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Laboratory Experiments in Economics: The Implications of Posted-Price Institutions

CHARLES R. PLOTT

In recent years a methodology for performing laboratory experiments in economics has been developed. The object of the methodology is to integrate clearly motivated but largely subjectively determined human decisions with the organizational features of markets. The nature of the incentive system and the use of market organization as an independent variable are described. Initial results of basic research that involved assessment of the effects of the "posted-price" institution demonstrated that the effect of the institution is to raise prices and lower market efficiency. The existence of such effects and the close proximity of the laboratory posted-price institution to the rate-posting institution required by the government in several industries has led to a series of policy-related experiments. The results have also led to more basic research efforts on seemingly unrelated topics.

EXPERIMENTAL RESEARCH IN ECONOMICS HAS BEEN RAPIDly expanding for several years. The number of papers published annually has increased from two or three in the 1960's to over 70. Laboratory experimental research in economics was being done at no more than one U.S. university at a given time in the early 1970's, while more than 20 universities are involved now. Major topics have expanded from one area of applied game theory (the oligopoly problem) to include almost every subfield of economics and some of the management sciences. Research that was purely basic a few years ago has already had policy applications.

In this article I examine the experimental treatment of one topic that has contributed to the increased interest in the methods: the implications of posted-price institutions. The experimental methodology is explained and then the results and the applications are summarized.

Traditionally, economics has not enjoyed the benefits of an experimental methodology. Naturally occurring economic processes are so complex that complete experimental control with multiple replications defies the imagination. Yet, in spite of that seemingly insurmountable obstacle, the methodological posture taken by experimentalists is straightforward. General theories intended for application in complex markets should be expected to work when applied to the simple special cases. Such theories that do not work in the special cases should be discarded or modified. In order to create the necessary simple special cases, significant financial incentives are used to create markets in which buying and selling take place and in which people actually keep the profits they make. General theories

Charles R. Plott is a professor of economics, California Institute of Technology, Pasadena, CA 91125.

about the development of prices and the pattern of trading and profits are tested. It is hoped that the experience gained from the operation of the simple markets will lead to a deeper understanding about the behavior of complex systems, for which experimental testing is impractical. The laboratory data can be used to screen models that are ultimately to be applied to much more complicated situations.

Much current research can be traced to two discoveries about the behavior of laboratory markets. The first discovery, which evolved from research in the late 1950's and early 1960's, was that a market equilibrium model could be used to predict and explain several important behavioral features of laboratory markets. One implication of the discovery and subsequent research is that reliable principles of market behavior exist. The second discovery was that the posted-price form of market organization has an influence on both prices and market efficiency. This second discovery provides an important empirical connection between market organization and performance. While connections between market organization and performance were demonstrated experimentally many years ago (*1*), the posted-price institution is different by virtue of its relation to the tools that are used in market regulation and policy.

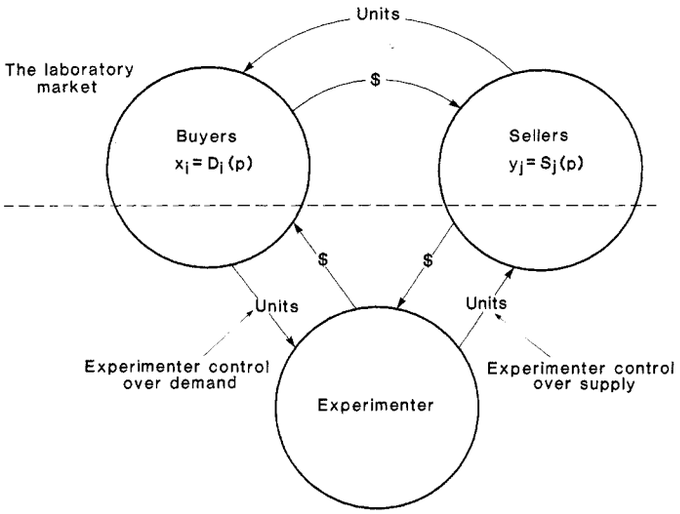

Fig. 1. Structure of incentives in a laboratory market. x_i, quantity demanded by buyer i; y_j, quantity supplied by seller j; and p, market price.

The Creation of a Market

There are substantial differences among laboratory markets, but similar procedures are used to create them all. Laboratory markets can differ in the number of people participating and the relative market shares of participants. Some markets are influenced by random events, with information about those events differing across participants, while others have no uncertainties. Market organizations can differ, as do the posted-price markets and oral double auction markets discussed in the next section. In spite of many differences, the basic approach is the same.

