and quality of merchandise carried on Venetian vessels. Specifically, each vessel was required to include among its crews an officially certified "scribe" who was responsible for maintaining records of the quantity and quality of goods that were both loaded shipboard and off-loaded at all points of a vessel's travels. Knowledge of both quantities delivered shipboard and knowledge of the initial investments would permit investors to determine returns. The highest realization an agent could report would then correspond to the true realization x.

So, what's going on here? Principals offer to agents sharing rules that apply to single ventures. Sharing rules are observable in the contracts. However, these sharing rules are implicitly contingent on agreement across the k agents' reports. The sharing rules characterized by (14) discourage agents from unilaterally under-reporting returns and encourage them to report the highest returns that the their physical evidence – the actual goods acquired abroad – can permit them to report. These highest returns correspond to the actual realization x. The power of the sharing rules, however, is greater. The sharing-rules also discourage collusion among agents. As (15) indicates, an agent can always profitably deviate from a collusive agreement to report inferior returns by reporting a higher return. Were agents to agree to report a return inferior to the actual return, any agent could profitably deviate by reporting the highest return that the physical evidence would permit, which, again, would be the actual return. The equilibrium that obtains, then, is not only only a Nash equilibrium but also a strong Nash equilibrium.

The results are summarized in the following proposition.

Propostion 3: Given each of k agent's utility is increasing in income, each agent i cannot report $\hat{x}_i > x$, and k>1, the k-vector of sharing rules characterized by $\sigma_i(\hat{x}) = s_i(\hat{x}_i) + (\hat{x}_i - \max(\hat{x}_{-i}))$ for each $i \in \{1, \ldots, k\}$ where $\hat{x}_{-i} = \{\hat{x}_1, \ldots, \hat{x}_k\} - \{\hat{x}_i\}$ and where $s_i'(\hat{x}) > 0 \; \forall \hat{x} \in [\underline{x}, \overline{x}]$, induces an "agreement game" in which $\hat{x} = x$ corresponds to the unique, strong Nash equilibrium.

Proof: We show that agent i reports $\hat{x}_i = x$ given any k-1 vector of reports $\hat{\mathbf{x}}_{-i}$, even the k-1 vector in which all other agents report the same outcome. Given $\sigma_i(\hat{\mathbf{x}}) = s_i(\hat{x}_i) + (\hat{x}_i - \max(\hat{\mathbf{x}}_{-i}))$ and any k-1 vector of reports $\hat{\mathbf{x}}_{-i}$, the agent indexed i rendering a report $\hat{x}_i$ extracts a payoff

$$
\begin{aligned}
\pi_i(\hat{x}_i;\hat{\mathbf{x}}) &= \sigma_i(\hat{\mathbf{x}})I + (x - \hat{x}_i)I \\
&= s_i(\hat{x}_i)I + (\hat{x}_i - \max(\hat{\mathbf{x}}_{-i})) + (x - \hat{x}_i)I \\
&= s_i(\hat{x}_i)I + (x - \max(\hat{\mathbf{x}}_{-i})).
\end{aligned}
$$

Accordingly, $\pi_i(\hat{x}_i;\hat{\mathbf{x}})$ is differentiable everywhere in $[\underline{x}, \overline{x}]$. Differentiating $\pi_i(\hat{x}_i;\hat{\mathbf{x}})$ with respect to his choice variable $\hat{x}_i$ yields $s_i'(\hat{x}_i)$. Since $s_i'(\hat{x}_i) > 0 \; \forall \hat{x}_i \in [\underline{x}, \overline{x}]$, agent i chooses $\hat{x}_i = x$. In equilibrium, $\hat{\mathbf{x}} = \mathbf{x}$.

III Predictions

The modeling exercise lends itself to a pair of simple qualitative predictions:

Prediction 1: In contexts in which the investor must rely on the agent alone to report realized returns, loan contracts will emerge. In these contexts, the incentive compatibility constraint (6) binds, and debt contracts emerge as the optimal contracts. Specifically, s′(x)=1 for all x and any I, and R(x) is indeterminate.

Prediction 2: In contexts in which the principal can rely on other, costless sources of information, risk-averse contracting parties will share risk. The existence of other sources of information permits the principal to relieve the incentive compatibility constraint, leaving a programming program out of which contracts featuring risk-sharing, i.e., equity-like contracts such as *colleganze*, emerge as the solution to the principal's program.

The modeling shows that in contexts in which the principal must rely on the agent alone to report realizations, requiring the agent to reveal realizations in turn requires the investor to impose a finely-tuned sharing rule. Among the contracts featuring such finely-tuned rules, the principal will choose one that corresponds to a "corner solution" of his program; the principal imposes a contract that yields to him a payoff that is, in fact, independent of the agent's report of realized returns.

The data set discussed here features contracts that involved ventures in which the investor was required to rely exclusively on the agent's report of realizations and ventures that involved abundant (and low cost) public information against which agents' reports could be compared. According to the modeling exercise, "sea loans" should dominate contracting of the former variety of ventures whereas *colleganze* contracts should only appear among ventures involving public information.

Notation

x	the rate of return, a random variable with support $[\underline{x}, \overline{x}]$
$\hat{x}$	the agent's report of the realized rate of return
$f(x)$	a probability density over $[\underline{x}, \overline{x}]$
I	the principal's investment in a venture
$U(\cdot)$	the principal's von Neumann-Morgenstern utility scaling function
$V(\cdot)$	the agent's von Neumann-Morgenstern utility scaling function
$\overline{V}$	the agent's reservation utility
$s(\hat{x})$	the "Sharing Rule" that maps the agent's report $\hat{x}$ of the realized rate into the proportion of the reported rate that the principal yields to the agent
$s(\hat{x})I$	the *ex post* portion or "share" of the realized return the principal yields to the agent
$(x - \hat{x})I$	the portion of the realized return xI the agent expropriates
$[\hat{x} - s(\hat{x})]I$	the *ex post* payoff yielded to the principal
$R(\hat{x})$	the "Retaining Rule" that determines the probability as a function of the agent's report $\hat{x}$ by which the agent's services are retained in the succeeding trading season
$n+k$	the size of the pool of available agents
k	the number of agents retained in any one trading season
V_E	the *ex ante* continuation value of being employed as a trading agent
V_U	the *ex ante* continuation value of reverting to unemployed status
$(V_E - V_U)$	the "prize"
δ	a discount factor
EV	the agent's expected utility from participating in a venture
ER	the *ex ante* expected probability with which an employed agent is subsequently retained

Chapter 2

Organizing Venture Capital I: Maritime Trade in Venice, 1190-1220

The early years of the 13th century marked a profound shift in Venice's commercial prospects. Well before crusades were first organized Venice had already established a tradition of trade with the Levant and the Northeastern Mediterranean. Indeed, Saint Mark himself contributes to the lore of Venetian experience with the Eastern Mediterranean. Two Venetian merchants are credited with absconding with the body of Saint Mark from Alexandria in the 8th century. While the story may not be true, it suggests that the Venetian experience in the Levant precedes the age of crusades by a few centuries. By 1200 Venice had already emerged as major trading center and as a potent naval presence, but by 1204 both Venice's naval presence and trading prospects experienced a discrete improvement. The Venetians participated centrally in the Fourth Crusade (1202-1204), a military venture through which the crusading parties supplanted the emperor of the Latin Empire in Constantinople with a regime favorable to their interests. The Venetians benefited principally by gaining favorable commercial access to Constantinople itself as well as to the Black Sea. Moreover, the Venetians effectively secured the trade routes leading into the Aegean and beyond. They acquired control of islands of the Aegean from which they could service naval and maritime fleets.

The limited record suggests that maritime contracting practices remained largely stationary from the time of the heist of Saint Mark into the 13th century, and the data presented here indicate that contracting practices remained largely stationary at least through the 14th century. For example, the earliest extant *colleganza* dates from 1067, and the records of wills indicate that *colleganze* were applied to such things as the Egyptian trade in earlier centuries. (See, for example, Lopez (1967)). To be sure, similar contracting practices were employed elsewhere in the Mediterranean world even before Venice's ascendancy. (See, for example, Pryor (1977)). The data upon which this study is based indicates that from 1190 through 1353 that contracting practices remained largely stationary. Nonetheless, the data reveal discrete changes in the relative frequencies of some types of contracts. After 1204, for example, a variety of *colleganze* ,known elsewhere in the historical literature as "bilateral *commenda*," disappear from the notarial records and become supplanted with a variety "unilateral" *colleganza*.

Changes in contracting practices aside, the focus here is on the strategic viability of *colleganza* in the years 1190-1220. Historians have appealed to various devices such as family relations or reputation mechanisms to explain the strategic viability of *colleganza*. Avner Greif (1989), for example, has formalized reputation mechanisms in contexts pertaining to medieval maritime trade, and

Grief's seminal work sparked interest in the general features of reputation mechanisms. (See Kreps 1990, Milgrom North and Weingast 1990, and Milgrom, Greif and Weingast 1991.) This chapter applies the apparatus developed in chapter 1 to a set of Venetian maritime contracts extracted from the interval 1190-1220. A fundamental critique of reputation mechanisms is presented, and observations from the contract data concerning family relations are discussed.

The chapter proceeds in five parts. The first part discusses the contracting practices in operation in 1190-1220 and identifies hypotheses about the contracting practices, and the second part describes the economic environment of 1190-1220. The third part specifies the maintained hypothesis under which the data are examined, and the fourth part asks of the data questions motivated by hypotheses posed in part one. Part five concludes.

I The data and the technology of contracting in 1190-1220

The data set is composed of 123 maritime contracts dated between 1190 and 1220, an interval that is centered on the year 1204. The data set was generated from an effort to collect from the State Archives of Venice *all* maritime contracts pertaining to ventures conducted between these years. All contracts were drawn up by commercial notaries, and 57 notaries are featured in the data set. Most of the contracts derive from the notarial archive the *Cancelleria Inferiore Notai* maintained at the State Archives of Venice, and the others derive from monasterial archives also maintained at the State Archives. Many of these contracts have been transcribed into the *Codice Diplomatico Veneziano*, and nearly all have been published in della Rocca and Lombardo (1940).

In contrast to modern business practice, overseas trade in the Late Middle Ages entailed the purchase of goods for import and export *before* their sale to end-users, local distributors, or re-exporters. Merchants had to commit financing up front for trades that might not yield positive returns and that would not yield any results for most of a year. Diversifying investments would yield obvious benefits, but operationalizing a diversified portfolio would require merchants to rely on the services of agents. The risks posed by sea, political events, and foreign markets aside, the hazards of agency might preclude merchants from employing resources in ventures that would otherwise be profitable. What remedies, if any, were instituted and at what cost?

The focus here is on the remedies, or in other words, on the technology of contracting agency services. Traders traveled with their merchandise or funds to foreign ports and returned with the proceeds of their foreign ventures. Merchants could exercise full control by undertaking ventures personally, that they often did, but they also hired agents to do the same. Agency provided merchants with a means of investing in ventures that they were logistically constrained from conducting themselves, were not disposed to conduct themselves, or were unequipped to conduct. Trading in foreign ports required skills -- language skills among them -- that not all traders equally possessed. There was obvious scope for specialization.

The defining characteristic of agency is that it allows agents the discretion to act on a principal's behalf. Discretion, however, invites obvious agency hazards. Crafting superior contract entails, among other things, partitioning the set of state-contingent actions available to the agent into those that constitute satisfactory performance and those that constitute unsatisfactory performance. The costs to the principal are dual in nature: on one hand, restricting the agent's freedom defeats the purpose of agency, because unspecified contingencies will arise in which the agent will be unable to respond effectively on behalf of the principal. On the other hand, unspecified states will arise in which the agent will be able to expropriate from the principal. The costs to the agent are parallel: restrictions do not permit him to respond effectively in all contingencies, and contingencies may arise in which the principal may expropriate.

Before the late thirteenth century, maritime contracts almost exclusively pertained to the financing of single, round-trip ventures. The data set is composed of two broad classes of contracts. The first class is composed of "sea loans" and "sea exchange" contracts. Exchange contracts are similar to "sea loans," but they specify repayment in foreign currency. While both types of contracts concentrate the sea risk on the principal -- the principal bears all loss due to shipwreck, piracy, or other such disruption -- they concentrate all of the business risk on the agent. The chief *strategic* features of both types of contracts are that returns to the principal are independent of the agents' reports of the outcome of the venture and that, accordingly, the agent can be granted broad discretionary powers to conduct the venture.

Colleganze comprise the second class of contracts. These contracts featured piece-wise linear profit-sharing rules. After the investor and agents sold their imported merchandise to other parties, the agent would produce to the investor an account of the profit (or loss) generated by the entire venture, and profits would be divided by some fixed ratio. The investing party would bear all losses, and, again, the investing party assumed the sea risk.

The moral hazard problem attending *colleganza* is plain: the determination of the returns to the agent and principal are functions of the agent's report of trades conducted in foreign ports, and reporting unfavorable trades would yield to the agent increasingly favorable payoffs. Why would the agent not report that prices in foreign markets were high when they might actually have been more favorable? Explaining how such problems were solved has not proved so plain. The theses advanced in the historical literature are 1) principals endeavored to contract *colleganza* with "efficient and honest" agents (See, for example, See R. de

Roover (1965), Lane (1964), Lopez and Raymond (1965).), and 2) *colleganza* were chiefly family affairs[1]. Implicit in much of the historical literature is a third thesis: the threat of recourse to legal sanctions would align incentives. Avner Greif provides a game-theoretic treatment involving reputation effects.[2] Although I do not deny that reputations and family relations placed some structure on the conduct of maritime ventures, their power is limited. (See, for example, Williamson (1991) with specific reference to Milgrom, North and Weingast (1990)). Further, I believe that we can place more structure on the problem by examining the informational flows involved in the conduct of ventures. Specifically, on my interpretation, principals could enter into *colleganza* with agents with the understanding that agents' reports would subsequently be compared with the reports of other agents.

Because trade involved tremendous lags in delivery and communication, it was incumbent upon agents to exercise much discretion when operating in foreign markets and when determining that markets to investigate. Most often, agents would leave Venice with one of the convoys (or *muduam*) organized by the Venetian Republic. These convoys would stop at various sites on their way to Alexandria. In Alexandria, the Venetians would participate in markets for spices (principally pepper). After leaving Alexandria, the convoys would

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[1] Greif (1989) partly characterizes Italian practices this way (pp. 874-875). Byrne (1916) observes that family relations figured prominently in the operation of a certain type of Genoese *colleganza* (pp. 143-144, 151).

typically proceed northeast to the "Syrian" ports of Acre and Tyre (Sur). From there they would return to Venice.

Colleganza themselves can be partitioned into two broad classes: bilateral *colleganza* required agents to contribute part of the capital (usually one-third) to the venture, and unilateral *colleganza* involved only investment by the principal(s). The sharing rules of *colleganza* were typically structured such that one-quarter of any profit derived from the venture would be payable to labor, i.e., to the agent. Capital would receive three-quarters of the profit and would absorb any loss.[3] Principals and agents would sometimes engage a unilateral *colleganza* and a bilateral *colleganza* between them simultaneously.

Sharing rules aside, contracts would often specify, among other things, destinations, convoys on which the agent must travel, and often the specific vessel on which agents must travel. Some contracts left the choice of destination

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[2] See Greif (1989), and a related work, Milgrom, North, and Weingast (1990).

[3] Payoffs to a principal and an agent joined in a *colleganza* can be characterized as follows:

Principal's payoff	$= 0.75(\alpha I)r$	$r > 0$
	$= (\alpha I)r$	$r \leq 0$
Agent's payoff	$= 0.75(1-\alpha)Ir + 0.25Ir$	$r > 0$
	$= (1-\alpha)Ir$	$r \leq 0$

where α = share of total investment, I, contributed by principal,
$1-\alpha$ = share of total investment, I, contributed by agent, and
r = return on the investment.

open to agents: they could, for example, choose to trade at any point along a convoy route, but more often they were directed to trade at specific sites. Very few contracts failed to specify convoys and/or vessels, and, even fewer explicitly indicated that the agent was to determine independently the transport and itinerary he was to take.[4]

II The regime shift in the economic environment in 1204

The year 1204 marks what was credibly the single largest discrete advance in Venice's standing as an economic power and a naval power in the Mediterranean. The organizers of a fourth crusade to the Holy Land had contracted Venice to build a fleet capable of delivering and supporting an army of about 35,000. By 1202, the organizers of the crusade had assembled only a fraction of the army and financing they had promised whereas the Venetians had committed enormous resources to satisfying their part of the contract. In the rounds of contract renegotiation that developed over the next several months, the Venetians successfully redefined the objective of the crusade. Most importantly, the crusade was to be re-directed from the Holy Land to Constantinople, the capital of the Byzantine Empire. By the end of 1204, the

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A unilateral *colleganza* corresponds to α=1 and a bilateral *colleganza* corresponds to α=0.

[4] In my data set of 123 contracts, 20 contracts do not specify a vessel or a convoy, and only 1 explicitly directs the agent to determine independently what ship to take. Of these contracts, one is a *compagnia*. The *compagnia* involves a contract between partners who both contribute investment resources and labor. *Compagnia* were typically assigned termination dates although they could very well be renewed. This particular *compagnia* was designed to last for the

Venetians and crusaders had installed in Constantinople a government favorable to the commercial interests of Venice, and Venice extracted authority over three-eighths of the territories of *Romania* (Byzantine territories), including three-eighths of Constantinople itself.

The Venetians were not interested in territorial agglomeration *per se*. Rather their ambitions were strictly economic -- to secure trade routes to the Eastern Mediterranean and to the Black Sea and to secure favorable trading status within *Romania*. The Venetians acquired possession of most of the islands of the Aegean, including Crete, and the Venetians established bases at points on the Peloponesus such as Modone and Corone. Furthermore, the Venetians extracted from the settlement of 1204 the favorable trade rights that the Byzantine authorities had been revoked in 1171. These rights and Venice's status in the Aegean remained secure until the late 1200's when the Genoese managed to supplant the Venetians in Constantinople.

III The strategy of the paper

The strategy of the paper is to apply the framework developed in Chapter 1 to structure analysis of a data set of Venetian maritime contracts. Principally, observed contracts are assumed to correspond to equilibria, and, as such, they provide clues about the mechanisms that were employed in the conduct of

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duration of a trading season. I exclude the *compagnia* from statistical exhibits in which I maritime trade. In particular, we observe a number of *colleganza* contracts that, when examined in isolation, do not appear to offer terms that are incentive compatible. We often observe broad discretionary powers being granted and, further, we observe terms of contract that depend on agents' reports of transactions conducted in foreign markets. What mechanisms external to the contract protected principals from cheating?

The mechanisms offered here are multi-agent mechanism and the loan contract mechanism detailed in Chapter 1. The data indicate that *colleganze* were overwhelmingly assigned to ventures that specified modes of transportation, modes that would be common to a large number of agents. The interpretation advanced here is that agents operating under *colleganza* contracts were restricted to operating in commercial environments that were common to many other agents. Requiring agents to operate in parallel provided principals with multiple sources of information about transactions that they could not observe or verify, and these reports could be exploited to impose on agents' an "agreement game" out of which truth-telling would emerge as the unique equilibrium. In the absence of parallel agency, principals reverted to the basic mechanism out of which loan contracts emerge as optimal.

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compare incentive compatible contracts to *colleganza*.

Implicit in the strategy is the assumption that the technology of contracting -- both the modes of contracting and the methods of conducting trade -- remained stationary through the period under examination, and that parties to contract understand the technology. Institutions are not endogenous in this treatment but are presented as the structure within which the contracting game is conducted. With these assumptions in hand, changes in the composition of observed contracts are interpreted as manifestations of agents' optimizing adaptations to shifts in the economic environment rather than as manifestations of institutional innovation.[5]

IV Making contact with the data

Examination of the data is intended to address how the data relate, if at all, to the various principal-agent models including the one formalized here.