Subjects are typically college students, but subject pools can range from high school students to employed adults. On occasion an effort is made to use only subjects from some particular industry. The differences among subject pools have not been sufficient to motivate intensive testing of different pools.

In simple experiments, subjects are randomly partitioned into a set of buyers and a set of sellers. Instructions are read and subjects are either tested on the market rules and the financial incentives or given a practice session or both. The parameters for economic models that predict market behavior are sensitive to the exact nature of incentives. While much latitude is left for subjectively determined individual decisions, care is taken to avoid incentives not precisely controlled by the experimenter. The commodity traded is never given a name, and references to specific commodities or markets are avoided. If subjects neglect the controlled incentives in order to act as they imagine they or someone else in some particular market might act, the control necessary for testing quantitative models is lost.

Figure 1 identifies the incentives and controls that are common across experiments. The incentives are profits that the subjects keep. Buyers in a market purchase units from sellers by paying real dollars for them. The buyer then resells units acquired in the market to the experimenter at the end of a trading period or trading day. The difference between what a buyer pays for units in the market and what the buyer receives when redeeming them with the experimenter are the buyer's profits. This profit potential is the only reward or incentive that the buyer is given. In formal terms each buyer, i, is given a redemption value schedule, $R_i(x_i)$. This function identifies the gross income the subject buyer will receive from the experimenter if the buyer acquires x_i units in the market, and can be called an induced value (*2*). The net income that the buyer keeps is the difference between $R_i(x_i)$ and what the buyer paid to sellers. The theory of competitive demand maintains that the function $R_i(x_i)$ can be transformed into a new function, called the individual demand function (*3*)

$$x_i = D_i(p) \tag{1}$$

The function can be interpreted as the quantity that i would purchase if facing a fixed price p at which any quantity desired can be obtained. Equation 1 is a theoretical construction derived from theory as applied to the incentives the subject is known to have. Behavior could be something very different.

Sellers are given cost schedules $C_j(y_j)$ that identify the amount that seller j must pay the experimenter should he or she sell y_j units to buyers. The profit kept by the seller is the difference between the receipts the seller gets from selling units to the buyers and the cost of those units. The potential profit is the total incentive provided sellers. This idea is also shown by Fig. 1. Application of the theory of competitive supply (*4*) yields individual supply functions

$$y_j = S_j(p) \tag{2}$$

The function can be interpreted as the quantity that i would sell if a constant market price p existed at which i could sell any quantity desired. Again, the theoretical nature of Eq. 2 should be made clear. The function is postulated before any behavior of subject j is observed.

The law of supply and demand can now be applied. According to the model, market price will be that which equates market demand (the sum of individual demands) to market supply (the sum of individual supplies)

$$\sum_i D_i(p) = \sum_j S_j(p) \tag{3}$$

That is, the solution to Eq. 3, $\hat{p}$, is the predicted equilibrium price. Market volume is predicted to be the quantity $\Sigma_j D_i(\hat{p})$. Efficiency of a market in a cost-benefit analysis sense is maximized by a pattern of trades that maximizes the total earnings of all participants. Market efficiency, as predicted by the model, is 100 percent.

The efficiency feature, while easy to understand from the theory, is nevertheless striking. According to the model, the total earnings of participants will be maximized even though (i) each individual knows only his or her own incentive functions and not those of

others, (ii) individual discussions about incentive functions are precluded by the rules, and (iii) subjects know nothing of the theory and probably could not solve the relevant optimization problems even if all information were available to them. The theory suggests that the efficiency levels will be attained as a result of decentralized actions taken by individuals who are presumably acting in their own self-interest. The idea is a version of Adam Smith's invisible hand.

The markets are open for a fixed period. Trading takes place and usually a number of contracts are made. The market is closed and profits are calculated. The market is then reopened for the next period with traders operating from the schedules relevant for that period. Frequently the schedules remain unchanged for a number of periods. The price patterns, income, and efficiency levels can be compared with those predicted by the model.

Market Organization

The model as outlined above makes no explicit reference to market organization. However, from its inception the theory has been evolving to capture the potential importance of organization. There are many different types of markets. In the English auction, with which most Americans are familiar, prices are bid up and the item is awarded to the last (highest) bidder at a price equal to the bid. By contrast, the Dutch flower auction is almost the inverse. A "price clock" is initially set at a very high price. The price falls with the hand of the clock until someone stops the descent. Sealed bid auctions are yet another common type of market. Bids are usually tendered privately and opened simultaneously, but the method of determining price differs according to the market organization. According to the first-price auction, the item goes to the highest bidder at the price bid. By contrast, in a second-price auction the high bidder is awarded the item, but the price paid by the high bidder is the price bid by the second highest bidder.

When faced with such alternative ways to organize a market, one may ask which should be chosen if one is interested in the profits of the seller? Or, which should be chosen from the point of view of social policies? What difference does it make in terms of prices and efficiency? Questions such as these motivate experimental research.

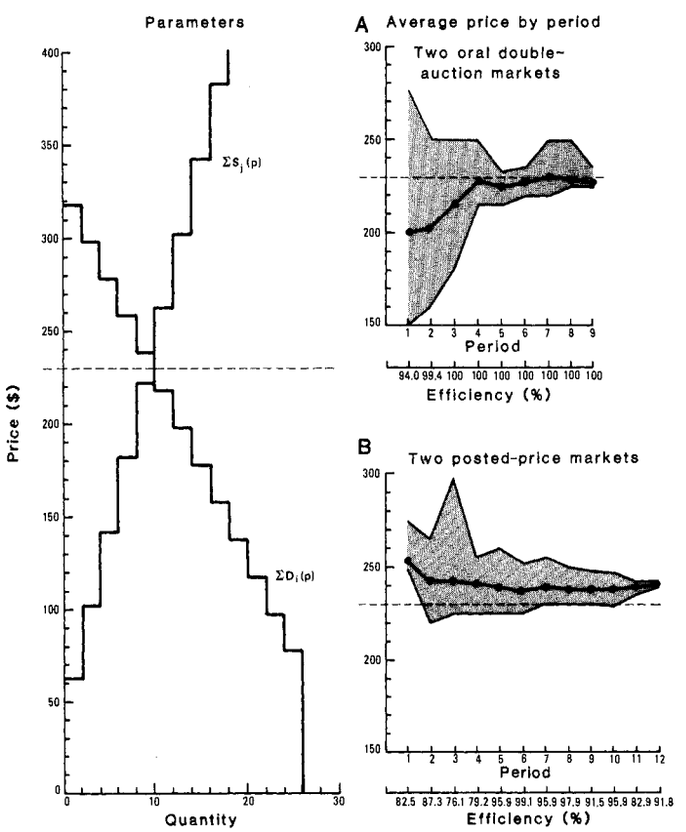

Fig. 2. Parameters and average price per period for oral double auction and posted-price markets.

The Oral Double Auction and Posted Prices

In the oral double auction both sides are active. Buyers verbally tender bids to buy one unit of the commodity and sellers verbally tender offers to sell. The outstanding (last) bid to buy and offer to sell are publicly displayed. A buyer is free to make a higher bid at any time, thereby replacing the outstanding bid, or to accept the outstanding offer to sell. Similarly, any seller is free to tender a lower offer than the outstanding offer or to accept the outstanding bid. If the outstanding bid or offer is accepted, the person who tendered the bid or offer and the person accepting have a binding contract at the specified price for one unit. After a contract the floor is open for new bids and offers of any amount. The dynamics of the market are characterized by many bids and offers converging to a formal contract. Contract prices normally differ from unit to unit.

Oral double auction market experiments are usually characterized by considerable activity as subjects yell their bids or offers to the auctioneer. The auctioneer records the outstanding bids or offers on a chalkboard, where they remain until accepted or replaced by better bids or offers from other subjects. Recent computerization of this type of market has removed much of the noise, but the fast pace remains.

The posted-price institution resembles a rate bureau more than an auction. The market is not so filled with activity as is the oral double auction. In a posted offer (as opposed to a posted bid) market, each seller submits a price, presumably in a sealed bid fashion without benefit of consultation with other sellers. All prices are publicly posted, typically on a chalkboard, and cannot be changed by the seller for some fixed period. Buyers first approach the lowest priced seller, who can sell only at the posted price and who sells units until he wishes to sell no more at that price. As the low price sellers run out of stock, buyers move to the higher priced sellers. Since buyers will seek the low price advantages of the first buyer, a random device is usually applied to determine orderly access. After all buyers have had an opportunity to purchase, the period ends and sellers make pricing decisions for the next period.