The data are composed of 57 original contracts and 71 receipts from the interval 1190-1220.[6] Receipts constitute records of the successful accounting of ventures. Original contracts contain the same information regarding the terms of contract

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[5] Douglass North (1993) poses economic historians with a more ambitious agenda: to answer "How have economies in the past developed institutions that have provided the credible commitment that has enabled more complex contracting to be realized; and what lessons can we derive from that experience that will be of value today in the ongoing process of building or rebuilding economies?" (pg. 11) Including institutional development in the framework generates more degrees of freedom with that to explain the data. I explicitly chose the interval 1190-1220 so that I might restrict the indeterminacy more degrees of freedom introduces into the interpretation.

specified in receipts, but receipts do not systematically record all of the details that can be found in originals. Accordingly, I use the set of original contracts to evaluate certain issues such as those concerning the frequency with that agents were assigned to convoys or to specific vessels.

Establishing the representativeness of the data

The composition of contracts shifts dramatically post-1204 suggesting that the data are sensitive to the regime shift attending the settlement of the Fourth Crusade. Most notably, bilateral *colleganza* virtually disappear post-1204. The proportions of colleganza and loans/exchanges do not change from one regime to the next, but unilateral *colleganza* supplant bilateral *colleganza*. (See Table 1.) The data also show that both sea loans and unilateral *colleganza* were usually assigned to two types of ventures: 1) "discretionary" ventures, i.e., those in which the agent was expected to choose where to trade along a route, and 2) "long-haul" ventures, i.e. ventures to Egypt, the Levant, and to Greek territories. (See Table 2.) According to the framework developed here, the assignment of sea loans (or exchanges) to discretionary ventures is sensible, because agents can exercise discretion without engaging any kind of moral hazard. However, we need to make reference to a mechanism such as the multi-agent framework developed above to explain the viability of the unilateral *colleganza*.

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[6] The contracts and receipts were gathered from the Archivio di Stato di Venezia. Many of them come from the series the *Codice Diplomatico Veneziano*. Others derive from the notarial series the *Cancelleria Inferiore Notai*.

The data also suggest that trade routes were more secure post-1204. Before 1205, all of the (original) contracts specified that the agent was to travel via convoy and/or via a specific vessel. Post-1204, 9 of 44 contracts do not constrain the agent's choice of transport. (See Table 3.)

Evaluating Principal-Agent models

The data can speak to the role of family relations in contracting and to the multi-agent framework developed above. The data show that relations were chiefly assigned to unilateral *colleganza,* most of which were engaged post-1204. (See Table 4.) Nonetheless, relations hardly monopolized such contracts: the majority of them were to assigned agents for whom no family relation has been established. Non-relations, however, were assigned the overwhelming majority of bilateral *colleganza* and virtually all of the sea loans and exchange contracts. The data also show that relations were chiefly assigned either to ventures in which the itinerary was discretionary or to short ventures down the Italian peninsula.[7] (See Tables 5 and 6.) In contrast, non-relations were assigned to all destinations, and they were assigned to *all* ventures to Egypt and the Levant.

[7] "Discretionary" ventures are identified as those in which no itinerary was specified or those in which the agent may trade, at his discretion, at sites along a specified route. Ventures to Venice originated at other sites, principally Constantinople.

A prediction generated from the multi-agent framework is that *colleganza* would be assigned to vessels and/or convoys so that principals could compare agents' reports about market conditions. A stronger prediction is that, given no value is derived from the protection afforded by convoys or by specific vessels that principals would have armed, *none* of the incentive compatible contracts would be assigned to vessels or convoys. The data bears out that *colleganza* were in fact assigned in such a manner. (See Table 7.) Of the 44 *colleganza* among the original contracts, only 2 were not assigned to vessels or convoys. Of the 12 incentive compatible contracts, 6 were assigned, and 6 were unassigned. Of these 56 contracts, 14 involve family relations, and all of these 14 contracts were *colleganza* assigned in one way or another to a mode of transport. Family relations, evidently, were not excluded from the multi-agent mechanism.

V Conclusion

Although research on the contracting practices of Italian merchants of the Middle Ages has received attention for more than a century, a systematic examination of a data set of contracting has been lacking. This study provides an examination informed by principal-agent theory. The maintained hypothesis is that the contract data are derived from a complex process that can be characterized jointly by an agency game and a matching process. Specifically, a mode of contracting is viewed as a game between a principal and agent. Principals and agents factor into the matching process outcomes from candidate modes of contracting and jointly determine the mode that will be engaged. This very general framework permits us to bring more structure to the analysis of contract than do other frameworks that have been offered in the literature We are able to do what the literature has failed to do: to extract sharp and testable predictions, and, in fact, to test those predictions.

Viewing observed contract as the product of a matching process and an agency game permits us to bring structure to our analysis of contracting behavior. Viewing a contract as a game requires us to ask, for example, what mechanisms supported the viability of contracts such as *colleganza*. When examined in isolation, these contracts are puzzling; they distribute payoffs to principals and agents as functions of agents unverifiable reports. Where is the information that principals need to monitor agents? *Colleganza* do provide a clue about how agent opportunism was suppressed: principals appear to have coordinated ventures arranged by *colleganza* with other commercial traffic. Such coordination would permit principals to compare agents' reports. This, in fact, is what the data suggests the principals did.

The data also permit us to evaluate the role of family relations in contracting. We could have expected two things: 1) that principals would have contracted *colleganza* chiefly with family members, and 2) that principals would have been able to grant agents broad discretionary powers. The data discloses that principals did not grant to family members powers broader than those granted to non-relations. Family members were subjected to the same monitoring mechanism as anyone else, but it is the case that principals would grant to family members risk-sharing and would exempt family members from having to bundle their investment resources with those of the principals.

More importantly, however, we find that *colleganza* were not dominated by family members. Instead, principals were able to contract the agency services in a more impersonal way. This is a felicitous conclusion that bears restatement: the Venetians crafted a mechanism that permitted them to arrange complex contract outside the narrow bounds of the family and within a professionalized class of agents. Accordingly, the mechanism permitted the Venetians to mobilize both investment and labor for maritime trade in excess of what a family-oriented mechanism would have allowed.

Table 1

Unilateral *colleganza* supplanted bilateral *colleganza* after 1204.

Year	Unilateral *Colleganza*	Bilateral *Colleganza*
1190	1	4
1191		3
1192		2
1193		
1194		
1195		1
1196		
1197	1	2
1198		4
1199	2	
1200		2
1201		1
1202	1	
1203		
1204		1
1205	7	
1206	3	2
1207	5	4
1208	6	
1209	7	
1210	2	
1211	4	
1212	2	
1213	2	
1214	1	
1215	1	
1216	1	
1217	2	
1218	1	
1219		
1220	3	
	52	26

Table 2

Unilateral *colleganza* and incentive compatible contracts were applied to long-haul ventures (Greece/Black Sea and Egypt/Levant).

Contract type	Italy Sicily	Balkan	Greece Black Sea	Egypt Levant	Discretionary	Total Contracts
Unilateral *Colleganza*	3	2	13	14	20	52
Bilateral *Colleganza*	10	1	6	5	4	26
Sea loan	4	1	4	3	12	24
Exchange	4	1	5	9	0	19
Compagnia	0	0	0	1	0	1
	21	5	28	32	36	122

$\chi^2_{0.99,16} = 32.000$

χ^2 statistic = 32.082

Table 3

Post-1204, the trade routes were more secure. Agents were less likely to be assigned to vessels.

Original Contracts — Convoy and/or Vessel Specified?

Regime	No	Yes	Total Contracts
Pre-1205	0	13	13
Post-1204	9	35	44
	9	48	57

$\chi^2_{0.90,1} = 2.706$

χ^2 statistic = 3.158

Original Contracts — Vessel Specified?

Regime	No	Yes	Total Contracts
Pre-1205	1	12	13
Post-1204	23	21	44
	24	33	57

$\chi^2_{0.99,1} = 6.635$

χ^2 statistic = 8.182

Table 4

1. Relations were chiefly assigned to *colleganza.*
2. Incentive compatible contracts were chiefly assigned to non-relations.
3. Relations were chiefly assigned to unilateral rather than bilateral *colleganza.*

Contract type	NO Relation	Relation	Total Contracts
Unilateral *Colleganza*	39	13	52
Bilateral *Colleganza*	23	3	26
Sea loan	23	2	25
Exchange	19	0	19
	104	18	122

$\chi^2_{0.99,3} = 11.345$

χ^2 statistic = 104.305

Table 5

Relations were reserved for long-haul ventures or for local ventures. The trade along the established routes was assigned to non-relations.

Region	NO Relation	Relation	Total Contracts
Italy/Sicily	15	6	21
Balkan	5	0	5
Greece/Black Sea	24	4	28
Egypt/Levant	32	0	32
Discretionary	28	8	36
Other	1	0	1
	105	18	123

$\chi^2_{0.95,5} = 11.070$

χ^2 statistic = 11.442

Table 6

1. Relations were assigned largely to "discretionary" ventures.
2. The established, long-haul routes (Alexandria, Syria, Constantinople) were assigned to non-relations.

Primary Destination	NO Relation	Relation	Total Contracts
Abidum	6	0	6
Alexandria	18	0	18
Ancona	1	0	1
Arta	1	0	1
Brundusium (Puglia)	**1**	**0**	**1**
Constantinople	**9**	**2**	**11**
Corinth	**1**	**0**	**1**
Corone	**1**	**0**	**1**
Crete	**3**	**1**	**4**
Discretionary	**28**	**8**	**36**
Durazzo	**5**	**0**	**5**
Limisso and Black Sea	**1**	**0**	**1**
Messina	**0**	**1**	**1**
Modone	**1**	**0**	**1**
Milo	**1**	**0**	**1**
Negroponte	**1**	**1**	**2**
Pesaro	**1**	**0**	**1**
Puglia	**6**	**2**	**8**
Ravenna	**1**	**0**	**1**
Salonika	**1**	**0**	**1**
Sipanto	**0**	**1**	**1**
Soldadea (Black Sea)	**2**	**0**	**2**
Syria (Tyre, Acre)	**9**	**0**	**9**
Thebes	**1**	**0**	**1**
Torre di Palma	1	0	1
Venice	5	2	7
	105	18	123

$\chi^2_{0.90,25} = 16.473$

χ^2 statistic = 26.645

Table 7

Colleganza are assigned to vessels and/or convoys thereby permitting principals to compare agents' reports.

Original Contracts

	No Convoy No Vessel	Convoy OR Vessel	Total Contracts
Colleganza	2	42	44
Loans/Exchanges	6	6	12
	8	48	56

$\chi^2_{0.99,1} = 6.635$
χ^2 statistic = 15.909

All Contracts

	No Convoy No Vessel	Convoy OR Vessel	Total Contracts
Colleganza	7	71	78
Loans/Exchanges	12	32	44
	19	103	122

$\chi^2_{0.99,1} = 6.635$
χ^2 statistic = 7.164

Chapter 3:

Organizing Venture Capital II: Venetian Crete, 1303-1351

A great advantage of research on the maritime contracting practices of 14th century Venetian Crete over early 13th century Venice or even over 14th century Venice is the abundance of maritime contracts.[1] The data discussed here only constituted a small portion of all available contracts from the first half of the 14th century, yet the data set is large enough to support more aggressive tests. The qualitative predictions of Chapter 1 motivate discrete-choice econometric analysis of a data set of 779 contracts. Loan contracts are found to dominate in trade ventures that are less amenable to parallel agency, whereas *colleganza* contracts are found to dominate those that are more amenable to parallel agency.

The data support a few devices for distinguishing commercial traffic that supports parallel agency from traffic that denied parallel agency. In particular, established types of trade, such as trade between Crete and Egypt, Crete and Venice, and Crete and Constantinople, are distinguished from other trade, particularly the trade with the emerging Turkish emirates on the Anatolian peninsula. The established trade, involved, among other things, regular, state-sponsored convoys on which agents could travel. In contrast, the data indicate

[1] I have to thank Sally McKee for first suggesting that I even consider the data from Crete.

that trade with Turkish territories before the late 1320's was limited. However, the data conspicuously indicate that trade with Turkish territories started to surge starting in the late 1320's, a time when Venice engaged a conspicuous effort to reassert its naval presence in the Aegean and the Black Sea.

This chapter proceeds in four parts. The first part outlines salient features of the historical context that generated the data. The second part identifies salient patterns in the data, and the third part applies a discrete-choice econometric analysis to the data. The final part concludes.

I The historical context

Venice annexed Crete in 1212 and ruled Crete until the late 17th century. The Venetians were not interested in territorial acquisitions *per se* but with securing the maritime routes to the Eastern Mediterranean and into the Black Sea. The Venetians developed and fortified the ports on Crete to service their merchant and naval fleets, but they left the interior of Crete largely undisturbed.

By the middle of the 13th century Venetian Crete supported a vigorous community of merchants occupied with both the export and import of various goods as well as with the re-export of commodities coming to and from the Eastern Mediterranean, the Black Sea, and the Italian peninsula. While most of the trade was handled by Venetians resident in Crete, a large number of Greek traders show up in contract data, and many of these Greeks maintained the family names of (once?) prominent Venetian families. Genoese traders sometimes appear in the contract data, and a number of Jewish merchants resident in the Jewish quarter of Candia in Crete also appear.

Crete was well situated to command access to the various trade flows since it lies mid-way along such maritime routes as the one linking Venice and Constantinople and the one linking Venice and Alexandria. In the Aegean traders acquired alum, an aluminum sulfate ore used in various stages of a major industrial segment, the processing of wool. In Alexandria traders had already for hundreds of years participated in the annual market for such high-margin goods as pepper and other spices. The invasion of the Tartars into the Black Sea region in the 13th century provided a new, albeit less regular and less secure, channel to the trade in spices and other Eastern goods. A regular slave trade also emerged from the Black Sea.

II Some salient patterns in the contract data

The contract data all derive almost entirely from the notarial series *Notai di Candia* maintained at the State Archives of Venice. The remaining contracts derive from the notarial series *Cancelleria Inferiore Notai.* The data indicate, among other things, that merchants and trading agents arranged trade ventures through contracts known as *prestitti marittimi* (loan contracts) and *colleganze* (share contracts). Contracts offering agents a fixed payment never emerge in the data.

The data set is comprised of 779 contracts sampled from the years 1303-1352. These years include various phases of the Venetian experience in trade in and around the Aegean. In 1347, for example, plague (The Black Death) descended from Central Asia into the Aegean region. One might have expected that plague might have distracted the merchant community in Crete, but casual inspection of the notarial records suggests that trade activity remained unabated. Indeed, Western Europe yet remained untouched by plague, and the traders in Crete, seeing half of their competitors perish, may have been particularly keen to capitalize on the thinning of the ranks of merchant class. By the early 1330's the Venetian authorities in Crete had established formal trade settlements with the emerging Turkish emirates, including the Ottoman emirate, on the Aegean coast of the Anatolian peninsula. Although the Pope had at times recruited the Venetians in various small-scale naval crusades against the Turks, trade with selected Turkish ports persisted.

The data indicate that before 1328 almost all trade was occupied with short-distance trade ventures around the Aegean with the remainder being occupied with trade along established long-haul convoy routes to the Levant, Constantinople, Cyprus, and Venice. Most of this traffic – especially the traffic on the long-haul routes – involved trade in commonly traded commodities along well-traveled routes, and it is in exactly this type of trade that contracts featuring non-degenerate sharing rules, the *colleganze* contracts, dominate. In these years 229 of 249 contracts in the data set (92%) are *colleganze* with the remainder comprised of "sea loans."

Events in the late 1320's prompted a conspicuous expansion in the trading opportunities available to the traders operating in Crete. Venice began for the first time since 1294 to vigorously reassert its military presence in the Aegean. In 1328 Venice sent a naval task force into the Aegean and to Constantinople in order to impose on the authorities in Constantinople a settlement under which Venetian traders could regain access to the Black Sea region. At the same time Venetian authorities in Crete were establishing contacts with Turkish emirates, and, indeed, merchants in Crete began directing some trade ventures to Turkish ports.

The data indicate that after 1328 loans emerge more prominently, and they emerge prominently in selected types of trade, such as the Turkish trade. The interpretation that proceeds from the model is that the early years of the trade with the Turkish territories constituted activity that, at the very least, was not well-attended. Accordingly, the Turkish trade involved transactions about which public sources of information were not available. The few investors who became involved in the Turkish trade had to rely on agents' reports of transactions, and, accordingly, they secured agents' services by means of "sea loans." Meanwhile, the trade along the established routes such as the trade with Alexandria, Cyprus, Constantinople, and Venice continued to be dominated by *colleganze* contracts.

The data indicate that the proportion of trade directed to the Turkish territories plunged after the emergence of plague in 1347. A larger proportion of the contracts in the data set involve trade along the established routes, and, at the same time the proportion of contracts featuring risk-sharing rises. As traders substituted out of more exotic types of trade such as the trade with the Turkish territories into more established trade, they substituted out of contracts that offered agents no risk-sharing into contracts offering some degree of risk-sharing. The interpretation that proceeds from the model is that contracting parties substituted into ventures in which the investor's problem of securing the incentive-compatibility of the agent's report was neutralized. Without having to impose an incentive-compatibility condition on the design of the agency contract, the investor and agent could agree to a contract that permitted first-best risk-sharing.

The data also indicate that coming into the 1340s that contracting parties started to employ a third type of contract, identified hereafter as the "pooling contract."

By the terms of these contracts the parties would distribute returns in the proportion of shares assigned to principals in a venture common to several participants. Investors would jointly outfit a specific vessel and would share the proceeds of trade that accrued to the vessel. In other respects, these contracts are formulated like *colleganze* and loans. Unlike these other types of contracts, however, these pooling contracts are not recognized in the historical literature. It is known that in Venice itself that investors sometimes invested in shares of a vessel. Vessels would typically be divided into 24 shares or "carats." The literature ignores such practices in Venetian Crete, and, indeed, the language of the contracts from Crete deviate from the language of "carats" employed in Venice.[2]

Lastly, patterns in the data suggest that principals sometimes assumed the lead in determining where to direct trade ventures. The idea stems from the model. Some investors maintained superior informational contacts in trading areas less commonly visited by other traders. Having such information permitted them to identify superior but idiosyncratic trading opportunities. The problem facing such well-informed principals was to find agents willing to conduct such ventures and to contract the services of these agents in ways that would permit

[2] I have discussed the pooling contracts I have found with various historians. While no one could confirm my findings – indeed, my interpretation of the contracts was disputed – François-Xavier LeDuc has in November 1997 visited the States Archives of Venice to review my findings. His interpretation of the contracts agrees with mine. Moreover, the statistical analysis of Part V agrees with the interpretation I have applied.

the principal to capitalize on his information as well as extract from the agent reliable reports. These investors or "informed principals" would more likely engage in idiosyncratic ventures, and that, accordingly, they would secure the services of agents for these ventures by means of loan contracts.

III Testing the data

In the context examined here, the fundamental prediction about the selection of compensation schemes is that share contracts (*colleganze*) would be applied to ventures featuring transactions in commonly traded goods along commonly attended trade routes whereas the "sea loans" would be applied to ventures featuring idiosyncratic activities – that is, ventures featuring transactions in uncommonly traded goods along or transactions along uncommonly traveled routes. Part of the theory is that *colleganze* would be applied to trade in which principals would have access to ready sources of information against which agents' reports could be compared. An agent reporting returns that were inferior to the returns reported by other agents would distinguish himself unfavorably and invite sanction. In contrast, the strategic viability of ventures involving idiosyncratic transactions would only be supported by modes of contracting that distribute payoffs to the principal that are independent of agents' reports whereas other trade. In the context examined here, such contracts are the "sea loans." Pooling contracts, on the other hand, are like *colleganze* in that they implicate multiple agents in the conduct of parallel transactions. Again, such contracts permit principals to exploit agents' reports in ways that induce them to truthfully account for transactions.