The results of two experimental oral double auction markets are shown in Fig. 2A and the results of two experimental posted offer markets are shown in Fig. 2B. Each market consisted of four buyers and four sellers. The graph in the left of the figure is the market supply and demand model constructed from the parameters. The parameters of all markets were the same, but the participants differed. In Fig. 2A the average price during the first period is shown as the first dot and the average price during the second period is shown as the second dot. The price range during the period is the shaded area. Similar data are shown for the two posted offer markets (Fig. 2B). The results are typical of data that have been generated by many replications.

Each market consisted of a series of market periods or trading days. Each period lasted about 5 minutes during which trading took place. After the profits were calculated, the experience was replicated with each participant facing exactly the same incentives as in the beginning of the first period. Each market lasted about ten periods.

Market Performance

Two aspects of the results are of interest. First, with repetition under fixed conditions, the market prices are near those predicted by the model, and efficiencies approach 90 to 100 percent. Second, prices tend to be higher for posted-price markets than for oral double auctions (about 10¢ higher in these markets) and efficiencies are lower. The efficiencies for the posted-price markets are in the low 90's, compared to 100 percent for the oral double auction markets.

The implications of the first aspect, the equilibrating property, should be emphasized. As can be seen from the figures, the simple supply and demand model works reasonably well under both institutions, in the sense that other widely held beliefs can be dismissed in favor of this model. For example, a strictly held labor theory of value can be dismissed as being applicable to these markets. Labor had nothing to do with the development of prices, so price formation in these markets is governed by different principles. Particular personalities or other psychological characteristics do not seem to be necessary for the price convergence, except to the extent that they are operative in allowing people to read instructions, calculate profits, and so forth. Collusion does not automatically develop among sellers, even though a harmony of interest in keeping prices high is immediately apparent to all. Experiments have been conducted with a large and variable subject pool; major differences among subjects have not been detected to date.

The key to the price formation process is captured by the simple theory of supply and demand, but generalizations should be offered with caution. Complicated naturally occurring markets can be characterized by a host of features not present in the laboratory markets. As such features become recognized, the stage is set for new experiments that determine their effects.

The posted-price institution induces an upward pressure on prices. It also exerts a downward pressure on efficiency, even though this is not readily apparent in the market (Fig. 2). This result signals a potential delicacy in the market's performance by showing how it can be influenced by subtle features of organization.

The relative effect of the posted prices was first demonstrated by Plott and Smith (*5*) in comparison experiments. The phenomenon had been observed earlier by Williams (*6*) who believed that it was due to the fact that individuals could trade multiple units. Cook and Veendorp (*7*) also observed the phenomenon and attributed it to asymmetries in information. Even now no theory about the influence of the posted-price institution has been published to my knowledge, but the effect has persisted under a variety of parametric situations. Extensive replications were made by Ketcham *et al.* (*8*). Markets with speculators were investigated by Hoffman and Plott (*9*). Markets with a relatively large number of sellers were studied by Hong and Plott (*10*). Mestelman *et al.* (*11*) studied markets in which sellers acquired and paid for units before sale. A variety of supply and demand configurations and asymmetries were studied by Davis and Williams (*12*). The higher prices and lower efficiencies of posted-price markets, relative to the oral double auctions, have held up so far.

Further Developments

What began as an interesting basic research result stimulated other research questions and also found its way into policy applications. Figure 3 shows a flow chart of the research and applications that have followed from the initial study on the posted-price institution by Plott and Smith (*5*). The first set of applications led to an understanding of the institution as a facilitating device that helped one side of a market gain an advantage over the other. A second line of investigation was stimulated by the recognition that the institution might be used as a means of control of monopoly. That is, the posted bid institution might be used as a decentralized method that helps one side (customers) overcome an inherent advantage of the other side (a monopoly). A third line of investigation that developed from the other two rested on the recognition that the institution helps overcome a classic problem in public finance, the free rider problem. Finally, a recognition that the posted-price institution has such an independent effect on behavior has led to a reinterpretation of many experiments conducted in the 1960's (*13*).

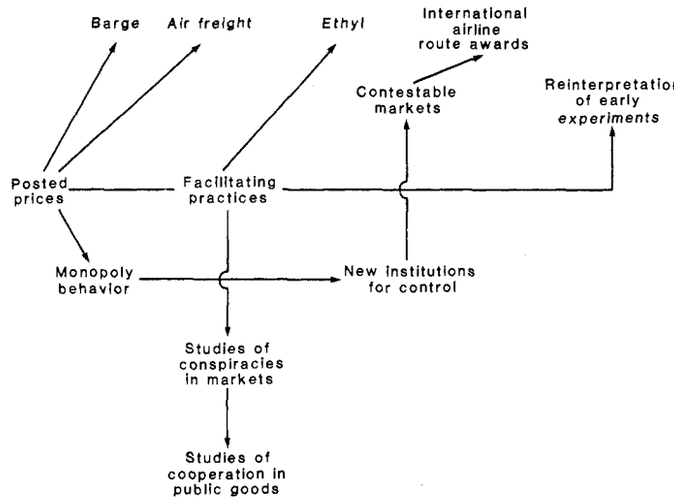

Fig. 3. Connections among research topics.

Applications

Soon after the discovery of the posted-price phenomenon, the Department of Transportation became concerned about a proposal to require freight rate posting for inland-water barge traffic carrying dry bulk. The railroads, which compete with the barges for dry bulk traffic, claimed that freight rate posting would improve the performance of the barge industry. Sellers would be free to post whatever prices desired with the Interstate Commerce Commission. Such price postings would be publicly available and would dictate the terms of all sales. Any seller would be free to change its price if the ICC received a 30-day advance notice. The railroads argued that public information on prices would make prices more competitive and protect small barge owners from large barge owners, who were allegedly making secret price concessions. The Hong and Plott study (*10*) was first commissioned to study the claims of the railroads. A laboratory industry was created that reflected the prominent statistics for an appropriate section of the Mississippi River. The demand elasticities, supply elasticities, relative market sizes of buyers and sellers, demand shifts, and so on were those of the industry. The absolute market sizes and the time frame were scaled down dramatically to accommodate existing laboratory technology. Experiments were conducted with the posted-price institution as proposed by the railroads and with a market organization (privately negotiated prices) that is similar to the organization that had naturally evolved.

The results of these experiments were the opposite of those that would be predicted by the railroad industry's analysis. Contrary to the railroads' claims, the posted-price institutions caused prices to go up, efficiency to go down, and the small participants to be disadvan-

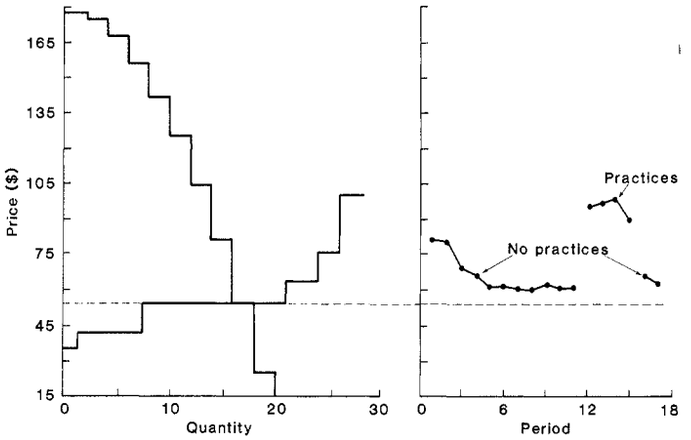

Fig. 4. Parameters and average price per period.

taged. The experimental results raised questions about the railroad industry's analysis and placed a burden on those who advocated price posting to explain why the policy they were proposing had such deleterious effects when examined under laboratory conditions. The proposal was dropped.

Posted-price research was used again in 1979. The air freight forwarding industry posted prices with the Civil Aeronautics Board in a manner similar to that which had been proposed for the barge industry. After deregulation CAB was forced to decide about how the industry was to be organized in the future. Citing the experimental literature on the effects of posted prices, CAB issued a notice of proposed rule making calling for the abolition of the posted-price institution. After having reviewed the response, CAB eliminated all aspects of rate posting. Clearly the experimental work did not provide a scientific basis for a decision about the organization of the industry. However, the experimental results did provide the only source of background data about the potential effects of a policy decision and a presumption about what those effects might be.

The importance of posted-price research took on a new dimension when the Federal Trade Commission noticed a possible relation between posted prices and certain industrial practices that had evolved in the industry that makes lead-based antiknock compounds. The FTC brought action against Ethyl Corporation, E. I. DuPont, Nalco Chemical Company, and PPG Industries for four practices that existed in the industry. The individual contracts of these sellers contained language that obliged sellers to (i) absorb all transportation costs, (ii) meet the lowest price of any competitor or release the buyer from any obligations, (iii) deliver to the buyer at the lowest price received by any other buyer, and (iv) provide the buyer with a 30-day notice of any price change.