Determining what contracts correspond to idiosyncratic ventures takes some detective work and some assumptions. For the purposes of this paper, ventures are distinguished by the destinations to which agents travel and by the commodities in which they trade. "Idiosyncratic ventures" are defined by those ventures that can be distinguished by space and/or commodity from all other ventures conducted simultaneously. The idea is to identify ventures for which no external accounts of an agent's performance would be available. The trade between Crete and pre-Ottoman Turkey, for example, likely provides a good source of idiosyncratic ventures, because the trade experienced inordinate flux in the first half of the 14th century. Regular trade with the Turkish Emirates had only been renewed in the 1320's and 1330's. The authorities in Crete negotiated commercial treaties with selected Turkish emirates, and trade persisted through the 1330's and the 1340's even though Turkish pirates sometimes disrupted commercial traffic.

Four devices, labeled "Informed Principals," "Plague," "Turkish Trade," and "Regime Shift" are constructed for distinguishing idiosyncratic trade from other trade. The device "informed principals" identifies principals who show up in the data as "informed" and were therefore more likely to have had access to idiosyncratic ventures. Contracts featuring informed principals are differentiated from those featuring uninformed principals.

Being "informed" is defined as having superior information about flows of commodities through foreign ports. As interpreted here, being better informed entails having access to a wider set of trading opportunities rather than being able to operate with less "noisy" probability distributions. Being better informed would permit principals to identify trade ventures that would likely render superior returns. For example, knowing that an irregular shipment of spices would be likely to arrive in Trebizond on the Black Sea would permit informed traders to avoid competition for spices in the established markets for spices in Egypt.

While the data do not permit an obvious means of identifying which principals were at any one time better informed, i.e., endowed with superior information, a device is employed here that does permit sharp distinctions in the data to be made. Specifically, "informed principals" are identified as those principals in a given contract who in an earlier contract emerged as a trading agent. The idea is that investing time as trading agents permitted "informed principals" to build up informational capital. They established commercial contacts overseas, and they acquired information about the local trade environment. Maintaining contacts would permit privileged access to, among other things, information about irregular flows of particular commodities. Although contracts often featured more than one principal, all contracts featuring at least one informed principal are identified as being financed by informed principals.

Second, 1347 is identified as "the plague year." By early 1347, plague had reached Crete, and, undoubtedly, it had reached other parts of the Aegean before then. Plague is assumed to have constituted a negative shock to the informational capital of the economy, and the informational advantage enjoyed by informed principals is assumed to have degenerated in that year. One quarter to half the population in a locality would have perished in a short time. Informed Principals might lose their contacts, and upon receiving news that plague had emerged abroad, they might not be in a position to know the status of their contacts or of the conduct of markets.

The device "plague" is also intended to identify the particular role (if any) of pooling contracts. One advantage of pooling contracts was that they engaged the services of a group of agents thereby increasing the prospect that some number of agents would have survived the physical hazards encountered in the course of a venture. Securing the survival of agents would have secured the prospect of recovering proceeds from trade ventures. In the plague year, securing the survival of any number of agents would have been a greater concern – a concern addressed by substituting loan contracts and *colleganze* with pooling contracts.

An entire year, rather than some other interval, is distinguished as the interval capturing the effects of plague for few reasons. First, plague itself had reached Crete by late winter in 1347, a time of the year when most of the maritime fleet would have been idle but just as investors and agents would have been organizing the financing of ventures to be launched in the spring. The emergence of plague in the Eastern Mediterranean, in the Black Sea, and on the Anatolian peninsula would have disrupted, to some extent, the flows of information about market prospects from these regions to Crete. In turn, at the time of contracting the informational advantage of "informed principals" would have been marginalized. Any informational advantage may not have been restored without taking time to ascertain the effects of plague on trading opportunities in afflicted regions, and taking time would have required at least another cycle of ventures through which investors may gain new information. Documents also suggest that outbreaks of plague persisted through the year in Crete and other regions beyond its initial emergence thereby complicating efforts to restore informational contacts. Indeed, plague typically presented itself as a hazard in the warmer months of the year before abating with the onset of winter.

The third device for distinguishing types of trade to which loan contracting would have been more amenable involves distinguishing trade with particular regions. Specifically, the trade with Turkish territories (hereafter, the "Turkish Trade") is distinguished from all other trade. The trade with the Turkish emirates was subject to greater physical and institutional hazards than trade with other regions. Various Turkish entities periodically and independently pirated commercial traffic. In the 1330's naval "crusades" were periodically organized. Moreover, political affiliations on the Anatolian peninsula were ever changing. In all of this the merchants operating out of Crete could more likely expect the prospect of gaining access to idiosyncratic trade.

The last device, identified as "regime shift," distinguishes trade contracted after 1328 from trade ventures contracted before and through 1328. The year 1328 marked a resurgence of the Venetian naval presence in the Aegean and with it a resurgence of Venetian influence in and beyond the Aegean. The year 1328 also marked formal efforts to re-establish regular trade with Turkish Emirates. By assumption, these two events prompted an immediate expansion in the range of trading opportunities available to traders operating out of Crete, and with these new opportunities came an expanded set of potentially idiosyncratic ventures. As operationalized here, the notion of regime shift is identified as a shift from a regime that favors *colleganze* over loan contracts to a regime favoring a shift from *colleganze* to loans.

The four devices provide a means of coding the data that will support statistical analysis of the selection of compensation schemes. The idea is that, other things equal, ventures featuring "informed principals," or trade with Turkish territories, or trade in the plague year more likely involved idiosyncratic transactions and therefore more likely involved loan contracts rather than other modes of contracting. The proportion of contracting by loans is also predicted to increase with the discrete (and favorable) shift in 1328 in the range of available trading opportunities.

The four devices are employed as explanatory variables in a logistic regression (or "logit"). The logit generates predictions of the probabilities with which each mode of contracting is selected. Three modes are distinguished: 1) "Loans"; 2) "Pools" includes all pooling contracts; 3) "*Colleganza*" includes all contracts featuring non-degenerate linear sharing rules.

The Logit Model

Discrete choice models, of which logits are one variety, generate estimates of the probabilities with which modes of contracting are selected, but they generate parameter estimates that are not amenable to ready interpretation. The model estimates equations of log-odds ratios that are linear in the regressors. The parameter estimates do not correspond to the marginal effects of the explanatory variables on the probabilities, but such marginal effects and corresponding t-ratios can be extracted with some manipulation and computation.

The marginal effects are functions of the predicted probabilities, and this leaves the prospect of reporting marginal effects for each of the 779 data points. Means of the marginal effects have been calculated for each of four intervals. Mean marginal effects are reported for 1) the years before the shift in the trading regime, 2) the years leading up to the emergence of plague in the Aegean, 3) the plague year 1347, and 4) the years succeeding the plague. T-ratios for the estimated marginal effects are reported for each of the four intervals.

Table 1 summarizes the predicted signs of the marginal effects of the variables "informed principal," "Turkish Trade," "plague," and "regime shift. The probability the parties to contracting engaged a loan contract is predicted to be increasing in "informed principal" and "Turkish Trade" whereas it is predicted to be decreasing in the variables "plague" and "regime shift." The probability with which parties select pooling contracts is predicted to increase with the emergence of "plague" as contracting parties substitute out of both loans and *colleganze.* The effects on the selection of *colleganze* contracts should, for the most part, run counter to the effects on the selection of loans. Principally, "informed principals" substitute out of *colleganze* into loans except in the plague year when their informational advantage was marginalized.

Table 1

Predicted Signs of the Marginal Effects of the Regressors on the Probabilities

	Pr(Mode = Loan)	Pr(Mode = Pool)	Pr(Mode = *Colleganza*)
Informed Principal	+	+/-	-
Turkish Trade	+	+/-	-
Plague	-	+	-
Regime Shift	-	+/-	+

Table 2 presents the results of the calculations for each of the four intervals. The probability of loans, labeled Pr(Mode = Loan), emerging from the process of contract selection is predicted to be increasing in the factors "Informed Principal" and "Turkish Trade." At the same time, Pr(Mode = *Colleganza*), the probability with which *Colleganza* contracts emerge, is predicted to be decreasing in both "Informed Principal" and "Turkish Trade." Pr(Mode = Pool) is predicted to be increasing in the factor "Plague" and decreasing in the other two factors. Lastly, Pr(Mode = Colleganza) is anticipated to be increasing in the factor "Regime."

Table 2 is presented in four segments with each segment corresponding to one of the four intervals. In the first segment (1303-1328), the predicted effects of three of the four regressors emerge. The data from this period indicate, that other things equal, informed principals are more likely to contract the services via loan contracts and less likely to contract via *colleganza.* At the same time, the Turkish trade attracts an inordinate share of loans and an inordinately small share of *colleganza.* Lastly, the data indicate that the trade regime prevailing at the time overwhelmingly favored the application of *colleganza.* The data from 1303-28, however, do not have much to say about the effects of "Plague." Moreover, the data have little to say about the selection of pooling contracts.

The years 1329-46, the second interval, precedes the arrival of plague and includes the years during which the Turkish Trade was formally established. The results indicate the marked effects of the "Turkish Trade" and "Informed Principals" on the selection of loans over *colleganza.* Curiously, the results also indicate that the "Turkish Trade" effects a substitution out of both *colleganza* and pooling contracts into loans. The data does not sharply distinguish an effect of "Regime Shift," but the data do indicate that plague would effect the predicted substitution out of loans and *colleganza* into pooling contracts.

The results from both the third segment, the plague year, and the fourth segment, 1348-1351, are striking. First, the results generated in the fourth segment mirror those of the years preceding plague, whereas in the plague year the effects of "Plague" emerge sharply as predicted. Plague induces a substitution out of loans and *colleganza* into pooling contracts. The effects of the "Turkish Trade" remain – other things equal, participants in the Turkish trade are more likely to contract via loans rather than via pooling contracts or *colleganza.* Meanwhile, "Informed Principals" remain more likely to substitute *colleganza* with loans, but the results are less sharp in the data. A dulling of the effect of "Informed Principals" in the plague year, however, agrees with the idea that informed principals informational capital suffered a severe negative shock as a result of plague. The similarity of the results from the years succeeding plague to those from the years preceding plague suggests that although the effects of the plague may have been severe, the effects were short-lived and did not upset the fundamental pattern of contracting practices once it had passed.

Table 2
Marginal Effects of the Regressors on the Probabilities

1) 1303 – 1328: Before the Regime Shift

	Pr(Mode = Loan)	Pr(Mode = Pool)	Pr(Mode = *Colleganza*)
Informed Principal	**3.75%** (1.97)	**0.00%** (0.02)	**-3.75%** (1.97)
Turkish Trade	**4.68%** (2.75)	**0.00%** (0.02)	**-4.68%** (2.75)
Plague	**1.34%** (0.80)	**0.00%** (0.02)	**-1.34%** (0.80)
Regime Shift	**-19.31%** (6.20)	**0.00%** (0.02)	**19.31%** (6.20)

2) 1329 – 1346: After the Regime Shift

	Pr(Mode = Loan)	Pr(Mode = Pool)	Pr(Mode = *Colleganza*)
Informed Principal	**10.29%** (1.96)	**0.88%** (0.29)	**-11.17%** (2.20)
Turkish Trade	**17.23%** (4.16)	**-6.09%** (2.23)	**-11.14%** (2.67)
Plague	**-2.84%** (0.56)	**10.95%** (5.91)	**-8.12%** (1.60)
Regime Shift	**7.94%** (0.02)	**-104.08%** (0.20)	**96.15%** (0.47)

Table 2 (Continued)
Marginal Effects of the Regressors on the Probabilities

3) The Plague Year 1347

	Pr(Mode = Loan)	Pr(Mode = Pool)	Pr(Mode = *Colleganza*)
Informed Principal	**7.58%** (1.37)	**1.30%** (0.22)	**-8.89%** (2.06)
Turkish Trade	**18.71%** (4.32)	**-12.53%** (2.43)	**-6.19%** (1.67)
Plague	**-10.99%** (2.14)	**21.42%** (3.43)	**-10.43%** (3.10)
Regime Shift	**89.12%** (0.28)	**-202.81%** (0.39)	**113.69%** (0.55)

4) 1348 – 1351

	Pr(Mode = Loan)	Pr(Mode = Pool)	Pr(Mode = *Colleganza*)
Informed Principal	**10.31%** (1.97)	**0.91%** (0.31)	**-11.22%** (2.18)
Turkish Trade	**17.12%** (4.19)	**-5.93%** (2.23)	**-11.19%** (2.69)
Plague	**-2.63%** (0.52)	**10.78%** (5.95)	**-8.15%** (1.60)
Regime Shift	**5.98%** (0.02)	**-102.50%** (0.20)	**96.52%** (0.47)

IV Conclusion

The paper characterizes contract selection in a context that involves the financing and conduct of risky commercial ventures and finds that under very general conditions debt contracts dominate contracts featuring non-degenerate degrees of risk-sharing. The reason debt contracts dominate is that the contracting parties must commit to terms of contract, including profit sharing rules, before the realization of uncertain outcomes . Investors can neither observe nor verify outcomes *ex post*, yet the terms of contract must structure a mechanism that will neutralize the incentives of agents to cheat their investors after outcomes have been realized. The theoretical framework identifies a set of contracts under which agents will reveal outcomes. The set includes equity-like sharing contracts and debt contracts, yet under equity-like modes of contracting the agent is able to extract informational rents from the principal (See equation (IC′)). Debt contracts neutralize informational rents, but they also neutralize risk-sharing that would obtain in the absence of informational rents. In general, however, informational rents dominate the contracting problem, and debt rather than equity-like modes of contracting emerge as the optimal mode of contracting.

Classical principal-agent theory provides a framework for identifying issues and for organizing analysis. In particular, the theory suggests that the risk preferences of the candidate parties to exchange and the risk attributes of prospective ventures go a long way toward characterizing the risk-sharing features of the contract (if any) that will obtain. In the context examined here, considerations for risk-sharing are found to be subordinate to other strategic considerations. In particular, principals are faced with a problem of extracting truthful reports about the conduct of commercial ventures they have financed. These ventures involve transactions that principals can neither observe nor verify *ex post*. That agents would misreport outcomes would seem to be a natural concern. The modeling exercise presented here demonstrates two means by which a principal can induce an agent to provide truthful reports. First, the principal can present the agent with the prospect of receiving a prize for reporting the truth. While the mechanism by which the agent receives the reward can be very complex, the modeling exercise also demonstrates that the optimal contract – optimal from the principal's perspective – corresponds to a "corner solution" of the contract design problem. Specifically, the principal imposes on the agent a contract that renders to principal a payoff that is independent of the agent's report of transactions. Second, the principal can contract an agent's services in a context in which the agent's report can be costlessly compared to other reports. In such contexts, an investor could detect deviant reports and apply sanctions. The prospect of sanction would induce truthful reporting.

The modeling exercise suggests that particular patterns in the contract data should emerge. Specifically, contracts featuring payoffs that are independent of agents' reports should emerge in contexts in which principals have no means of inducing truthful reporting. At the same time, contracts featuring risk-sharing (if any) should emerge only in trade along well-traveled routes involving commonly traded commodities. The data indeed indicate that parties involved in *colleganza* contracts were found to participate almost exclusively in trade along established, well-traveled trade routes. On my interpretation, principals could easily obtain independent reports on the performance of other trading agents operating along these routes thus permitting them to gauge the performance of their own agents. At the same time, contracts featuring payoffs to the principal that are independent of any stochastic factors were found to be applied with greater regularity to ventures along less established routes. Presumably, trade along less well traveled routes generated more opportunities for idiosyncratic trades – trades for which principals could not extract independent reports and trades that principals could neither observe nor verify *ex post*.

The contracting practices of the time were in place for a *long* time, for most of a millenium. Taken together, these practices and the institutions supporting them constituted a system that promoted the mobilization of financial resources in a world fraught with physical hazards – war, piracy, and plague among them – in addition to commercial hazards. Moreover, the system did not appeal specifically to Venetian business culture. Rather it permitted the participation of culturally diverse parties to contract. Even peoples of divergent political affiliations and loyalties, such as Genoese traders, show up conspicuously in the contract data. The system may have been Venetian, but Crete supported a vigorous community of traders who derived from various parts of the Mediterranean world, various parts that themselves were variously at war or truce.

The focus of the paper here has been on the hazards of agency, and modes of contracting were predicted to line up in a systematic way with the particular agency hazards posed by particular trade ventures. Alone, the simple problem of extracting truthful reports from agents dominates contract selection. Fine-tuning contracts with respect to other considerations such as risk-sharing proves to be secondary.

Appendix

The Logit Model

The statistical analysis of PART III involves characterizing the selection of modes of contracting with respect to a set of environmental variables. Characterizing contract selection involves assigning probabilities to each of three modes of contracting in each of 779 instances in which contract choice is observed. The statistical model maps attributes of the economic environment and of the parties to contracting into probabilities associated with each mode of contracting.

Modes are distinguished by the rules by which parties to contracting would share proceeds from commercial ventures. Modes of contracting are identified as "loans," "pooling contracts," and "sharing rule contracts." Loans specify fixed payoffs to the investing party with the trading agent claiming the residual. Pooling contracts join a group of investors, each of whom shares in the proceeds generated by the venture in the proportion that he invested. The sharing rule contracts (or *colleganza*) specify non-degenerate linear sharing rules. Contracts specifying fixed payoffs to trading agents, e.g., wage contracts, do not appear. Pooling contracts and sharing rule contracts are hereafter identified as "pools" and "sharing" contracts, respectively.

A model appropriate for an exercise that maps attributes external to the objects of choice (modes) into modes is the multinomial logit. The model assigns probabilities to modes of contracting according to a logistic function. As operationalized here, the probability assigned to the mode "share" is expressed as a function of the probabilities assigned to "loan" and to "pool."

where

$i \in \{1, \ldots, 779\}$
y_i = Observed mode of contracting $\in$ {*Loan*, *Pool*, *Share*}
x_i = vector of regressors = [*Intercept*, $Informed_i$, $Turkish_i$, $Plague_i$, $Regime_i$]
$Informed_i \in \{0, 1\}$
$Turkish_i \in \{0, 1\}$
$Plague_i \in \{0, 1\}$
$Regime_i \in \{0, 1\}$
$\beta_{Loan} = [\beta_{Loan,0}, \beta_{Loan,Informed}, \beta_{Loan,Turkish}, \beta_{Loan,Plague}, \beta_{Loan,Regime}]$
$\beta_{Pool} = [\beta_{Pool,0}, \beta_{Pool,Informed}, \beta_{Pool,Turkish}, \beta_{Pool,Plague}, \beta_{Pool,Regime}]$

Each of the observations $i \in \{1, \ldots, 779\}$ in the data set are indexed by the selected mode of contracting y_i and by a set of four binary variables. These variables, labeled *Informed, Turkish, Plague,* and *Regime,* indicate respectively 1) the "informedness" of the investing party, 2) the participation of the contracting parties in the Turkish trade, 3) the conduct of trade during the emergence of plague in the Aegean, and 4) the conduct of trade before the aggressive expansion of trade routes that the Venetians effected in the late 1320's.

Transforming the logistic equations into log-odds ratios produces pair of equations that are linear functions of the explanatory variables.

From these two equations ten coefficients are estimated. The coefficients themselves are not amenable to ready interpretation, but simple manipulations will generate formulas of the estimated marginal effects of the regressors on the selection of modes of contracting. The marginal effects of the regressors on the probabilities can be expressed as functions of the estimated probabilities and of the estimated regression coefficients.