One theory of these practices, which is consistent with the FTC complaint, holds that provisions (i) and (iii) eliminate secret price concessions in a manner similar to the way rate posting might do. Condition (ii) reduces the incentive to lower prices by ensuring that price decreases are met immediately by competitors. Condition (iv) acts as a vehicle to coordinate price increases through a policy of announcing a price increase in advance of the 30-day deadline. The price increase is thereby made contingent on a favorable competitor's response before the deadline. The net effect of all these practices, according to the government's theory, would be to raise prices above the supply and demand equilibrium as defined earlier.

The defense advanced a competing theory. Two sellers of about equal size accounted for approximately 70 percent of industrial sales; the other two sellers were also of about equal size. With such a high degree of concentration and the existence of excess capacity, sellers realized that price decreases would stimulate a competitive response. Sellers anticipating this reaction would keep prices high. Industrial structure would account for high prices and profits and not the practices as claimed by the FTC, so the relief sought by the FTC would have no effect.

Experimentation was of interest to the FTC in the context of possible rebuttal evidence. Is it true that industries with a structure and concentration like those of the antiknock compound industry will necessarily maintain prices so high that the practices will have no room for an effect? The "Ethyl" experiments reported by Grether and Plott (*14*) were designed to answer that question. Many market experiments were conducted with laboratory industries that had the same concentration measures and numbers of participants as the industry. Demand and cost elasticities were the same as those thought to characterize the industry. Of course, the actual magnitudes of prices and costs were scaled down to manageable numbers for the laboratory. Figure 4 shows the results for one market that operated without practices for several periods, with the practices for four periods, and without practices for three more periods. The results are typical of the experimental results for several replications that the collective effect of all practices is to increase prices. The magnitude of the effect depends on the baseline practices that one hypothesizes would exist should the FTC have won the case. The claim of the defendants that concentration alone, unaided by practices, unnecessarily fosters collusionlike prices is incorrect.

The nature of the contribution of experimental methods should be made clear. All interesting questions have not been answered, and some of the most interesting might not be answerable with experiments. The question addressed in the Ethyl experiments conducted by Grether and Plott was: Is the general theory offered by the defendants reliable? That question, which is the content of rebuttal testimony, is answerable experimentally. The question not asked was: Do the practices make a difference in the lead-based antiknock compound industry? The latter question was the one posed for the court and could probably not be approached experimentally. The first question is only one step in answering the second. The data were not introduced as rebuttal testimony, so the treatment by the court has not yet been tested (*15*).

The recognition that posted prices constitute a facilitating device has stimulated a basic research effort as opposed to an applied research effort. If posted offers tend to raise prices, perhaps posted bids by buyers could be used to lower prices when buyers face a monopoly seller. The flip side of a facilitating practice might be a tool for control. It depends on whom one wants controlled. This observation by Smith (*16*) led him to ask a more general question. Can institutions and organizations be used to control monopoly pricing?

Figure 5 shows the results of two of Smith's experiments. Both markets have only a single, monopoly seller. When the monopolist must use the oral double auction, prices tend to be lower than when monopolists use posted prices. Such results demonstrate the reasonableness of Smith's question and suggest that the answer is yes.

The Smith research was the first to initiate a laboratory study of monopoly. The results, that the classical monopoly model was not always reliable and that the reliability depended on market organization, set the stage for a series of additional studies of monopoly. The most prominent are those that focus on "contestability theory."

The theory of contestable markets grew from an attempt to find alternatives to the traditional administrative rate-setting process of regulating monopolies (*17*). Competition has traditionally been regarded as being unworkable in certain types of industries in which costs continue to fall with volume. The basic idea of contestability theory is that potential entry together with an organized method of facilitating entry can effectively maintain prices below monopoly

levels even though a single seller necessarily exists. No politicized rate-setting process would be necessary. In effect, sellers post prices and the seller with the lowest posted price supplies the whole market. Because of the importance and complexity of monopoly regulation, the theory has been a subject of substantial interest.