The marginal effects are functions of the x_i (or, rather, of the predicted probabilities), and that leaves one with the prospect of evaluating sets of derivatives for each of the 779 data points. While that is easy to do, 779 sets of derivatives do not permit ready interpretation of the marginal effects, and, indeed, that is not what is done here. Rather, the means of the marginal effects over selected intervals have been reported. Means, labeled $m_{Mode,R}$, have been computed over four intervals, 1303-1328, 1329-1346, 1347, and 1348-1351.

To calculate standard errors of the means of the marginal effects[3], the means were differentiated with respect to the (10×1) vector $\boldsymbol{\beta}$ of regression coefficients.

For each of the 779 observations, 10×3×4 = 120 derivatives were and means were computed over the four intervals. The standard errors of the mean marginal effects were computed from the derivatives and from the covariance matrix of the ten regression coefficients.

Both the marginal effects and t-ratios are reported in Part III. The regression results are reported here.

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[3] See Greene (1993) pp. 108, 645-646, and 666-667.

Results of the Logit Estimation

Equation 1:

Regressor	Coefficient Estimate	Standard Error	t-statistic
Intercept	0.15966	0.14507	1.10057
Informed	0.53350	0.25054	2.12939
Turkish	0.66549	0.20281	3.28129
Plague	0.19040	0.23563	0.80802
Regime	-2.74697	0.27118	-10.12978

Equation 2:

Regressor	Coefficient Estimate	Standard Error	t-statistic
Intercept	-1.12841	0.21254	-5.30928
Informed	0.41644	0.35188	1.18345
Turkish	-0.21529	0.30634	-0.70280
Plague	-12.32401	54.32001	-0.22688
Regime	1.23663	0.29191	4.23629

Likelihood ratio test of the significance of the regression:

Likelihood ratio statistic = -2(-739.56 + 569.13) = 340.86.
The corresponding critical value is χ^2 with 9 d.f. = 16.92.

Chapter 4:

Markets for Contracts: Experiments Exploring the Compatibility of Games and Markets for Games

The research presented here examines the compatibility of game theoretical models with the classical model of market equilibrium. The experimental approach is "exploratory" in the sense that it is motivated by questions of economic behavior in the context of institutions even though there is neither good theory nor a clear line of previous experiments that point to what might be expected. Yet, the experiments seem to be central to both the thrust of theory and applications of theory. Thus, we will report on the outcomes of data generated in a particular institutional setting. While the models we apply are very suggestive, we leave open to speculation and further theory a more fundamental explanation of what we report.

The experimental design links a market process to a contract process. A contract is modeled as a game, and the purchase and sale of contracts (or games) is modeled as a market. The market involves the purchase and sale of rights to participate in a follow-on stage of strategic interaction (the game). Compatibility concerns how the two different processes – games and markets -- interact when they exist side by side as subsystems in economic environments.

Are the equilibria in the two processes reinforcing, each promoting the convergence of the other process, or do they confound convergence? Is the selection of equilibrium in one process systematically linked to the selection of equilibrium in the other? Of course, the focus on institutions produces a deeper question about which we can only speculate: what dynamic process drives the *joint* selection of equilibrium in the two processes.

Clearly there are many alternative environments in which a study such as this could be initiated. The setting we chose reflects many arbitrary components in part, because there seemed to be no obviously unique place to begin. Contracting problems and even markets for contracts emerge naturally and abundantly in the context of industrial organization. Procurement contracts, for example, engage buyers and suppliers in strategic interactions that can be modeled as principal-agent games, and such contracts are often awarded to suppliers via market mechanisms such as auctions. Equity and debt certificates ("stocks and bonds") constitute contracts that confer various rights over the control of corporations and can thus be modeled as games. Obviously these contracts are exchanged in markets. Futures contracts engage buyers and suppliers in a game that involves follow-on delivery of goods and services. Insurance contracts are clearly a case of markets for games. The insurance contract involves the insurer and the insured in classic relationships of moral hazard. Wage contracts frequently can be viewed as games involving principleagent components, and of course the labor market is for the contract. Guarantees and warranties that accompany sales are in fact simply games. Thus the purchase and sale of games is common and arise naturally in the course of commerce. In all such cases two equilibrating processes exist side by side -- the market process and the game. The problems are pervasive.[1]

It is interesting to note that even though markets for games appear frequently in the applied literature, there is no explicit study of their compatibility. It is typically assumed that equilibria in both markets and games must be jointly determined and that the joint convergence of the two processes would conform to the convergence each of the two processes would obtain in isolation. The possibility that conduct in one process might confound convergence in the other process is not raised. For example, previous realizations of conduct in the game might setup price dynamics in the market that in turn would disrupt agents' expectations of successive conduct in the game. Alternatively, agents might maintain diverse expectations. In contexts involving multiple equilibria, expectations might fail to become aligned on particular equilibria. Furthermore

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[1] For example the original research questions were motivated by contracting problems that pertain to the financing of Mediterranean trade in the late Middle Ages. The prominent features of the organization of the Mediterranean trade, it turns out, emerge in a natural class of problems. The Mediterranean trade problem involves the joint equilibration of markets for traded commodities, of markets for agency contracts, and of principal-agent games. Specifically, the Mediterranean trade implicates the simultaneous equilibration of (geographically dispersed) markets. Coordination between these markets involves inputs from dispersed agents, and the contracting of these inputs generates a sequence of strategic interactions (games). Multiple equilibria may emerge in the games that obtain between the various functionaries of trade.

markets have properties, such as the fact that they are continuous time processes, that are abstracted away in most theory. The influence that such variables might have is not obvious.

The results reported here are striking. Equilibria in the game are found to be systematically linked to competitive equilibria in the market. The convergence of the market to equilibria lags the convergence of behaviors in the game to equilibria, and the games move quickly to a solution of the game even though the market was in substantial disequilibrium. The markets then settled into the equilibrium that would exist if rational expectations prevailed, i.e., if agents were able to predict perfectly what the outcome of the game would be. Thus, the research demonstrates that equilibria in games and in the institutional contexts in which they are embedded can be jointly determined and of course that fact suggests that institutional context might influence selection.

The Chapter proceeds in six parts. The next segment, Part I, relates the research to other work on equilibrium selection. Parts II and III detail the experimental design, and Part IV presents the models and predictions. Results are presented in Part V, and Part VI concludes.

I Background and Experimental Research

The research was motivated chiefly by the two observations. 1) Markets for contracts emerge in a broad range of applied contexts, and 2) the success with which certain types of solution concepts are able to characterize play in a game seems to depend on the institutional context in which the game is embedded. In some contexts, for example, traditional solution concepts help characterize play in a particular game whereas in other contexts they fail to characterize play in that same game. These contexts generally involve multiplicity of equilibria in games and the attendant problem of equilibrium selection. Much experimental research on games has approached problems such as the selection of equilibria by examining behaviors in increasingly simple environments, and yet other experimental research suggests that institutional context helps resolve the selection of equilibria in games.

Three branches of research suggest that the behavior in games can be influenced by placing the game in particular institutional environments. First, Cooper, DeJong, Forsythe, and Ross 1993, 1994 and Van Huyck, Battalio, and Beil 1990, 1991, and 1993 study special ways of allocating rights to participate in games. They suggest that prices might play a role in a process of forward induction that facilitates equilibrium selection. Secondly, research on "cheap talk" suggests that embedding particular games in contexts that permit specially tailored pre-game communication can promote the selection of equilibria. This research also points to a concept of forward. (See the survey of Crawford 1998. Examples include Cooper, DeJong, Forsythe, and Ross 1989 and 1992.)

A third body of research points to the possibility of very different institutional influences. It suggests that in properly structured environments variables exist that are unanticipated by game theory and may dominate or even confound convergence. Examples abound of games in which behaviors fail to line up with predictions in even starkly simple strategic contexts. (See Camerer and Thaler 1995 for examples.) The resulting paradoxes have motivated exciting lines of research. Implicit in some of this research is that the shortcomings of theory results from 1) the failure of theory to incorporate psychology that routinely emerges in strategic interactions, or 2) the failure of human actors to satisfy the cognitive competencies required of traditional conceptualizations of "rationality." Behavioral game theory, for example, has involved efforts to innovate new equilibrium solution concepts, such as Mathew Rabin's "Fairness Equilibrium," that are informed by research in psychology. (See Rabin 1993 and Camerer 1997.) Related research has responded by operationalizing concepts such as "altruism" (See, for example, McKelvey and Palfrey 1992, Eckel and Grossman 1996, Cooper, DeJong, Forsythe 1996), "spitefulness" (Levine 1997), "manners" (Camerer and Thaler 1995), "fairness norms" (Kagel, Kim and Moser 1996), and "trust" (Berg, Dickhaut, McCabe 1995). Other research more closely linked to the evolutionary game theory literature has involved efforts to operationalize concepts of bounded rationality (Stahl and Wilson 1995, Stahl 1996) and by articulating dynamic processes by which "conventions" or "stable" outcomes emerge. (See, for example, Crawford 1991, 1995 Van Huyck **et al.** 1995, Van Huyck, Cook, Battalio 1997.)

The research presented here takes up a tack that is parallel to the research on special theories of equilibrium selection in games and the role of institutions in facilitating equilibrium selection and is complementary to the research that merges economics with psychological considerations and cognitive processes. Rather than focus on increasingly simple environments, we focus on games that take place in a more institutional context -- a context that incorporates many of the features of situations for which applications of the theory are intended. In particular, we examine an environment in which 1) agents assume diverse roles and 2) payoffs are private information. In contrast, previous research on the role of institutions in equilibrium selection involved environments in which agents were symmetric and in which payoffs could be credibly modeled as common knowledge. Such environments could support processes suggestive of forward induction. In the research presented here, the structure of strategic interactions does not obviously accommodate behaviors that can be characterized by forward induction. Prices do not provide an unambiguous means of signaling behaviors in the follow-on game. Instead, equilibria of the game map into equilibria of the market process in an intuitively accessible way that can also be characterized by backward induction. As will become obvious, the compatibility of the concept of a market and a game theoretic equilibrium will be established whether or not the vehicle was forward induction or backward induction is left open to speculation.

Simpler environments have permitted sophisticated applications of theory. For example, Crawford and Broseta (1998) present a theoretical framework on learning dynamics that they apply to the experimental results of Van Huyck, Battalio, and Beil (1990, 1991, and 1993). (Also see Cheung and Friedman 1998 on learning dynamics.)
Within these environments researchers have initiated a process of attempting to "work up" from basic principles to characterizations of dynamic processes that drive equilibration and selection in games. Of course, how one might go about generalizing theory developed in the special environments they studied to more complex settings is still in the realm of the unknown. The literature does contain suggestions such as provided by the spirit of Crawford and Broseta (1998), which may yet be generalized to accommodate environments that feature private information. By contrast, the research presented here works down from a more complex institutional environment -- an environment in which we lose the power of theories of learning dynamics. We provide an "exploratory leap" into a more complex setting and report what we see in hope that by working from "both ends" appropriate theory will be more rapidly developed.

II Design Overview

The experimental design involves a market institution in which agents buy and sell rights to participate in a follow-on game. The questions to be posed are whether or not outcomes in the game are systematically linked to outcomes in the market, and whether or not the game outcomes can be characterized by traditional game-theoretic solution concepts. Moreover, the question is whether or not outcomes in the market correspond to competitive equilibria, and if the competitive equilibria in the market map uniquely into equilibria in the game.

Game buyers were given redemption values for the number of games that were purchased in a market. That is, games were considered a commodity with a declining value for marginal units. Accordingly, the buyer generated some utility for playing the game independent of any of the outcomes of the game. Of course, if the game is interpreted as a contract, it would mean that the contract had value independent of what the consequences of its execution might be.

Game sellers were given costs for the number of games sold. These cost schedules reflected increasing marginal costs. The seller could, in a sense, "produce" the game at a cost and then sell it in the market for a price. In the context of a contract, sale of a unit may be interpreted as the seller selling a commodity or service under a contract and the production of the commodity or service having a cost independent of whatever might be involved in the execution of the associated contract.

If the game had no additional value to either the buyer or seller, the demand and supply functions induced in the market by application of the competitive model would be as shown in Figure 1. The redemption values can be used to produce a market demand function and the marginal costs can be used to produce a market supply function.

All games produced and sold are the same Battle-of-the-Sexes game displayed in Figure 2. If row player chooses up and column player chooses left, the payoff would be 700 to the row player and 300 to the column player. This matrix was common knowledge.

A market was opened for the purchase and sale of the games. Buyers and sellers both had the capacity to buy and sell units and so could generate some payoff buying trading units at different prices through the course of the market session. After the market closed all games were played buy the respective buyers and sellers. Buyers always chose among the rows of any game a buyer played and sellers always chose among the columns. Each buyer played all games that he or she purchased net of any sales. Similarly, each seller played all games that he or she sold net of any purchases. However, the pairings of the play did not necessarily match the pairings of the market transactions. That is, a buyer who purchased two games would make two choices, but the other player would not necessarily be the player who sold the games to this particular buyer. The pairings for play of the game were random and the identities of players were not known. The only things known at the time of play of the game were the number of games purchased and sold, the prices at which transactions took place in the market and the history of aggregate play in previous plays of the game. These aspects of information will be made more precise in the following section.

The total payoff of buyers was the profit from the market, the sum of the difference between the redemption values of units and the prices paid plus the sum of the payoffs from all games played. The total payoff to a seller was sum of the difference between selling prices and cost of units plus the payoffs from all games played. So, payoffs were determined jointly between the prices in the market and the subsequent patterns of play in the games that were bought and sold in the market.

III Experimental Design and Procedures

Four experimental sessions were conducted. The sessions were conducted in 1996 on February 14, February 22, November 13, and November 14. Hereafter each experimental session will be identified as Feb 14, Feb 22, Nov 13, and Nov 14. Respectively, 8, 12, 10, and 14 subjects participated in these four sessions.

All subjects were students drawn from the Caltech student body. None had experience with this particular set of experiments, but some may have had experience in either markets or games in other experiments. Each experiment employed an even number of subjects, half assigned the role of "buyer" and the other half assigned the role of "seller." (See the following table.)

Experimental Session	Number of Buyers	Number of Sellers
Feb 14	4	4
Feb 22	6	6
Nov 13	5	5
Nov 14	7	7

In each of four experimental sessions, an even number of agents participated in repeated rounds of a two-stage framework. In the first stage of each round agents bought or sold rights to participate in a second stage of strategic interaction. Exchange was organized via a double auction operationalized with standard software on a computer network. Agents were provided with sets of marginal cost schedules *or* with marginal redemption value schedules. Agents used a new schedule in each round. Costs and redemption values were denominated in an experimental currency called "francs." These marginal cost schedules determined the marginal cost of supplying to the market as many as

10 units (called "assets"). Similarly, marginal redemption value schedules determined positive marginal payoffs for as many as 10 units that a buyer could acquire in the market. The experimenter provided half of the agents with marginal cost schedules and the other half with marginal redemption value schedules. Those agents with cost schedules were designated "sellers," and the other agents were designated "buyers."

In the first stage of each round, agents purchased and sold assets in a double auction that lasted 5 minutes. Buyers and sellers were permitted to speculate or "trade" during the process of price formation. That is, buyers could both buy units and resell units and sellers could do the same. Total costs and total benefits were determined by the net inventories buyers and sellers maintained at the end of each double auction. These costs and benefits were recorded on record sheets, and in each round agents' inventories were restored to zero.

After each double auction closed, buyers assumed the right to choose the actions "Up" or "Down" in a binary choice process, the Battle-of-the-Sexes game. Sellers assumed the right to choose "Left" or "Right." Agents chose one action for each of the units they sold or purchased. These action choices were made without knowledge of other agents' choices. Agents recorded each of their choices on a separate piece of paper. The pieces of paper or "tickets" were color-coded and were labeled with the index number of the current round of the experiment and with an index number assigned to each of the agents. Sellers' tickets were printed on green paper whereas buyer's tickets where printed on pink paper. Agents were supplied with ten tickets for each of as many as 22 rounds of interaction.

After all agents had chosen their actions, the experimenter shuffled the sellers' tickets (the green tickets) and paired each of a seller's tickets with a buyer's ticket. In this way sellers' and buyers' tickets were randomly and anonymously matched. The resulting pairs dictated one of four possible pairs of payoffs. (The actions and payoffs are arrayed in the 2x2 matrix below.) Payoffs were denominated in an experimental currency called "francs." For example, a pair of action "Left," "Right" determined payoffs of 700 francs to the buyer of that unit and 300 francs to the seller of that unit. The experimenter indicated payoffs of 100, 300, or 700, as appropriate on each of the buyers' and sellers' tickets. Tickets were re-distributed to the agents, and agents were permitted to account their payoffs on an account sheet.

The aggregate frequencies of choices were public information. After payoffs were distributed, the experimenter announced and posted aggregate results from the stage of strategic interaction. Posting the results entailed indicting the frequencies with which pairs occurred in each of the four cells of the 2x2 matrix. The four marginal frequencies were also posted. Thus both buyers and seller could see the relative frequencies with which strategies were chosen. Of course they could not identify the strategy of any particular person or persons.

For each agent, accounting for payoffs entailed 1) summing payoffs indicated on each of the returned tickets, 2) summing, as appropriate, total costs or total benefits, and 3) identifying revenues or expenditures from the double auction. In turn, summing these three quantities generated each agent's total payoff from participation in the two-stage process. Agents accounted payoffs at the end of each round. Payoffs from the entire experiment were generated by summing the payoffs from each round.

Notation

In the succeeding sections we articulate models, predictions, and results. The models operationalize mechanical adjustment processes. It is these processes that permit examination of the data. Before we proceed, however, we need some notation.

A realization of the entire two-stage process is a 3-tuple (P, Q, f), and an equilibrium is a 4-tuple (P*, Q*, p*, q*)[2] where

P = price in the double auction,
Q = volume in the double auction,

[2] Generically, the marginal distributions (p, 1-p) and (q, 1-q) are not independent, in which case expected payoffs must be evaluated with reference to the joint distribution (f_{UL}, f_{DL}, f_{UR}, f_{DL}). On the other hand, the equilibrium strategies (p*, 1-p*) and (q*, 1-q*) are independent.

$f = (f_{UL}, f_{DL}, f_{UR}, f_{DR})$
f_{rc} = relative frequency with which the outcome (r, c) emerges in the succeeding second stage of interaction; $r \in$ {Up, Down} and $c \in$ {Left , Right} and $f_{UL}+f_{UR}+f_{DL}+f_{DR} = 1$
$(p, 1-p) = (f_{UL}+f_{UR}, f_{DL}+f_{DR})$ = row player's strategy over the strategy set {Up, Down},
$(q, 1-q) = (f_{UL}+f_{DL}, f_{UR}+f_{DR})$ = column player's strategy over the strategy set {Left, Right},
(p^*, q^*) constitutes a static equilibrium, under some solution concept, of the second stage, and
(P^*, Q^*) conform to the equilibrium price and quantity in the market.

Each realization of the second stage is identified by a 4-tuple $(f_{UL}, f_{DL}, f_{UR}, f_{DL})$ of relative frequencies. Associated with these relative frequencies are marginal frequencies (p, q). In an equilibrium of the entire two stage process, (p^*, q^*) and (P^*, Q^*) are simultaneously determined.

The models of market equilibration share a common structure. *Given* unit payoffs (b, s) to buyers and sellers in the second stage (determined under a given solution concept), the models of market equilibration satisfy the following:

$$P \in [D(Q) + b(\cdot)] \cap [S(Q) - s(\cdot)]$$

where $D(Q)$ = inverse demand correspondence,
$S(Q)$ = inverse supply correspondence,
$b(\cdot)$ = unit payoff to buyers, under some solution concept, in the second stage,
$s(\cdot)$ = unit payoff to sellers in the second stage,
and $D(Q) + b(\cdot)$ = derived demand,
$S(Q) - s(\cdot)$ = derived supply.

IV Models and Predictions

A particular advantage of the experimental method is that it permits examination of dynamic processes by which equilibria (if any) emerge. Accordingly, analysis of the experimental data is organized around both static predictions and dynamic adjustment processes. The predictions pertain to the identification of static equilibria (P^*, Q^*, p^*, q^*) of the two-stage process, to the selection of equilibria, and to the evolution of prices.

Models

The models pertain to price formation, the determination of volume in the market and of action choices in the second stage of the two-stage apparatus, and to the relation (if any) of prices to action choices. Specifically, the models include two sets of partial equilibrium models: those that characterize equilibration in the second stage process, and those that characterize equilibration in the market process. The real power of the models, however, derives from the characterization of the simultaneous equilibration of the market process and second stage process. Such models link equilibria in the second stage with equilibria in the market and raise deep issues about the dynamic processes through which coordination between the market and second stage process is achieved (if at all).

The data are examined via three different classes of models. These models can be distinguished from each other by the nature of belief formation and the nature of the individual decision process. Two types of belief formation, labeled "Cournot expectations" and "perfect foresight," are distinguished. Cournot expectations involves repeated interaction of the entire two stage process. Agents generate beliefs with reference to immediate history of interaction. In particular, determine how to behave in the second stage of interaction by referring to the last realization of second stage interaction. Perfect foresight, on the other hand, does not implicate interaction across rounds. Rather, it is a static concept. Agents forecast (correctly) outcomes in the second stage of interaction. In a general equilibrium of the entire two-stage process, beliefs implicate the pricing of units.

Two types of decision making processes are distinguished, and they are labeled "dynamic" and "partial backward induction." These processes link outcomes in the market to outcomes in the second stage of interaction. Under the model of dynamic decision-making, agents factor the structure of other agents' actions into ones own choice of actions in the second stage and into pricing decisions. Behaviors that conform to partial backward induction, however, are less sophisticated. Under this behavioral model, agents fail to factor their own responses into their pricing decisions. Rather, agents lose their identities in the pricing decision and act as if they were a representative agent.

The two models about belief formation and the two models about individual decision-making identify four general equilibrium models, three of which we operationalize. We identify and label these models in the following table:

		Belief Formation	
		Cournot expectations	Perfect foresight
Individual Decision-making	partial backward induction	Myopia	Not Operationalized
	dynamic	Cournot	Rational Expectations (RE)

These models determine 1) unit payoffs b(·) and s(·), 2) market outcomes (P, Q), and 3) the nature of coordination (if any) between market outcomes and unit payoffs. The RE model, for example, incorporates the perfect foresight hypothesis with the dynamic behavioral hypothesis. Behaviors in the second stage of interaction conform to the Nash hypothesis, Nash outcomes of the second stage imply payoffs to buyers and sellers, and agents factor these payoffs into their pricing decisions. Nash equilibria of the second stage are thus linked to equilibria in the market.

a) A Static Rational Expectations model (RE)

RE operationalizes the concept of Simultaneous Equilibration. Under RE agents know the structure of the model and coordinate behaviors on outcomes of the two-stage process. Agents have perfect foresight: they anticipate behaviors will converge in the second stage of each round, and they anticipate *which* behaviors will obtain. More specifically, agents anticipate a Nash equilibrium (p^*, q^*) of the second stage, and they factor the payoffs that derive to them in their pricing decision. As under SEP, (p^*, q^*) map uniquely into equilibrium prices and volumes (P^*, Q^*). We label the predictions (P^*, Q^*, p^*, q^*) "RE-consistent."

Mechanical Adjustment Processes

b) Cournot (C)

The Cournot model assigns to agents a lesser degree of rationality than RE. Agents assume outcomes of the two-stage process result from the active strategizing of the other agents in the market; in the model agents' best-reply to some subset of past realizations of second stage play. Agents factor into their pricing decision some subset of past marginal frequencies (p, q) and their own best-replies to that subset of frequencies. Under this model, however, agents do not factor other agents' best-replies into their own best-replies. Rather, they assume that past frequencies characterize other agents' next-period choices.

Examined here is a particular case of "Cournot expectations" where agents craft best-replies with respect to the last realization of second-stage play. The model then predicts that second-stage frequencies converge on one of the RE-consistent predictions or that second-stage frequencies collapse into an infinite sequence of out-of-equilibrium play. Formally, the pair

> $(p_t, q_t) = (p_t(q_{t-1}), q_t(p_{t-1}))$, characterizes agents' strategies where
>
> $g_t = g_t(\cdot)$ denote best-reply functions, and
>
> $(P_t, Q_t) = (P_t(p_t, q_t), Q_t(p_t, q_t)$ denotes the equilibrium in the double auction implied by the anticipated frequencies (p_t, q_t).

Second-stage interaction converges on one of the two pure strategy equilibria of the two stage process or collapses into an infinite, non-convergent sequence of out-of-equilibrium play. The frequencies $p_t(q_{t-1})$ and $q_t(p_{t-1})$ may not correspond to any Nash equilibrium of the second stage but may generate a non-convergent sequence of mis-coordinated play. A realization $(p_{t-1}, q_{t-1}) = (1, 0)$ generates $(p_t, q_t) = (0, 1)$ which in turn generates $(p_{t+1}, q_{t+1}) = (1, 0)$, and so on. On the other hand, $(p_2, q_2) = (1,1)$ or $(0, 0)$ generates a forward invariant sequence $(p_t, q_t) = (p_2, q_2)$.

The static predictions (P^*, Q^*, p^*, q^*) can be arrayed in the following table:

Price (P^*)	Quantity (Q^*)†	Strategies (p^*, q^*)	Surplus†
790 - 810	17	(1, 1)	8,540
760 - 780	4	alternately (1, 0) and (0, 1)	410
690 - 710	9	(0.75, 0.25)	1,980
390 - 410	17	(0, 0)	8,540

†Values correspond to the double auction conducted with six buyers and six sellers.

Observe that the RE-consistent predictions are also Cournot-consistent.

c) Myopia

Similar to the discussion of the Cournot model, Myopia assigns to agents a lesser degree of rationality than Cournot, and Myopia admits the Cournot-consistent (and therefore RE-consistent) predictions. Under the Cournot model, price and volume anticipate the frequencies (p,q). Under Myopia, prices and quantities respond to *previous* realizations of second stage interaction. Effectively, agents assume that observed frequencies are representative of the forthcoming frequencies, and they price their units accordingly. Formally, Cournot satisfies

$$P_t \in [D(Q_t) + b(p_t(q_{t-1}), q_{t-1})] \cap [S(Q_t) - s(p_{t-1}, q_t(p_{t-1}))]$$

whereas Myopia satisfies

$$P_t \in [D(Q_t) + b(p_{t-1}, q_{t-1})] \cap [S(Q_t) - s(p_{t-1}, q_{t-1})].$$

As under Cournot, agents best-reply in the second-stage of interaction to the previous realization (p_{t-1}, q_{t-1}).

Myopia does not pin down a countable set of predictions. Note however that the Cournot model can be distinguished from Myopia in the data in that Cournot predicts a larger period-on-period volume than Myopia, because under Cournot agents factor there own best-replies into their own decision to buy or sell units.

The models are summarized as follows:

Price formation:

1) RE: Agents factor anticipated frequencies (p_t, q_t) into pricing.

2) Cournot: Buyers factor ($p_t(q_{t-1})$, q_t) and sellers factor (p_{t-1}, $q_t(p_{t-1})$) into pricing decision.

3) Myopia: Prices respond to latest frequencies (p_{t-1}, q_{t-1}).

Determination of Volume:

1′) RE: Agents factor anticipated frequencies (p_t, q_t) into volume.

2′) Cournot: Buyers factor ($p_t(q_{t-1})$, q_t) and sellers factor (p_{t-1}, $q_t(p_{t-1})$) into volume.

3′) Myopia:Volume responds to latest frequencies (p_{t-1}, q_{t-1}).

Determination of second-stage behaviors:

1″) RE: Agents' behaviors jointly correspond to a Nash equilibrium of the second-stage process.

2″) Cournot, Myopia: Agents best-reply to previous frequencies (p_{t-1}, q_{t-1}).

The Simultaneous Equilibration Prediction (SEP)

Under SEP (p^*, q^*) constitutes a static Nash equilibrium of the second stage, and the behaviors (p^*, q^*) imply expected payoffs $b(p^*, q^*)$ and $s(p^*, q^*)$ to buyers and sellers. Agents factor these payoffs into their pricing decision in the preceding double auction. The usual analysis of competitive markets provides an obvious way of factoring payoffs into the double auction: buyers and sellers derive their demand and supply schedules in the preceding double auction by factoring their payoffs b(·) and s(·)into their marginal surplus computations. Specifically, buyers buy their *k*th units if they can secure prices which do not exceed the sum of b(p, q) and the marginal benefit of the *k*th unit. Sellers sell their *k*th units if they can secure prices which exceed the difference between the marginal cost of the *k*th unit and s(p, q). These derived demands and supplies in turn imply a unique competitive equilibrium in the double auction. The derived demand and supply schedules that are consistent with (p, q) = (1, 1), the Nash Equilibrium that corresponds to "Up-Left," are displayed in Figure 3.

In our notation, SEP satisfies

$$P^* \in [D(Q^*) + b(p^*, q^*)] \cap [S(Q^*) - s(p^*, q^*)]$$

As above, the static predictions (P*, Q*, p*, q*) can be arrayed in the following table:

Price (P*)	Quantity (Q*)†	Strategies (p*, q*)	Surplus†
790 - 810	17	(1, 1)	8,540
690 - 710	9	(0.75, 0.25)	1,980
390 - 410	17	(0, 0)	8,540

†Values correspond to the double auction conducted with six buyers and six sellers.

Whereas buyers and sellers oppositely rank the pure-strategy Nash equilibria (1, 1) and (0, 0) of the second stage, the surpluses available to each agent under each of the pure strategy equilibria (800, Q*, 1, 1) and (400, Q*, 0, 0) of the entire two-stage process are identical. All players rank the pure strategy equilibria above the mixed-strategy equilibrium (700, Q^*_{mixed}, 0.75, 0.25).

V Results

The chief result of the paper is that prices, volumes, and behaviors systematically converge *and* that they converge to a state consistent with RE. Moreover, the data indicate that convergence of prices lags the convergence of realizations in the second stage. Also, the data indicate that agents exercise some sophistication in their pricing decisions. Specifically, there is evidence that they factor their own action choices in the second stage into their pricing decision in the preceding double-auction.

To evaluate convergence of prices to predicted values, the following econometric model is enlisted: a second-order autoregressive process or AR(2) whereby

$$P_t = \alpha + \beta_1 P_{t-1} + \beta_2 P_{t-2} + \varepsilon_t,$$

and ε_t is assumed to be a "white noise" process.

Under this model a steady-state price P* corresponds to $\frac{\hat{\alpha}}{1-\hat{\beta}_1-\hat{\beta}_2}$ where $\hat{z}$ = the OLS estimate.[3]

Result 1: In each of the experimental sessions, behaviors in the second stage of strategic interaction converge to one of the two pure-strategy Nash equilibria.

Support: In 3 of 4 sessions behaviors converge to the pure-strategy Nash equilibrium that corresponds to "Down, Right" or (p, q) = (0, 0). In the one other session, behaviors converge on the other pure-strategy Nash equilibrium that corresponds to "Up, Left" or (p, q) = (1, 1).

Figure 4 exhibits the round-by-round convergence in session Feb 22 of behaviors in the Battle-of-the-Sexes to the pure-strategy Nash equilibrium conforming to "Down-Right." In session Feb 22, behaviors converged on (0, 0) by round 6. A single buyer deviated with a single unit in both of the succeeding rounds, but in the remaining 7 rounds behaviors conformed to (p, q) = (0, 0).

In session Feb 14, behaviors converged on (0, 0) by round 5. (See "Observed Frequencies" in Table 2.1.) A single buyer deviated from (0, 0) in round 6, but in the remaining 4 rounds behaviors conformed to (0, 0). Behaviors converged to the other equilibrium (1, 1) in session Nov 13. Behaviors converged by round 4. In rounds 6 through 11 some sellers deviated from the equilibrium, but behaviors conformed to (1, 1) in the closing 7 rounds of the session. Lastly,

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[3] Under the assumption that the error process corresponds to white noise, the assumptions of the Gauss-Markov theorem are satisfied, and, accordingly, OLS estimates are BLUE.

behaviors converged on (0, 0) by round 10 of session Nov 14. A single agent deviated with 8 units in round 13, and the same agent deviated with 3 units in round 14, but in the remaining 4 rounds behaviors conformed to (0, 0). (See "Observed Frequencies" in Tables 2.2, 2.3, and 2.4.)

Result 2: In each of the experimental sessions, prices converge to RE-consistent levels.

Support: In sessions Feb 14, Feb 22 and Nov 14, prices converged to 400, the price RE-consistent with the pure-strategy Nash equilibrium (0, 0). In session Nov 13, prices converged to 800, the price RE-consistent with the pure-strategy Nash equilibrium (1, 1).

Figures 5 and 6 exhibit the convergence of prices in sessions Feb 22 and Nov 13. Figure 5 exhibits the prices at which units were transacted over the course of 14 market sessions. After each market closed, test subjects participated in a round of strategic interaction. The round-on-round relative frequency with which the outcome "Down-Right" emerged is mapped against the right axis of Figure 5. By round 6, behaviors in the second stage of strategic interaction conformed to "Down-Right," and prices subsequently converged to the RE-consistent price of 400. In session Nov 13, prices converged to 800, the price that is RE-consistent with the outcome "Up-Left" to which behaviors converged.

Figure 7 presents prices and behaviors from all four experimental sessions. Average round-on-round prices are mapped against the left axis, and the statistic (p + q), the round-on-round sum of observed frequencies, is mapped against the right axis. The condition (p + q) = 2.00 indicates that behaviors in the second stage conformed to "Up-Left," and (p + q) = 0.00 indicates that behaviors conformed to "Down-Left." In the three sessions in which the statistic (p + q) converged to the value 0.00, prices converged to the RE-consistent price 400. In session Nov 13 (p + q) converged to 2.00, and average prices converged on the corresponding price of 800.

To substantiate the convergence of prices, we apply the AR(2) model to the price series that begin with the period succeeding the one in which behaviors in the second stage first lined up with a Nash equilibrium. For example, in the first session *all* action choices lined up with "Down, Right" for the first time in period 4. We argue that the data generating process shifts from one regime to another once agents begin to coordinate on an outcome in the second stage of strategic interaction. For the same reason, we apply the AR(2) to data commencing with period 7 in the second session, and to data commencing with periods 5 and 11 in sessions 3 and 4, respectively.

The AR(2) model $P_t = \alpha + \beta_1 P_{t-1} + \beta_2 P_{t-2} + \varepsilon_t$ generates estimates of the steady-state price that are consistent with the hypothesis that the prices are converging to 400 in sessions 1, 2, and 4, and to 800 in session Nov 13. The estimates of the steady-state prices from each session all lie within 1.33 standard deviations of the hypothesized steady-state prices. (See Table 4.)

Admittedly, we would prefer to model the entire data generating process either by endogenizing the regime shift or developing a different model that would incorporate all of the price data. However, our immediate purpose is to quantify the notion that prices "converge."

Figure 5 exhibits the convergence of prices to RE-consistent price of 400 in the experimental session Feb 22. Behaviors in the game converged to the pure-strategy Nash equilibrium corresponding to "Down-Left," and prices subsequently converged.

To substantiate the notion of "regime shift" in the data generating process, we also include in Table 4 F-statistics corresponding to Chow's test for structural change in the price series. "Large" values support the hypothesis that the data generating process has changed from one segment of the price series to the next, and three of our F-statistics are indeed significant at the 1% level. The fourth is significant at the 5% level.

Result 3: In each of the experimental sessions, volumes converge to RE-consistent levels.

Support: We apply a statistical criterion that indicates that volumes in all four sessions converge to RE-consistent levels. We apply an ARMA(1, 2) of the form $Q_t = \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + \alpha_4 d_4 + \beta Q_{t-1} + u_t$ where $u_t = \rho_1 u_{t-1} + \rho_2 u_{t-2} + \varepsilon_t$, ε_t is assumed to conform to the usual "white noise" process, and the terms d_i are dummy variables identifying each of the four experimental sessions. The model generates steady-state predictions of volumes in each of the four sessions that cannot be statistically distinguished from the RE-consistent predictions of volumes. (See statistical tests in Table 6.)

The ARMA(1,2) employs 57 of 61 observations of average volumes generated from all four experimental sessions. Four observations are omitted in order to accommodate the single lag on volume Q_{t-1}. The model pools the data to generate an estimate of the effect of the lag, but the four dummy variables permit estimation of an "intercept" α_i for each of the four experimental sessions.

The next result characterizes the evolution of prices in the system. Principally, the convergence of prices lags the convergence of behaviors in the game. The lag of prices itself suggests that prices respond to the equilibrium realizations that emerge in the second stage.

Two measures of the lag are articulated. First, it is observed that within the first four rounds of each experimental session behaviors on at least one side of the market make initial contact with the equilibrium of the second stage that subsequently obtains, and prices subsequently converge. Secondly, the AR(2) model of the evolution of prices employed in Result 1 substantiates the follow-on convergence of prices.

Result 4: In all four experimental sessions, the convergence of prices to RE-consistent values lags the convergence of behaviors to pure-strategy Nash equilibria.

Support: Figure 7 indicates the convergence of behaviors in the second stage and the follow-on convergence of prices. Within the first four rounds of all four sessions, behaviors on the side of the market receiving 700 in the equilibrium of the second stage game make initial contact with the equilibrium that eventually obtains. In sessions Feb 14, Feb 22, and Nov 14, sellers actions all conform to "Right" (q = 0) in the first round, the fourth round, and the fourth round, respectively. In each of the three sessions, behaviors in the second stage subsequently converge to the equilibrium conforming to "Down," "Right." By the fourth stage, prices have yet to converge. Average prices in the fourth round of each of these sessions were 780, 631, and 582. Prices in each of these sessions eventually converged to 400. In session Nov 13 the equilibrium conforming to "Up," Left" eventually obtained. In this case, buyers' actions first made contact with the equilibrium behaviors (p = 1) by round 3. Average prices were 720, well short of the equilibrium price of 800.

The AR(2) model $P_t = \alpha + \beta_1 P_{t-1} + \beta_2 P_{t-2} + \varepsilon_t$ employed in the discussion of Result 1 articulates the remainder of the experience of prices. The data support the hypothesis that the price series in each of the four experimental sessions exhibit structural shift by the time behaviors on both sides of the market first make contact with a pure-strategy Nash equilibrium of the second stage. The estimates of the coefficients on the lagged prices (β_1 and β_2) after convergence in behaviors are statistically significant, indicating that prices experience substantial evolution after behaviors have already converged. (Once again, regression results are presented in Table 4.)

Result 5 provides a clue about the strategic sophistication agents exercise, and it suggests that their behaviors can be partially characterized by backward induction. First, the result suggest that agents use the latest realizations of the second stage game to form expectations about the next stage. More importantly, however, the result suggests that agents are sophisticated enough 1) to factor expected payoffs into their pricing decisions -- they apply backward induction -- and 2) to factor their own best-replies to expected behaviors into their calculations of expected payoffs.

Result 5: The Cournot model characterizes the evolution of prices with markedly more success than the RE and Myopia models.

Support: The data indicate that the Cournot model predicts price intervals that capture 82.46% of the prices on the last units transacted in each round. The Myopia and RE models generate predictions that are consistent with 35.09% and 24.59% of the same data, respectively.