The role of experimental economics has been to supply data where no other source of data exists. Markets purposefully organized along the lines suggested by contestability theory do not exist, and firms in monopolized markets are not likely to offer their markets as field experiments. Relative to the cost of field experiments, the cost of laboratory experimentation is virtually nothing, even with highly rewarded adults as subjects. The cost of a field experiment would be measured in tens of millions of dollars as opposed to thousands. The laboratory methods are also forgiving in the sense that many alternative ideas can be probed and "debugged" before any large data-gathering effort is made. The first experiments with contestable markets (*18*) provided clear evidence that the theory could work. Subsequent basic research (*19*) has centered on special cases for which competing theories suggest that contestability theory will not work. Those basic research efforts have led to modifications of the theory and to a deeper understanding of the types of actual market organizations that help the theory work. The experimental work and organizational suggestions found in that research formed the basis of a method of awarding monopolized international airline routes (*20*). Such routes are monopolies by virtue of bilateral agreements with other countries, and the problem is to decide which carrier gets the right to operate on the route.

The third line of investigation that was stimulated by posted-price research takes a surprising turn toward issues in a different area of economics—public finance. The connections with this new line begin with a result that demonstrates the difficulty experienced by market conspiracies when operating in an oral double auction. Conspiracies are not especially effective in an oral double auction. In view of Smith's (*16*) results on the difficulties faced by a monopolist operating in such markets, it is not really surprising that a group attempting to behave like a monopolist would also have troubles. Isaac *et al.* (*21*) investigated the behavior of conspiracies when the market was organized as a posted offer as opposed to the oral double auction. The results demonstrate that, under the posted offer institution, conspiracies tend to be successful. The posted offer institution together with conspiracy is an effective way to maintain high prices.

In the eyes of a theoretician the problem faced by conspirators is similar to the problem faced by the public in the areas of pollution, environmental degradation, defense, and other common efforts (public goods). Oligopolists have a common interest in maintaining high prices. The problem is that each seller would prefer that other sellers contribute to their "common good" by maintaining high prices while the seller in question charges a slightly lower price and captures as much of the market as is desired. Each seller has the same motivation to "free ride" on the decisions of others. The net result is that, without facilitating practices, the common good is not easily attained. Similarly, in the case of environmental degradation each individual has an incentive to allow others to carry the burden of a common goal of cleaning up the environment and the expense of "proper" disposal of effluents. By free riding on the efforts of others, the individual sees an opportunity to enjoy the benefits of the common goal while not accruing any of the costs. Each individual is in the same strategic position and, as a result, common purposes frequently do not get accomplished. The problem is well documented experimentally. Even when people are fully cognizant of the problem, the collective goods tend not to be supplied.

If conspiracy and the facilitating practice of posted prices can help solve the free rider problem faced by conspirators, perhaps similar organization might help solve the free rider problem in other areas of collective action. The observation led Isaac and Walker (*22*) to study a process that combined a public meeting in which face-to-face conversations could take place with a method of making nonbinding a private commitment to contribute toward a common goal. In the technical jargon, they studied this combined mechanism as a means of financing a public good.

The results are promising in that the mechanism has greater efficiency properties than any studied to date. For decades the free rider problem was believed to have no solution at all—in principle. For centuries arguments similar to modern theories have used free rider arguments to justify the coercive and taxing powers of government. The phenomenon has deep philosophical roots and is at the foundation of many theories of government. From a basic research and theoretical perspective, the results of Isaac and Walker will force a reconsideration of some widely held beliefs.

Closing Remarks

Studies of the posted-price institution demonstrate how basic research motivated by scientific curiosity can lead to many unanticipated applications. Posted prices tend to induce price contracts above the competitive equilibrium and tend to induce market inefficiencies. The implications are direct for rate-posting regulatory arrangements. Indirectly, the phenomenon has implications for antitrust and for theories of facilitating practices. The indirect consequences have stimulated further experimental work on the public goods problem in public finance and political science. Perhaps most important, the research demonstrates that laboratory