To characterize the agreement of observed prices with the various price predictions, we tailor a series π_t to each the Cournot model, Myopia, and RE where

$$\pi_t = \frac{P_t - \hat{P}_t(\cdot)}{\left[\overline{P}_t(\cdot) - \underline{P}_t(\cdot)\right]/2},$$

P_t = the price of the *last* unit traded in period t,

$\left[\underline{P}_t(\cdot), \overline{P}_t(\cdot)\right]$ is the interval of prices consistent with the given model in period t,

$\hat{P}_t(\cdot) = \frac{\overline{P}_t(\cdot) + \underline{P}_t(\cdot)}{2}$ is the midpoint of the interval $\left[\underline{P}_t(\cdot), \overline{P}_t(\cdot)\right]$, and functions $g_t(\cdot)$ are specific to each model.

Under RE $g_t(\cdot)$ is a function of the (anticipated) marginal frequencies (p_t, q_t), whereas under Cournot $g_t(\cdot)$ is a function of both the observed frequencies (p_{t-1}, q_{t-1}) *and* the best-replies $p_t(q_{t-1})$ and $q_t(p_{t-1})$ to them, and under Myopia $g_t(\cdot)$ is a function of the observed frequencies (p_{t-1}, q_{t-1}).

Observe that a value of π_t in the interval [-1, 1] indicates that the observed last price P_t is consistent with the models under examination. If we define $\pi_t \in [-1, 1]$ as a "success" for trial t, we find that the RE model registers 15 successes out of 61 trials (24.59%). The Cournot process, however, captures 47 out of 57 available observations (82.46%), and Myopia registers 20 successes out of 57 trials (35.09%). (See Table 5.1.)

Figure 8 presents the distribution of the series $|\pi_t|$ for each of the models. The cumulative density of $|\pi_t|$ generated under each model is mapped against $|\pi_t|$ itself. Each cumulative density is bounded above at 100%. At $|\pi_t| = 1$, the density generated under the Cournot model captures 82% of the data.

Under the Cournot model agents best-reply to previous frequencies (p_{t-1}, q_{t-1}), and they determine price and volume by factoring the last period's frequencies *and* their best-replies to those frequencies into their calculations. The "Predicted

Prices" in Tables 3.1 through 3.4 indicate the price margins that are consistent with the realization that emerged.

The RE model generates a series π_t that is almost uniformly distributed around $\pi_t = 0$, the value of π_t that corresponds to predictions centered precisely on the observed last price P_t. The Cournot model, however, generates predictions that are more tightly packed. The median absolute divergence of π_t from zero under the RE and Myopia models exceeds 2. That is, under these models the mid-point of more than half the predicted prices diverges from the data by more than 1 price interval. Further, the standard deviation of the π_t series is nearly one-half or one-third the standard deviations of the series generated under the other three models. (See Table 5.2.)

One of the salient behavioral phenomena the models do not capture is the deviation, usually by a single agent, in the second stage of interaction from a pure strategy equilibrium of the second stage after convergence has initially been achieved. Nonetheless, the largest deviations of π_t from the observed prices do not correspond to the deviations from Nash equilibria of the second stage. In the experimental session of November 13, for example, the largest absolute values of π_t under the Cournot model correspond to periods 7 and 10. Neither of these periods corresponds to a period following a "deviation." The average absolute deviation of π_t from 0 under the Cournot model is 1.49. That is, on average π_t diverges from 0 by more than half a Cournot-consistent price interval. The average deviation of the data less the two largest deviations is 0.68. That is, if we exclude the largest deviations from our calculations, we find that on average π_t diverges from 0 by a magnitude that is Cournot-consistent.

V Conclusion

What happens when players buy the right to play a game? There is a body of experimental evidence, including the research presented here, that suggests that what happens depends systematically on features of the larger institutional context in which games are embedded.

Price coordination mechanisms have been the focus of attention of several studies. In the experiments of Van Huyck, Battalio and Beil, agents participate in a market through which the right to participate in a second stage of interaction is distributed. In their experiments market volume is predetermined and the structure of payoffs is common knowledge. In Cooper, Dejong, Forsythe, and Ross (1993), 18 agents bid for 9 units where each unit entitles the owner one action choice in a 9-player coordination game. In this framework, a forward-induction model entails mapping prices into Nash equilibria in an obvious way.[4]

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4. For references consult Van Huyck, Battalio and Beil (1990, 1991, 1993), Crawford (1990, 1995), Crawford and Broseta (1995), and Cooper, Dejong, Forsythe, and Ross (1993, 1994).

The framework we present is less accommodating. In the framework presented here agents do not know the entire structure of the two-stage apparatus: they know their own marginal cost or marginal redemption value schedules, and they commonly know the structure of the second stage process, but they do not know the demand and supply schedules. Accordingly, it is not obvious how agents might use prices to signal behaviors in the second stage. How would, for example, an agent know that a price of 800 is consistent (in our RE model) with the outcome ("Up," "Left")?

The first three results indicate that behaviors converge to RE-consistent equilibria, and the remaining results begin to illuminate the dynamic processes by which behaviors converge. From Result 4 one sees that agents do not coordinate behaviors in the game via equilibrium prices. Rather, the convergence of prices in the double auction lags convergence of behaviors in the second stage. Result 5 indicates that prices respond to realizations in the game. Specifically, the data indicate that agents factor their own actions in the second stage into their pricing decisions in the first stage. Finally, the conjecture presented above suggests that agents' expectations of realizations in the game become aligned after the opening stages of the game. Agents indicate that in the early rounds they anticipate a particular pure-strategy equilibrium of the second stage and, accordingly, they jointly bid up volumes in the early rounds and start coordinating on one of the two pure-strategy equilibria of the second stage. The sensitivity of agents to different payoffs remains and even after many periods some of them attempt to unilaterally motivate a shift from one equilibrium to the other. All of these attempts to unilaterally manipulate the selection of equilibria fail.

We speculate that both learning dynamics and solution concepts, whether new or traditional, can be systematically linked to attributes of the institutional context in which games are embedded. That is, we suggest that the issue of equilibrium can be naturally embedded within the larger issue of the institutional sensitivity of equilibria. In this context the research makes progress in characterizing a mapping from institutions into learning dynamics and into equilibria. First and foremost, the research demonstrates that agents' behaviors converge on static outcomes that are consistent not merely with a Nash prediction of behaviors in a static game but are consistent with a joint application of supply-demand analysis and Nash predictions. While none of the models completely characterize the learning and dynamics exhibited in the experimental data, one model out-performs all of the others. That model is one in which agents best-reply to some subset of past realizations of strategic interaction *and* in which agents factor their own actions into future realizations. This model outperforms those in which agents fail to factor their own actions into their calculus and those in which agents forecast (perfectly) other agents' actions.

Appendix

Tables and Figures

Table 1: Static RE Predictions

Session	Buyers:Sellers	Price	Volume	Frequencies (p, q)	Nash Equilibrium of Second Stage	Per Unit Surplus Buyers	Per Unit Surplus Sellers	Per Unit Surplus Total
1	4:4	790-810	12	(1, 1)	Up, Left	329.17	140.83	470.00
		690-710	6	(0.75, 0.25)	Mixed	143.33	58.33	201.67
		390-410	12	(0, 0)	Down, Right	329.17	140.83	470.00
2	6:6	790-810	17	(1, 1)	Up, Left	352.35	150.00	502.35
		690-710	9	(0.75, 0.25)	Mixed	156.67	63.33	220.00
		390-410	17	(0, 0)	Down, Right	352.35	150.00	502.35
3	5:5	790-810	14	(1, 1)	Up, Left	347.86	147.86	495.71
		690-710	7	(0.75, 0.25)	Mixed	167.14	67.14	234.29
		390-410	14	(0, 0)	Down, Right	347.86	147.86	495.71
4	7:7	790-810	21	(1, 1)	Up, Left	331.43	141.90	473.33
		690-710	11	(0.75, 0.25)	Mixed	142.73	58.18	200.91
		390-410	21	(0, 0)	Down, Right	331.43	141.90	473.33

Table 2.1: February 14 Results

Round	Observed Frequencies (p, q)	Average Payoffs		Observed		Per Unit Surplus Extracted			System Efficiency
		Buyers	Sellers	Avg Price	Volume	Buyers	Sellers	Total	
1	(1.00 , 0.00)	100.00	100.00	836	5	-148	-4	-152	-13.48%
2	(0.50 , 0.33)	266.67	333.33	842	6	-35	280	245	26.06%
3	(0.63 , 0.25)	325.00	375.00	833	6	-133	315	181	19.28%
4	(0.50 , 0.00)	200.00	400.00	780	6	-16	563	547	58.16%
5	(0.00 , 0.00)	300.00	700.00	734	9	147	315	462	73.67%
6	(0.33 , 0.00)	233.33	500.00	644	9	114	168	282	45.04%
7	(0.00 , 0.00)	300.00	700.00	574	9	250	330	580	92.55%
8	(0.00 , 0.00)	300.00	700.00	480	9	344	194	538	85.82%
9	(0.00 , 0.00)	300.00	700.00	459	9	365	228	593	94.68%
10	(0.00 , 0.00)	300.00	700.00	411	11	345	161	505	98.58%

Table 2.2: February 22 Results

Round	Observed Frequencies (p, q)	Average Payoffs		Observed		Per Unit Surplus Extracted			System Efficiency
		Buyers	Sellers	Avg Price	Volume	Buyers	Sellers	Total	
1	(0.57 , 0.36)	285.71	314.29	742	14	-89	50	-39	-6.44%
2	(0.60 , 0.07)	166.67	300.00	725	15	-63	-43	-106	-18.65%
3	(0.27 , 0.09)	300.00	554.55	692	11	129	286	415	53.49%
4	(0.35 , 0.00)	229.41	488.24	631	17	1	96	96	19.20%
5	(0.08 , 0.00)	284.62	653.85	535	13	287	240	527	80.21%
6	(0.00 , 0.00)	300.00	700.00	425	11	406	194	600	77.28%
7	(0.07 , 0.00)	286.67	660.00	369	15	377	93	470	82.55%
8	(0.07 , 0.00)	286.67	660.00	344	15	389	64	453	79.63%
9	(0.00 , 0.00)	300.00	700.00	355	17	367	95	462	92.04%
10	(0.00 , 0.00)	300.00	700.00	361	17	389	101	489	97.42%
11	(0.00 , 0.00)	300.00	700.00	386	15	411	152	563	98.95%
12	(0.00 , 0.00)	300.00	700.00	398	16	376	156	533	99.77%
13	(0.00 , 0.00)	300.00	700.00	402	16	372	153	525	98.36%
14	(0.00 , 0.00)	300.00	700.00	402	16	372	157	529	99.06%

Table 2.3: November 13 Results

Round	Observed Frequencies (p, q)	Average Payoffs		Observed		Per Unit Surplus Extracted			System Efficiency
		Buyers	Sellers	Avg Price	Volume	Buyers	Sellers	Total	
1	(0.43 , 0.86)	271.43	157.14	838	7	48	93	141	14.27%
2	(0.90 , 0.80)	600.00	320.00	728	10	264	125	389	56.05%
3	(0.78 , 1.00)	566.67	255.56	720	9	346	9	354	45.97%
4	(1.00 , 1.00)	700.00	300.00	724	11	375	85	460	72.91%
5	(1.00 , 1.00)	700.00	300.00	730	17	282	11	293	71.76%
6	(0.73 , 1.00)	536.36	245.45	746	11	221	53	275	43.52%
7	(0.71 , 1.00)	528.57	242.86	739	14	226	2	228	45.97%
8	(0.64 , 1.00)	481.82	227.27	751	11	127	34	161	25.58%
9	(0.73 , 1.00)	536.36	245.45	755	11	200	73	273	43.23%
10	(0.75 , 1.00)	550.00	250.00	751	12	216	71	287	49.57%
11	(0.77 , 1.00)	561.54	253.85	752	13	188	60	248	46.54%
12	(1.00 , 1.00)	700.00	300.00	751	15	344	89	433	93.52%
13	(1.00 , 1.00)	700.00	300.00	753	15	355	81	436	94.24%
14	(1.00 , 1.00)	700.00	300.00	765	14	364	107	471	95.10%
15	(1.00 , 1.00)	700.00	300.00	770	12	410	124	534	92.36%
16	(1.00 , 1.00)	700.00	300.00	782	12	408	152	560	96.83%
17	(1.00 , 1.00)	700.00	300.00	786	16	297	101	398	91.79%
18	(1.00 , 1.00)	700.00	300.00	790	15	319	123	442	95.53%
19	(1.00 , 1.00)	700.00	300.00	805	15	302	140	442	95.53%

Table 2.4: November 14 Results

Round	Observed Frequencies (p, q)	Average Payoffs		Observed		Per Unit Surplus Extracted			System Efficiency
		Buyers	Sellers	Avg Price	Volume	Buyers	Sellers	Total	
1	(0.63 , 0.19)	287.50	362.50	555	16	248	-94	154	24.75%
2	(0.33 , 0.40)	206.67	313.33	588	15	138	-28	111	16.70%
3	(0.63 , 0.13)	200.00	300.00	576	16	131	-97	34	5.53%
4	(0.44 , 0.00)	212.50	437.50	582	16	141	46	187	30.08%
5	(0.29 , 0.00)	241.18	523.53	546	17	187	82	269	45.98%
6	(0.24 , 0.06)	241.18	523.53	545	17	198	122	320	54.73%
7	(0.06 , 0.00)	288.89	666.67	533	18	236	226	462	83.60%
8	(0.20 , 0.00)	260.00	580.00	510	20	180	110	290	58.25%
9	(0.15 , 0.00)	270.00	610.00	465	20	250	100	350	70.32%
10	(0.00 , 0.00)	300.00	700.00	453	18	317	168	485	87.83%
11	(0.00 , 0.00)	300.00	700.00	440	20	304	159	463	93.16%
12	(0.00 , 0.00)	300.00	700.00	438	21	288	144	432	91.35%
13	(0.38 , 0.00)	223.81	471.43	441	21	183	-50	134	28.27%
14	(0.12 , 0.00)	276.47	629.41	442	17	331	117	447	76.46%
15	(0.00 , 0.00)	300.00	700.00	443	18	342	179	521	94.37%
16	(0.00 , 0.00)	300.00	700.00	436	20	309	156	465	93.46%
17	(0.00 , 0.00)	300.00	700.00	412	22	304	143	447	98.89%
18	(0.00 , 0.00)	300.00	700.00	431	19	333	165	498	95.27%

Table 3.1: February 14 Predictions

Round	Price Predictions			Volume Predictions		
	RE	Cournot	Myopia	RE	Cournot	Myopia
1	760 - 780			2		
2	627 - 707	660 - 740	760 - 780	8	8	2
3	660 - 690	560 - 740	627 - 707	8	8	8
4	390 - 410	560 - 740	660 - 690	12	8	8
5	460 - 673	390 - 410	390 - 410	8	12	12
6	460 - 673	520 - 580	460 - 673	8	9	8
7	390 - 410	520 - 580	460 - 673	12	9	8
8	390 - 410	390 - 410	390 - 410	12	12	12
9	390 - 410	390 - 410	390 - 410	12	12	12
10	390 - 410	390 - 410	390 - 410	12	12	12

Table 3.2: February 22 Predictions

	Price Predictions			Volume Predictions		
Round	RE	Cournot	Myopia	RE	Cournot	Myopia
1	654 - 718			11		
2	628 - 639	633 - 674	654 - 718	11	12	11
3	518 - 527	620 - 727	628 - 639	14	11	11
4	502 - 589	484 - 562	518 - 527	12	14	14
5	396 - 485	532 - 580	502 - 589	15	14	12
6	390 - 410	396 - 500	396 - 485	17	15	15
7	390 - 487	390 - 410	390 - 410	15	17	17
8	390 - 487	390 - 500	390 - 487	15	15	15
9	390 - 410	390 - 500	390 - 487	17	15	15
10	390 - 410	390 - 410	390 - 410	17	17	17
11	390 - 410	390 - 410	390 - 410	17	17	17
12	390 - 410	390 - 410	390 - 410	17	17	17
13	390 - 410	390 - 410	390 - 410	17	17	17
14	390 - 410	390 - 410	390 - 410	17	17	17

Table 3.3: November 13 Predictions

Round	Price Predictions			Volume Predictions		
	RE	Cournot	Myopia	RE	Cournot	Myopia
1	738 - 777			9		
2	764 - 816	647 - 724	738 - 777	11	16	9
3	764 - 847	770 - 780	764 - 816	11	12	11
4	790 - 810	794 - 900	764 - 847	14	12	11
5	790 - 810	790 - 810	790 - 810	14	14	14
6	775 - 816	790 - 810	790 - 810	11	14	14
7	777 - 809	816 - 820	775 - 816	11	13	11
8	763 - 842	809 - 820	777 - 809	10	13	11
9	775 - 816	772 - 810	763 - 842	11	14	10
10	770 - 830	819 - 820	775 - 816	11	13	11
11	766 - 842	800 - 900	770 - 830	11	12	11
12	790 - 810	796 - 900	766 - 842	14	12	11
13	790 - 810	790 - 810	790 - 810	14	14	14
14	790 - 810	790 - 810	790 - 810	14	14	14
15	790 - 810	790 - 810	790 - 810	14	14	14
16	790 - 810	790 - 810	790 - 810	14	14	14
17	790 - 810	790 - 810	790 - 810	14	14	14
18	790 - 810	790 - 810	790 - 810	14	14	14
19	790 - 810	790 - 810	790 - 810	14	14	14

Table 3.4: November 14 Predictions

	Price Predictions			Volume Predictions		
Round	RE	Cournot	Myopia	RE	Cournot	Myopia
1	654 - 671			13		
2	593 - 700	635 - 703	654 - 671	13	13	13
3	648 - 653	520 - 620	593 - 700	13	16	13
4	553 - 573	635 - 715	648 - 653	14	13	13
5	496 - 521	553 - 660	553 - 573	16	14	14
6	485 - 532	496 - 580	496 - 521	16	16	16
7	383 - 489	461 - 568	485 - 532	18	16	16
8	440 - 540	414 - 420	383 - 489	16	19	18
9	440 - 470	470 - 500	440 - 540	18	18	16
10	390 - 410	440 - 500	440 - 470	21	18	18
11	390 - 410	390 - 410	390 - 410	21	21	21
12	390 - 410	390 - 410	390 - 410	21	21	21
13	519 - 584	390 - 410	390 - 410	14	21	21
14	421 - 476	549 - 580	519 - 584	18	16	14
15	390 - 410	421 - 500	421 - 476	21	18	18
16	390 - 410	390 - 410	390 - 410	21	21	21
17	390 - 410	390 - 410	390 - 410	21	21	21
18	390 - 410	390 - 410	390 - 410	21	21	21

Table 4: The Convergence of Prices

Experimental Session	Periods	Observations	$\hat{\alpha}$	$\hat{\beta}_1$	$\hat{\beta}_2$	P*	$\hat{P} = \frac{\hat{\alpha}}{1-\hat{\beta}_1-\hat{\beta}_2}$	Standard Error σ_P	t-statistic $t_{n-3} = \frac{\hat{P}-P^*}{\sigma_P}$	DW statistic	Chow test $F_{3,n-6}$
Feb 14	**1 - 3**	**1 - 28**	**415.51** (2.82)	**0.70** (3.43)	**-0.23** (-1.14)					**2.08**	**6.68** ($F_{3,92\ 1\%} = 4.02$)
	4 - 10	**29 - 98**	**21.44** (1.01)	**0.67** (5.70)	**0.27** (2.36)	**400**	**406.37**	**39.56**	**0.16**	**2.16**	
Feb 22	**1 - 4**	**1 - 58**	**592.55** (4.42)	**0.03** (0.24)	**0.09** (0.69)					**2.02**	**20.03** ($F_{3,203\ 1\%} = 3.78$)
	5 - 15	**59 - 209**	**46.28** (3.16)	**0.64** (8.11)	**0.24** (3.05)	**400**	**384.13**	**26.15**	**-0.61**	**2.02**	
Nov 13	**1 - 3**	**1 - 28**	**660.79** (2.61)	**0.16** (0.21)	**-0.06** (0.31)					**2.01**	**4.46** ($F_{3,227\ 1\%} = 3.78$)
	4 - 19	**29 - 273**	**329.72** (6.96)	**0.34** (5.59)	**0.23** (4.24)	**800**	**763.78**	**28.65**	**-1.26**	**2.16**	
Nov 14	**1 - 8**	**1 - 178**	**298.31** (6.11)	**0.23** (3.08)	**0.23** (3.21)					**2.01**	**19.45** ($F_{3,397\ 1\%} = 3.78$)
	9 - 18	**179 - 405**	**211.74** (6.52)	**0.25** (3.94)	**0.27** (4.16)	**400**	**440.76**	**25.59**	**1.59**	**1.92**	