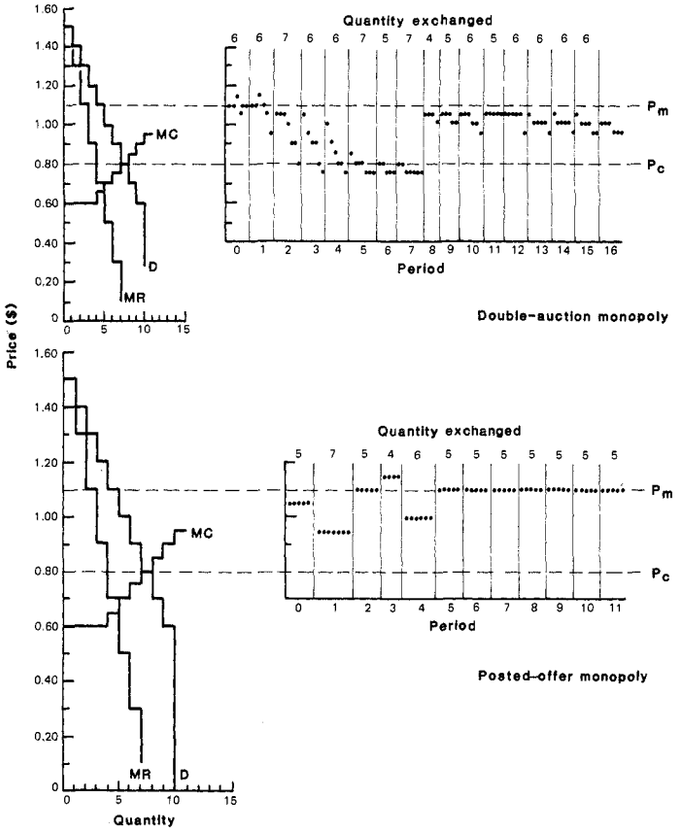

Fig. 5. Parameters and contract prices in the order of occurrence for two markets (*16*). P_m, monopoly price; P_c, competitive price; *MC*, marginal cost; *D*, market demand function; and *MR*, marginal revenue.

experimental methods can be used in economics for basic, applied, and policy research. Such a demonstration presents a real challenge to the commonly held belief that economics is not a laboratory science as a matter of principle.

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Research Articles

Delay of Disease Development in Transgenic Plants That Express the Tobacco Mosaic Virus Coat Protein Gene

PATRICIA POWELL ABEL, RICHARD S. NELSON, BARUN DE, NANCY HOFFMANN, STEPHEN G. ROGERS, ROBERT T. FRALEY, ROGER N. BEACHY

A chimeric gene containing a cloned cDNA of the coat protein (CP) gene of tobacco mosaic virus (TMV) was introduced into tobacco cells on a Ti plasmid of *Agrobacterium tumefaciens* from which tumor inducing genes had been removed. Plants regenerated from transformed cells expressed TMV mRNA and CP as a nuclear trait. Seedlings from self-fertilized transgenic plants were inoculated with TMV and observed for development of disease symptoms. The seedlings that expressed the CP gene were delayed in symptom development and 10 to 60 percent of the transgenic plants failed to develop symptoms for the duration of the experiments. Increasing the concentration of TMV in the inoculum shortened the delay in appearance of symptoms. The results of these experiments indicate that plants can be genetically transformed for resistance to virus disease development.

FOR A NUMBER OF YEARS, AGRICULTURALISTS HAVE INOCULATED plants with mild strains of viruses or viroids to prevent more virulent strains from infecting the plant and causing severe disease symptoms. This practice, referred to as cross-protection, has been used to reduce yield losses in crops such as tomatoes, potatoes, and citrus, due to tomato mosaic virus (TMV), potato spindle tuber viroid, and citrus tristeza virus, respectively (*1*). In addition to cross-protection, there are several other types of plant resistance responses to pathogens. These responses are often nonspecific and have been categorized as induced resistance. Extensive discussions on the nature and utility of cross-protection and induced resistance have been presented (*2–4*). Successful cross-protection is most often judged by the ability of the first virus to suppress or delay disease symptoms caused by the superinfecting (challenge) virus. In some cases replication of the superinfecting virus is suppressed (*5*). In most cases symptoms are suppressed or delayed for a period of time, after which the severe strain overcomes the protection, and symptoms develop (*6*).

A number of models have been proposed to explain cross-protection. Gibbs (*7*) suggested that replication of the inducing virus depletes the host cell of a component needed for replication of the challenger. Another hypothesis proposes that capsid protein

P. P. Abel is a graduate student, R. S. Nelson is a postdoctoral associate, and R. N. Beachy is a professor in the Department of Biology, Washington University, St. Louis, MO 63130. N. Hoffmann is a research assistant and S. G. Rogers and R. T. Fraley are research scientists at Monsanto Company, 700 Chesterfield Village Parkway, St. Louis, MO 63107. Barun De is research scientist at the Center for Disease Control, CID-Influenza Branch, 1600 Clifton Road, Atlanta, GA 30333.