Table 5.1

	π_t			$\lvert\pi_t\rvert$		
	median	mean	std. dev.	median	mean	std. dev.
RE	0.00	-0.07	10.81	2.22	4.85	9.65
Cournot	-0.15	-0.90	4.61	0.48	1.49	4.45
Myopia	-0.57	-0.83	8.55	2.03	3.93	7.62

Table 5.2

	"trials"	"successes" $\lvert \pi_t \rvert \leq 1$	Deviations from Observed Volume **0 units**	**≤ 1 unit**	**≤ 2 units**	**≤ 3 units**	"successes" **sign(ΔQ_t)**
RE	61	24.59%	14.75%	45.90%	68.85%	90.16%	52.63%
Cournot	57	82.46%	19.30%	50.88%	75.44%	96.49%	40.74%
Myopia	57	35.09%	17.54%	47.37%	71.93%	91.23%	37.04%

Table 6

Equations:

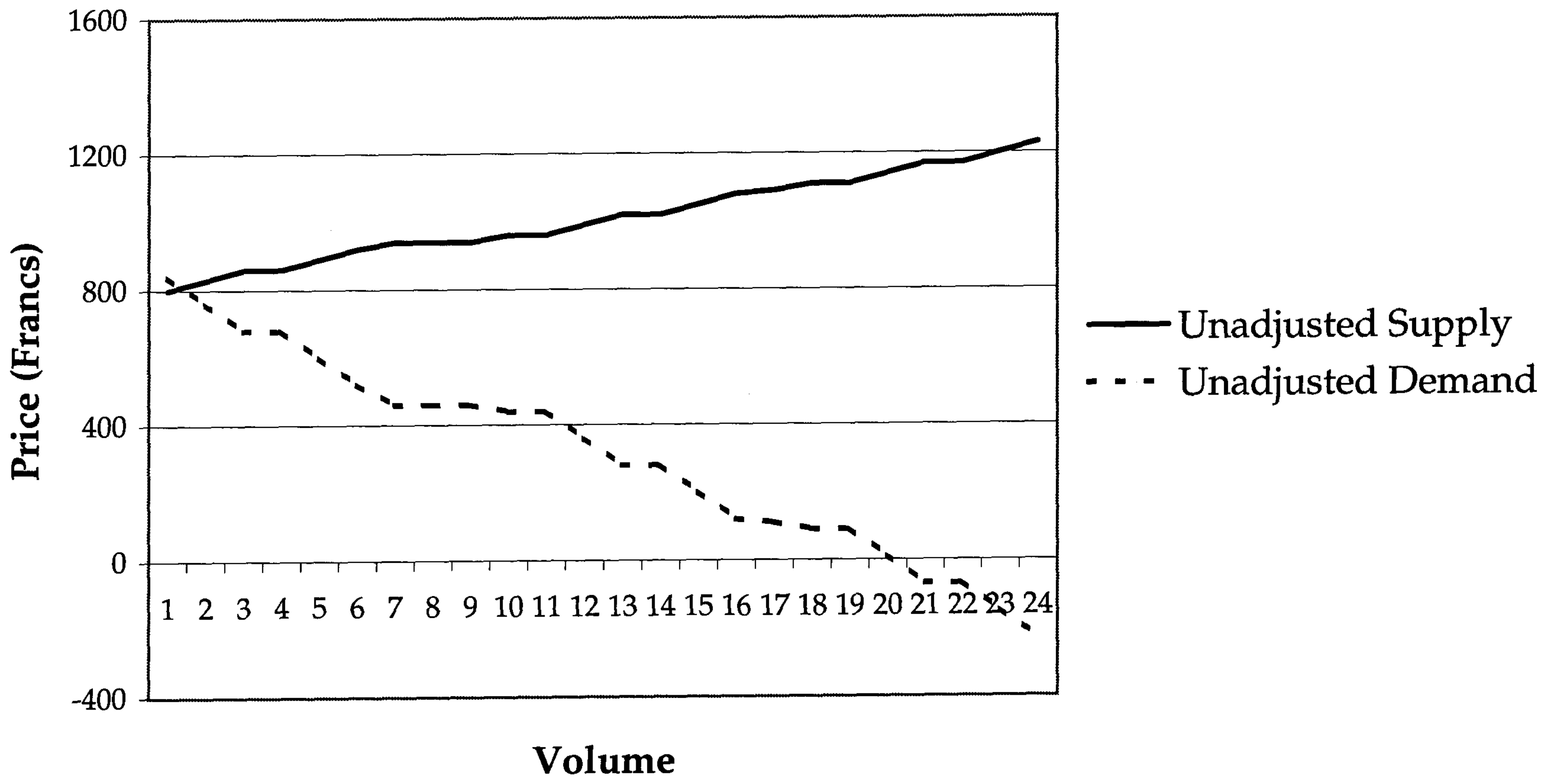
$$Volume_t = \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + \alpha_4 d_4 + \beta Volume_{t-1} + u_t,$$

$$u_t = \rho_1 u_{t-1} + \rho_2 u_{t-2} + \varepsilon_t, \qquad \varepsilon_t \sim N(0,\sigma^2)$$

Regressor	ML Coefficent Estimates $\hat{\alpha}_i, \hat{\beta}, \hat{\rho}_i$	Std. Error	Estimated Session Volume $\hat{V}_i = \frac{\hat{\alpha}_i}{1-\hat{\beta}}$	Predicted Session Volume V_i	t-ratio: $\left(\frac{\hat{V}_i - V_i}{\sigma_V}\right)$
Feb 14 Dummy: d_1	3.16	0.7737	9.43	12	-1.41
Feb 22 Dummy: d_2	5.16	1.3363	15.38	17	-0.89
Nov 13 Dummy: d_3	4.60	1.1416	13.72	14	-0.15
Nov 14 Dummy: d_4	6.41	1.6541	19.09	21	-1.04
$Volume_{t-1}$	0.66	0.0889			
u_{t-1}	-0.46	0.1273			
u_{t-2}	-0.28	0.1273			
Std. Error of $Volume_t$, σ_V	1.83				
DW-statistic	2.09				

Figure 1

Supply and Demand Schedules



These are the schedules that would obtain with a configuration of 6 buyers and 6 sellers.

Figure 2

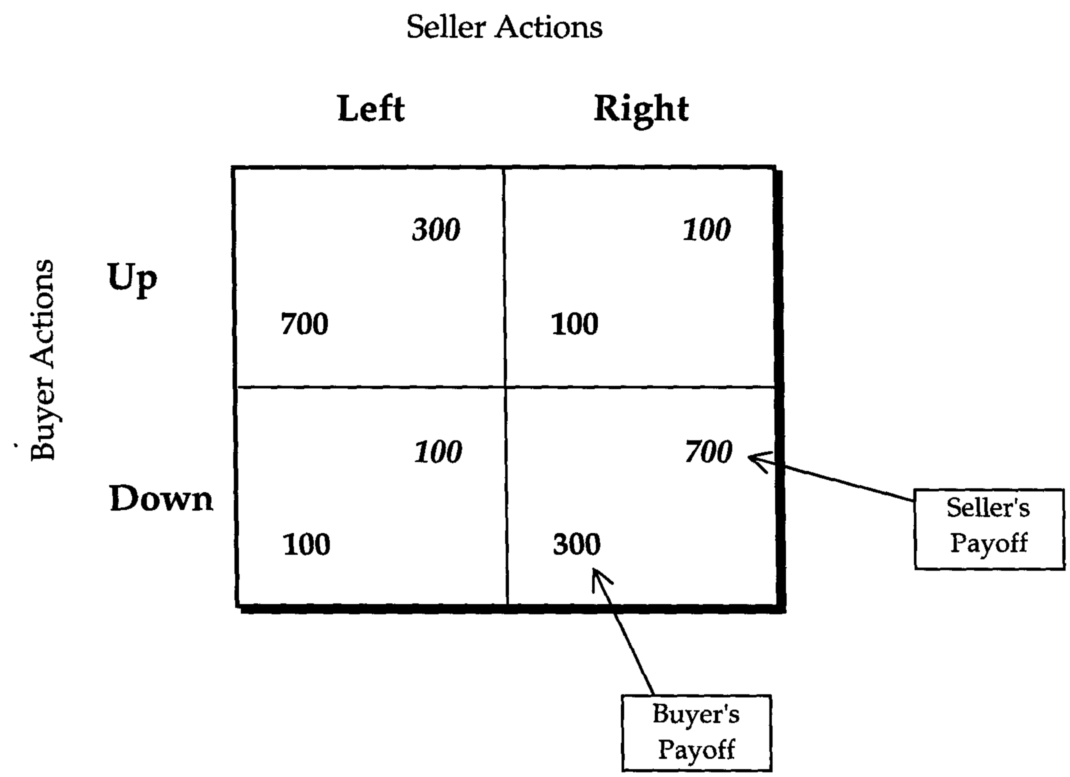

Seller Actions
Left
Right
Buyer Actions
Up
Down
300
700
100
100
100
100
700
300
Seller's Payoff
Buyer's Payoff

Figure 3

Derived Supply and Demand Schedules RE-consistent with the "Up-Left" Equilibrium of the Second Stage Game

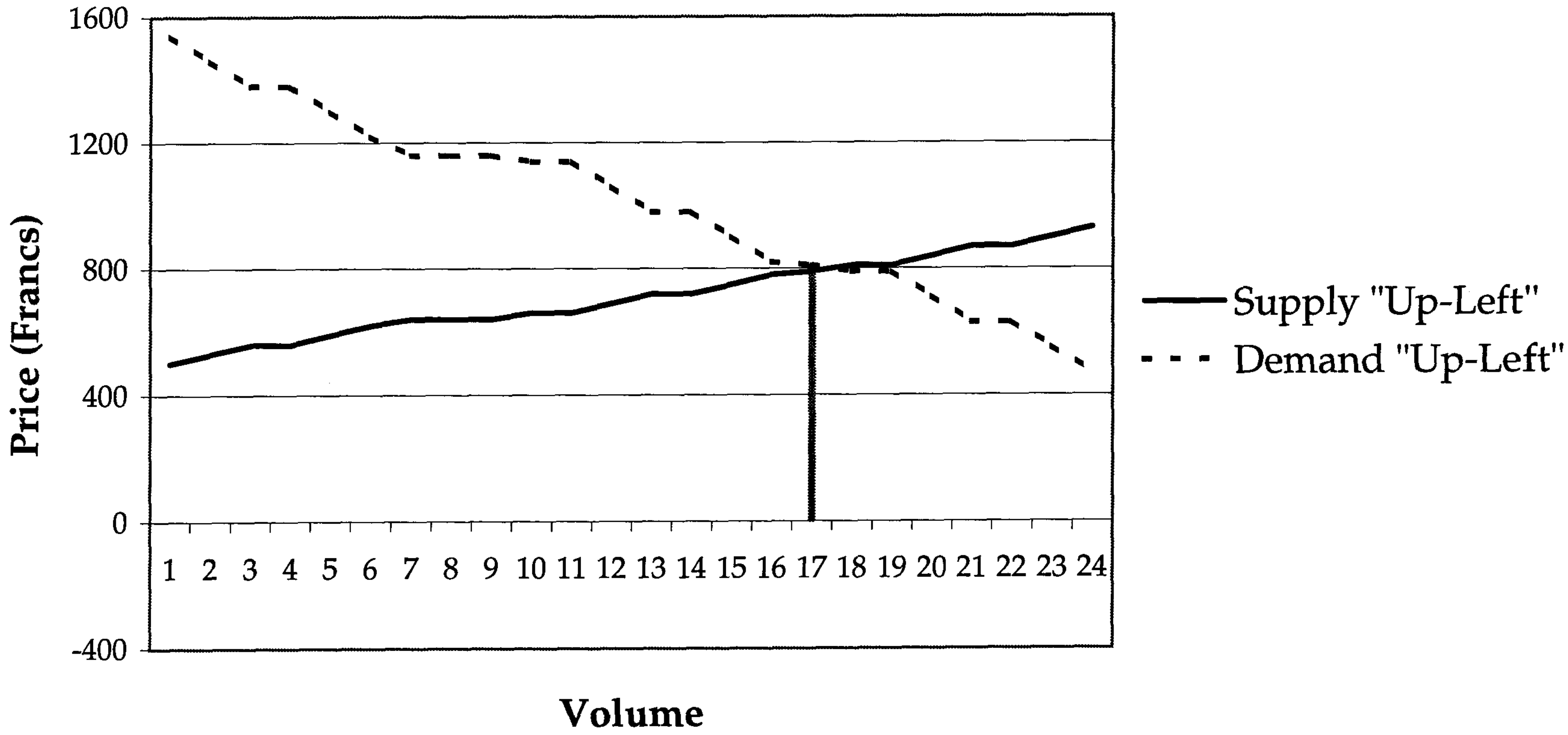


Figure 4

Behaviors in Session Feb 22
Converge to the pure-strategy Nash Equilibrium "Down-Right"

Period 1

	L	R
U	3	5
D	2	4

Period 2

	L	R
U	0	9
D	1	5

Period 3

	L	R
U	1	2
D	0	8

Period 4

	L	R
U	0	6
D	0	11

Period 5

	L	R
U	0	1
D	0	12

Period 6

	L	R
U	0	0
D	0	11

Period 7

	L	R
U	0	1
D	0	14

Period 8

	L	R
U	0	1
D	0	14

Period 9

	L	R
U	0	0
D	0	17

Period 10

	L	R
U	0	0
D	0	17

Period 11

	L	R
U	0	0
D	0	15

Period 12

	L	R
U	0	0
D	0	16

Period 13

	L	R
U	0	0
D	0	16

Period 14

	L	R
U	0	0
D	0	16

Figure 5

Prices and Behaviors Converge to the RE-Consistent Values (400, "Down-Right") on Feb 22

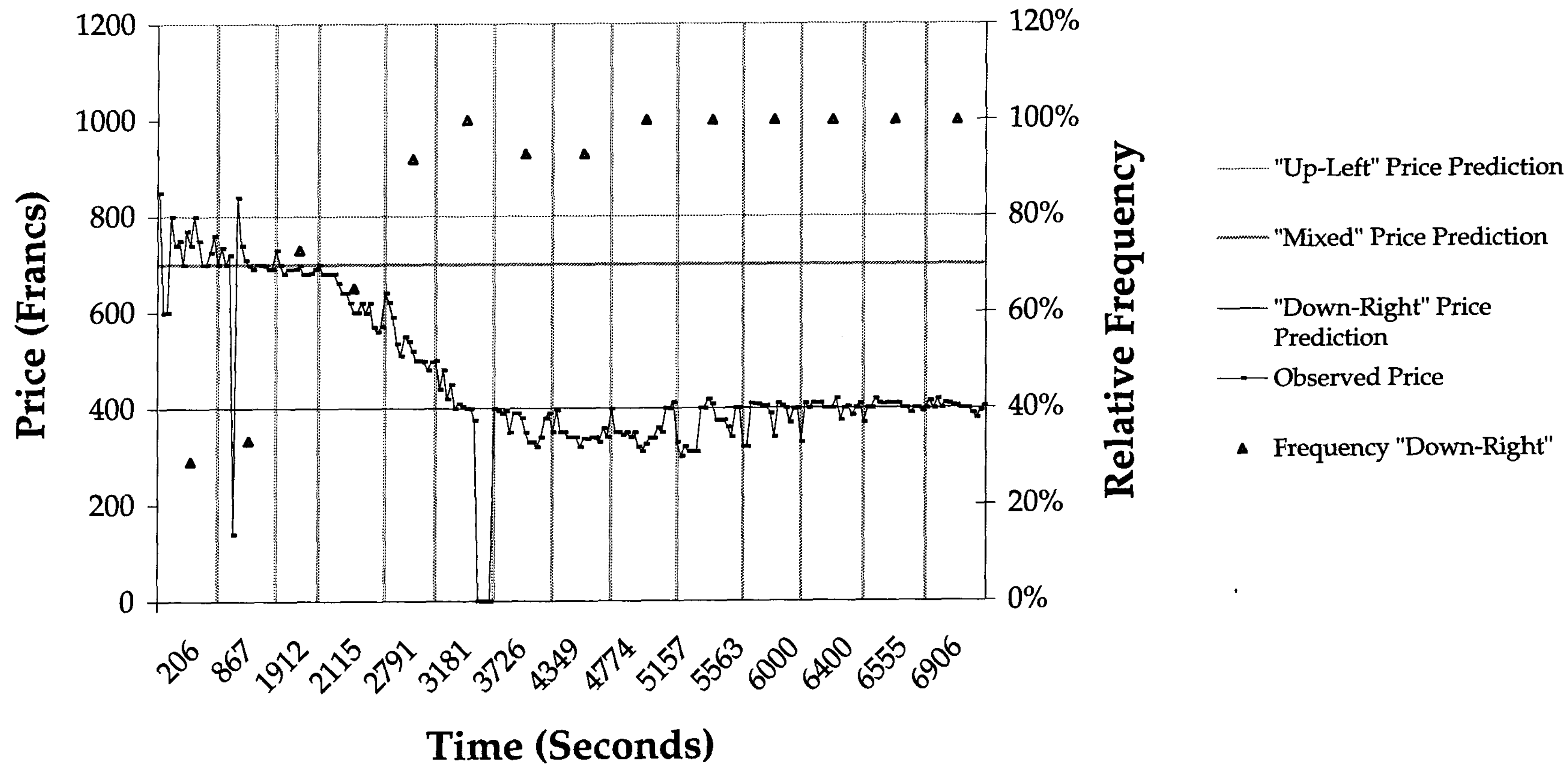


Figure 6

Prices and Behaviors Converge to the RE-Consistent Values (800, "Up-Left") on Nov 13

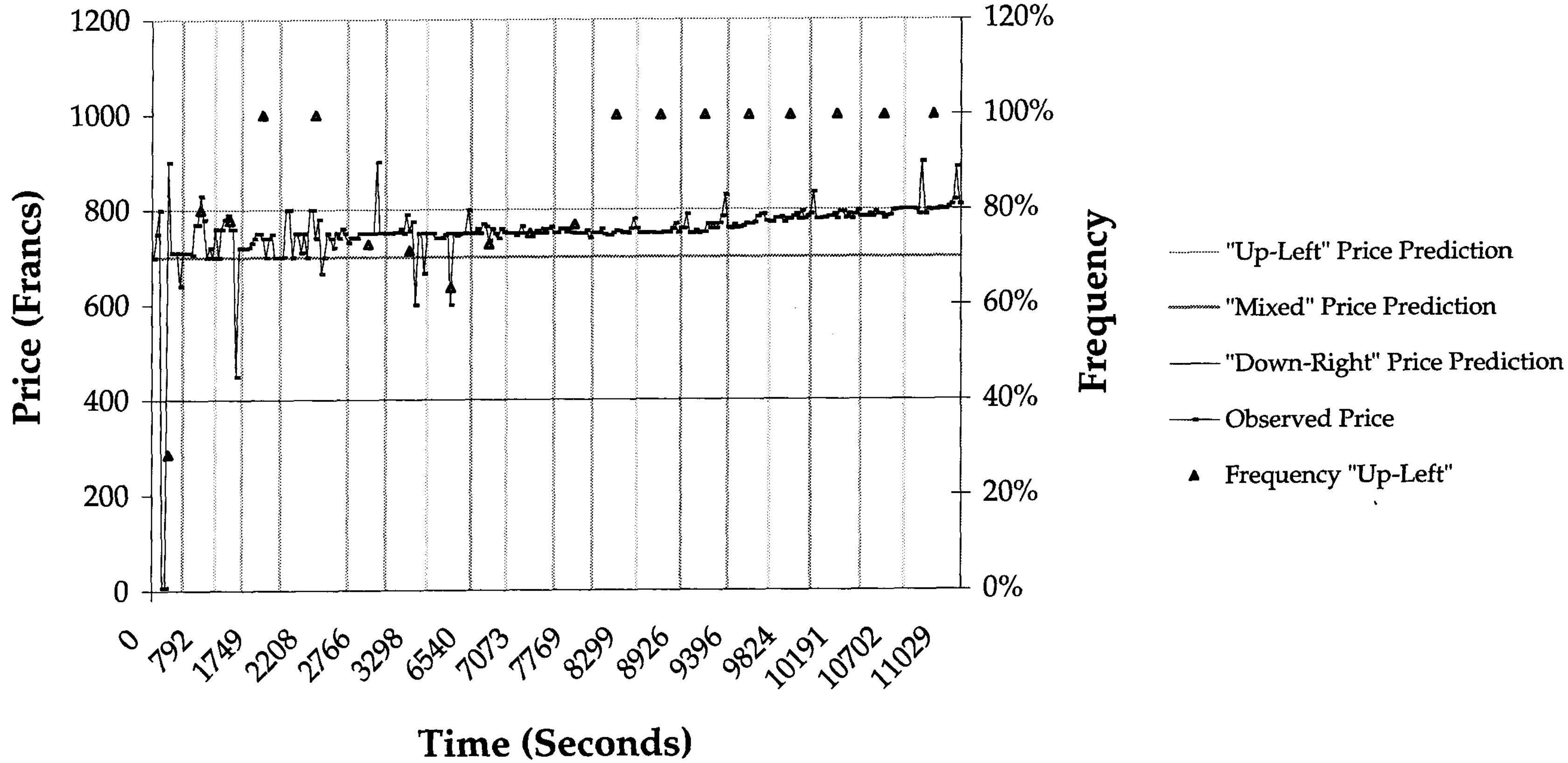


Figure 7

Prices and the Sum of Frequencies (p +q) Converge to Joint Rational-Expectations Equilbria

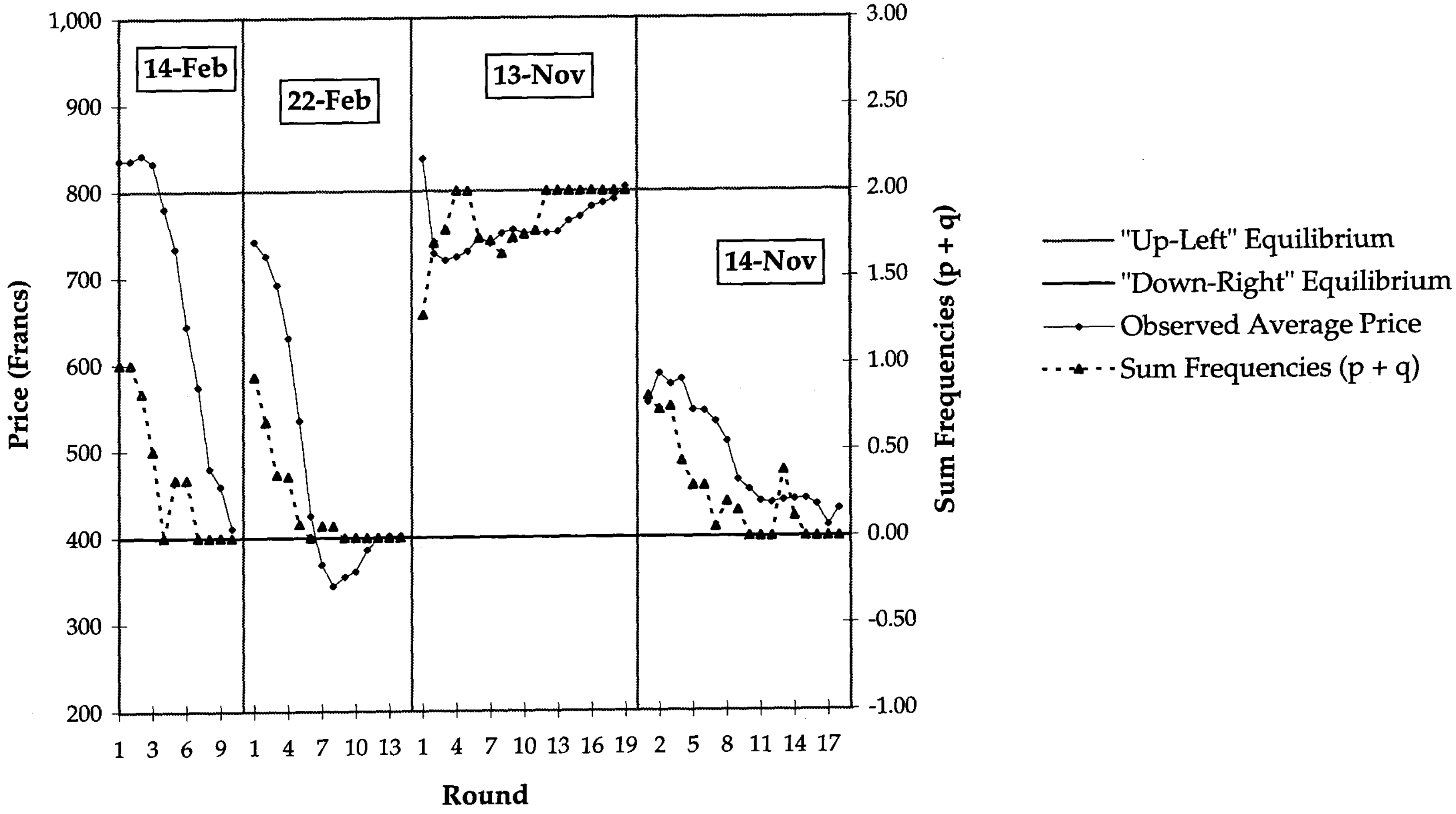
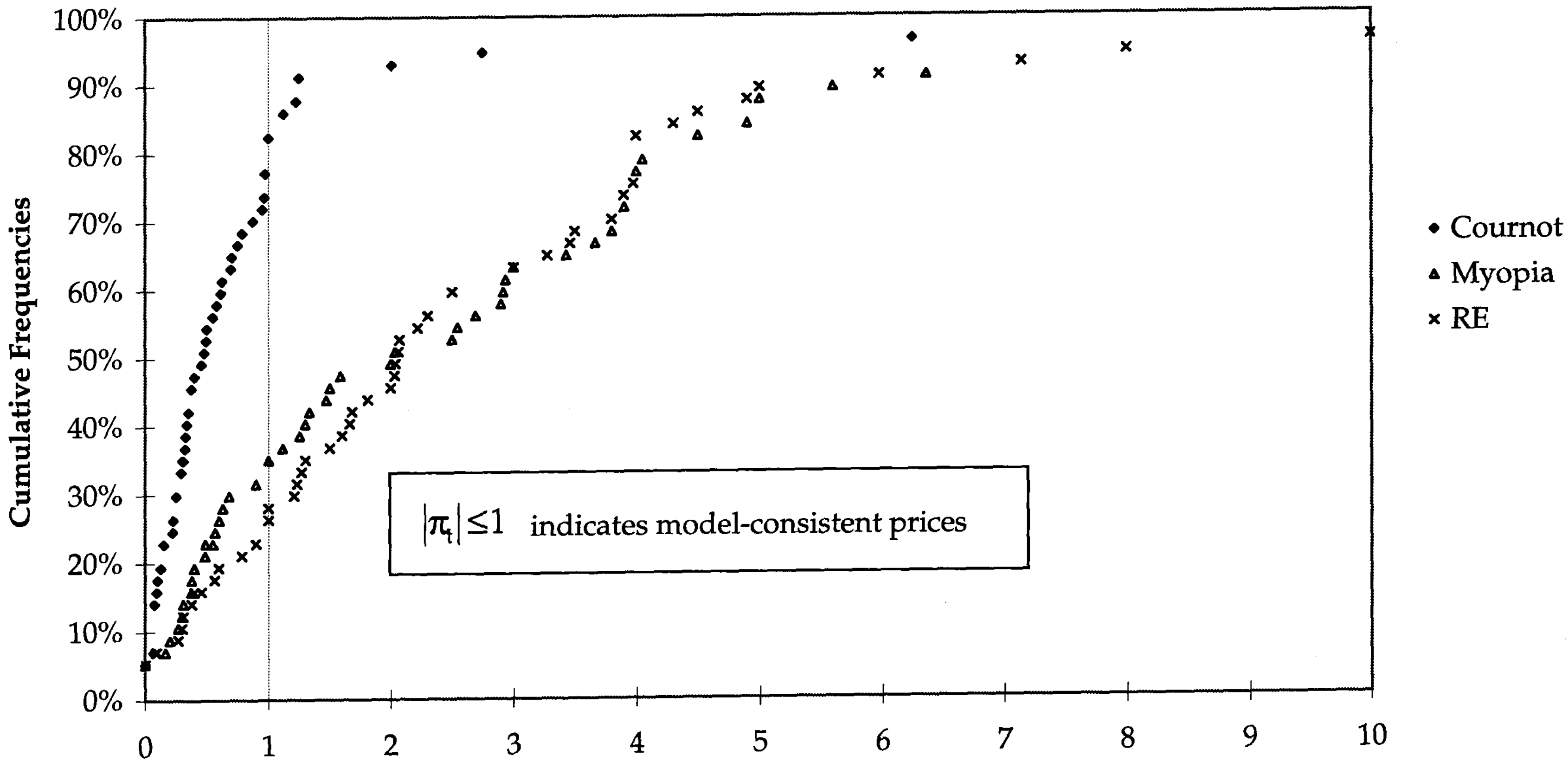


Figure 8

The Cournot process characterizes the evolution of prices with more success than the Myopia and RE processes



$|\pi_t| = \left| \frac{P_t - \hat{P}_t}{(\overline{P}_t - \underline{P}_t)/2} \right|$ **= a measure of deviation of prices each round from model-consistent prices**

Summary

The thesis is composed of four essays, all of which relate to the economics of contracting. Three of the essays discuss and analyze contracting practices that were common in medieval maritime commerce of the Mediterranean World. These contracting practices addressed the problem of mobilizing venture capital in the face of both daunting physical and commercial hazards. The focus here is on how contracting practices were differentially employed to deal with the most difficult of commercial hazards, the hazards posed by agency. Specifically, investments in commercial ventures involved more than subjecting capital and personnel to physical and commercial hazards. Rather, commercial ventures engaged trading agents in agency relationships with venture capitalists, and it was within the scope of these relationships that agents gained access to seemingly abundant opportunities to cheat their investors. The essays identify agency hazards and articulate contractual mechanisms that neutralize the hazards.

The fourth essay constitutes a first step toward bringing the power of experimentation to bear on matters of contracting. Although contracting problems can be very complex – and therefore difficult to subject to controlled experimentation – the experimental design featured in the research captures a particular feature of contracting that has not been subjected to explicit

examination in previous research. Contracts are often sold in markets. Contractors, for example, might distribute procurement contracts to producers via auction mechanisms. Two processes become linked, a market process through which parties to exchange become joined in contract, and a performance process through which exchange between the contracting parties subsequently unfolds. While economic theory and experimentation has much to say about market processes and performance processes separately, they have little to say about how such processes interact. Are equilibria in the two processes systematically linked (if at all)? Do the dynamic processes from which equilibria in the two processes confound or promote the *joint* selection of equilibria in the entire two-stage process? The research presented here considers these questions within the context of a particular market institution and a particular performance process.

Contracting in the Mediterranean World

Coming into the 15th century, trade firms started to dominate the flows of trade goods through and beyond the Mediterranean, but over most of the preceding millenium trade was organized via pair-wise contracts that would engage an investor and a trading agent in the conduct of single round-trip trade ventures. Typically, an investor would advance financing to a trading agent would venture shipboard to foreign ports in and around the Mediterranean. Agents would trade in such commodities as grain and spices in Egypt, in alum and wine in the

Aegean, and in cotton and spices in Syria. In the 14th century a spice trade through the Black Sea also developed, and from Central Asia and Central Europe a steady slave trade flowed into the Mediterranean. In the later Middle Ages an increasing flow of processed goods flowed from Italy to Muslim territories and beyond the Mediterranean to Northern Europe. Trading agents would return with goods acquired abroad, and investors and agents would arrange the re-sale of these goods in local markets are would re-export them to other European markets. They would share the proceeds generated by the ventures according to the terms of their contracts.

Contracts between investors and trading agents generally came in two forms: loans contracts by which agents would guarantee to investors a fixed payoff, and sharing contracts by which investors and agents would share fixed proportions of the profit (if any) generated by the trade venture. By the late Middle Ages in Venice investing in commercial ventures via loan contracts or sharing contracts was common, but pair-wise contracting and most notably contracting via sharing contracts has a history that precedes the emergence of the Italian city-states. Trade itself only experienced a resurgence during the "Commercial Revolution" that succeeded the years of Moslem invasions in Europe. Both sharing contracts and maritime loans have roots in Byzantine and Roman commerce.

The focus of the first essay, "Stopping Agents from Cheating and Venture Capital Contracting," is on the strategic features of loan contracts and sharing contracts. Sharing contracts have attracted much attention in earlier economic history literature. Some economic historians have suggested that sharing contracts promoted investment in trade ventures by permitting investors to share commercial risk. Other, Marxist historians have suggested that sharing contracts permitted investors to impose some share of the commercial risk on trading agents. Either way, the strategic features of sharing contracts deserve some attention. In particular, under sharing contracts the payoffs to investors are functions of agents reports of transactions conducted in foreign ports. These are transactions that investors can neither observe nor can verify *ex post.* Accordingly, agents could very well misrepresent the results of transactions or could even report completely fictitious transactions all with the purpose of under-reporting to investors the actual returns that obtained.

Given the agency hazard that attends sharing contracts, loan contracts would seem to dominate. Loan contracts do not permit agents to share risk with investors, but such contracts do neutralize the ability of agents to cheat investors by misrepresenting transactions. Nonetheless, contract data indicate that sharing contracts were abundantly employed. What the research presented here indicates, however, is that in the conduct of certain ventures investors could expect to compare agents' reports of transactions, and it is precisely for these types of ventures that investors contract the services of agents via sharing contracts. Specifically, investors could compare agents' performances in ventures that involved trade along established trade routes in commonly traded commodities. The trade between Venice and Egypt, for example, typically involved trade in spices and grain, and this trade attracted state sponsorship. Annually, the Venetian Republic organized a convoy that would sail to the Eastern Mediterranean at the same time of each year. Agents participating in the Egyptian trade would be trading in commonly traded commodities in the presence of other agents trading in these same goods. Investors in Venice could expect to extract several independent reports on the performance of commodities prices (and therefore on the performance of transactions). Agents providing conspicuously divergent (and inferior) reports could be identified.

The second essay on Venetian trade in the years 1190 – 1220 discusses contract data indicate that sharing contracts, known in Venice as *colleganza*, comprise an overwhelming proportion of the contracts that involved trade conducted in the presence of other agents. Loan contracts, on the other hand, tended to be applied to those ventures that were more likely to involve trade along less well-frequented routes. Along these routes investors would not be able to extract multiple, independent reports of the performance of commodities prices and therefore would not be able to apply the comparative performance mechanism.

The third essay on trade organized in Venetian Crete in the years 1303-1351 establishes patterns in a data set of 779 maritime. Although the data do not always distinguish idiosyncratic trade ventures from ventures in commonly traded commodities along commonly attended trade routes, the data do support construction of a number of devices that permit differentiation of the various trade ventures. The re-emergence of trade with Turkish emirates in the late 1320's, for example, provides and opportunity to examine the response of investors and trading via their selection of modes of contracting to new opportunities. As interpreted here, the trade with Turkish emirates was exotic. Unlike the Egyptian trade, the Turkish trade route was not well-traveled, and the commercial prospects were uncertain. Accordingly, idiosyncratic transactions could be abundantly secured.

The research indicates that those investors who were more likely to be informed about opportunities for idiosyncratic trades were more likely to secure the services of trading agents via loan contracts. The other ventures that made up the Turkish trade were predominantly arranged by sharing contracts until the emergence of the Black Death in 1347 in the Aegean. As interpreted in the research, the emergence of plague constituted a severe negative shock to the informational structure of the economy. Traders and investors lost informational contacts to plague, and commercial prospects in regions affected by plague become more uncertain. Moreover, those investors who were formerly better informed lost their informational advantage, and they reverted to modes of contracting employed by those investors who were (and remained) uninformed about idiosyncratic commercial opportunities.

The Experimental Research

The experimental research matches a market process to a "performance" process. Although any market mechanism drawn from a broad range of possible mechanisms could have been employed, the experimental design featured a double-auction, a mechanism that researchers have routinely featured in other types of experiments. Within the double-auction experimental subjects would buy and sell "units" that constituted the right to participate in the follow-on performance stage. The experimental design represents the performance stage as a game – specifically, the design features a static two-player game known in the game theory literature as a "Battle-of-the-Sexes" (BOS). The BOS does not constitute a general model of the structure of strategic interactions that attend contracting problems, but it does present some interesting questions for the research.

Operationalizing the double-auction involved assigning marginal cost schedules and marginal benefit schedules to experimental subjects. These schedules indicated the marginal costs and benefits that subjects would bear for each "unit" a unit being the right to participate in a single play of the BOS against an anonymous opponent. Aggregating these schedules would generate an upward sloping supply schedule and a downward sloping demand schedule. Experimental subjects bought and sold rights to participate in the BOS by posting prices over a computer network. Trading lasted five minutes, and after the close of trading subjects determined their action choices for each of the units for which they had acquired the right to play. Buyers of units assumed the right to choose one particular set of actions available in the BOS, and sellers of units assumed the right to choose actions from the opposing set of available actions. Buyers' action choices were subsequently matched randomly and anonymously to sellers' action choices. The pairs of buyers' and sellers' action choices identified payoffs to both buyers and sellers in the BOS, and these payoffs were reported to those experimental subjects who participated in the BOS games. After subjects accounted their payoffs from the entire two-stage market and game process, the two-stage process was repeated. In a single experimental session, for example, the two-stage process was repeated as many as 19 times.

One way of crafting equilibrium predictions of the entire two-stage process is to map equilibria from the BOS into the market process and to identify corresponding competitive equilibria. While this is easy to do, it is not obvious that the joint equilibrium predictions will bear out, and is less obvious what dynamic processes would generate the convergence to such equilibria. The research indicates, however, that the joint equilibrium predictions characterize the outcomes that obtain after several rounds of repetition, and the research makes some progress in characterizing the dynamic process by which the equilibrium outcomes emerge. Most notably, there is evidence that suggests that experimental subjects demonstrate some strategic sophistication. They anticipate outcomes in the BOS, they determine their best responses in the BOS to the outcomes they anticipate, and they factor both the anticipated outcomes and their best responses into their pricing decisions. Although the BOS features two pure-strategy Nash equilibria, expectations market-wide become aligned with one or the other of them within only a few rounds of interaction. Once expectations become aligned, prices start to converge to levels consistent with the anticipated outcome. In the end, both outcomes in the BOS and prices in the market converge.

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