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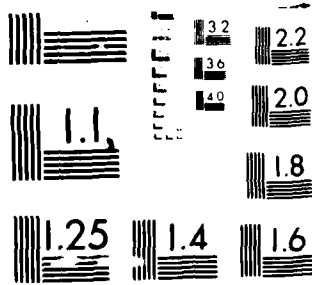
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DETERRENCE IN OLIGOPOLISTIC COMPETITION

by

Robert Wilson

Technical Report No. 506

March 1987

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DETERRENCE IN OLIGOPOLISTIC COMPETITION*

by

Robert Wilson

The purpose of this chapter is to report on theoretical studies of deterrence in the recent economics literature. The role of deterrence in market economies provides, in a familiar mundane context, a partial analogy that can be useful for studying propositions about deterrence in the military and political context. In both contexts, the methodology of game theory has been an important analytical tool; consequently, critical examination of the strengths and weaknesses of this methodology in the economic context may be instructive. Similarly, empirical and experimental studies of deterrence in market settings are easier. On the other hand, the situations in which deterrence is studied in market contexts differ markedly from those envisioned in political contexts. The validity of extrapolating positive propositions from an economic to a political context is therefore doubtful. But, an economic context remains useful for refuting purported generalizations.

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	Dist	Special

In economic contexts, deterrence (broadly construed) is an aspect of the competitive process among firms maneuvering for advantage in an oligopolistic market. Competitive battles for entry into a market, and subsequently for market shares or continued survival, include in modified forms many of the features that arise in military and political contexts. For example, an incumbent firm often has a variety of tactics available that enable it to threaten credibly to retaliate against incursions by opponents that would affect adversely the profitability of the incumbent. Some of the conditions that make a threat both credible and effective have analogs in political situations.

Within the economics literature, studies of oligopolistic competition are mostly included within the field of 'industrial organization', and especially, the topic called the structure of industries, which examines the factors that influence the number, size, and products of firms in a static or cross-sectional view, as well as the dynamics of the competitive interactions among firms within an industry.

Section 1 is an essay on the issues in the field of industrial organization, with particular reference to the topic of deterrence. Section 2 is a brief essay on the game-theoretic methodology that is the chief instrument in analytical studies. Section 3 summarizes the main theoretical conclusions about deterrence in oligopolistic competition that have been derived from simple game-theoretic models. These conclusions are amplified in an Appendix that describes some typical models and results, first for the case that participants have the same

information, and then for the more realistic case that some have private information.

Because the literature relies on institutional features peculiar to market competition among firms, the available case studies and statistical evidence are not described here. They have less transferable value for studies of military deterrence than direct political and military histories. For an admirably realistic and comprehensive examination of oligopolistic competition, I refer the reader to Scherer [1980], who includes generous citations to the evidence. Compendia of recent theoretical results are in Fudenberg and Tirole [1986, 1987], Roberts [1985], Schmalansee [1982] and Wilson [1985a, 1985b]. Experimental methodology and results are reviewed by Plott [1982], and with special relevance to deterrence by Isaac and Smith [1985]. Policy concerns are summarized in the several articles in Salop [1981].

The reader will likely conclude that all of the material included here reveals its vulnerability to the sorts of criticism directed at deterrence theory in the other chapters in this volume and in the earlier literature (e.g., George and Smoke [1974]; Jervis, Lebow, and Stein [1985]). In particular, the theoretical models rely on strong assumptions of rationality and common knowledge. Nevertheless, by delineating conditions under which deterrence fails to be credible and effective, even with such strong assumptions, these models serve at least to narrow the domain in which behavioral factors must be invoked to constrain the implementation of deterrence strategies. And, these models provide benchmarks for more realistic empirical and experimental studies.

1. Background

An oligopoly comprises the firms in an industry. The firms compete (or collude) continually via product designs, delivery conditions, and prices. Investments in factor supplies, plants and sites, R & D, and production technology and equipment have long-term effects on firms' options and their costs. Firms are interested primarily in (the expected present value of) profits, comprising both revenue (prices \times quantities) and costs (investments in capacity plus operating costs).

The salient case involves one or a few firms whose products are close substitutes, and other industries offer weak substitutes, plus possibly some potential entrants. Entrants are other firms that might enter the market in competition with the present incumbents, which is usually detrimental to the incumbents. Each firm can affect its market conditions through discretionary pricing, product designs, and productive investments. These also significantly affect the opportunities available to its competitors and to potential entrants; thus, firms' decisions are strongly interactive. Firms' behaviors are motivated, therefore, by strategic considerations derived from their mutual interdependence. In the U.S. at least, collusion is illegal and subject to civil liability, and contracts to that end are unenforceable. Hence, noncooperative behavior predominates, and in any case cooperative arrangements must be self-enforcing. If there is any predictable stable outcome, it necessarily results from an 'equilibrium' among the firms' strategies.

Dating from Adam Smith in the 18th century, casual empiricism has provided many 'stylized facts' about oligopolistic competition.

Systematic expositions date mainly from the 1930s (Chamberlin and Robinson), but without substantial empirical studies. Bain [1956] initiated what has become a continuing enterprise, studying empirically the 'structure, conduct, and performance' of industries -- a theme that dominates the journal literature. Some of this literature is statistical; some study industries longitudinally, replete with blow-by-blow histories. Other sources include anti-trust cases, Federal Trade Commission dockets, teaching cases (mainly written at Harvard Business School), and a few data bases; also, many authors bring first-hand experience from consulting, expert testimony, or service with government regulatory agencies. Recent texts, notably Scherer [1980], accompany expositions of the theory with ample references to empirical evidence and the body of legal precedent and interpretations from antitrust cases. The gap between the theory developed for simple models and the complexities of a case study can be great, however. Close examination of actual behavior has been rare, perhaps because such information is usually proprietary, but recently experimental methods have been used to examine behavioral aspects; cf. Plott [1982]. Few attempts have been made to examine empirically the effects of such features of preferences as risk aversion and intertemporal impatience.

Some economists argue that 'the oligopoly problem' is fundamentally indeterminate, but the main view is that theoretical models can provide salient, albeit rough, predictions about the processes and outcomes of competition. The theoretical literature, dating from Cournot [1838], is predominantly deductive and positive. That is,

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plausible assumptions are invoked to obtain predictions that are compared qualitatively against the stylized facts. Occasionally, predictions are estimated or tested econometrically, and recently experimentally. Because a model comprises many assumptions applied in concert, such studies test a complicated joint hypothesis that rarely allows separation of effects and identification of causal relationships. Theoretical constructions greatly exceed tests; explicit tests of underlying assumptions are rare.

The Role of Deterrence

In studies of oligopolistic competition among firms, mention of deterrence usually refers to the context of potential entry. Since profits accrue to monopoly power, incumbents want to prevent expansion of each other's market share, and as well to deter entries of other firms into their industry. Entry involves investments in capacity, product design and differentiation, spatial location and delivery conditions, etc. Deterrent strategies of incumbents likewise involve preemptive capacity expansion, threats of price wars, and the like. Thus, deterrence affects industry structure: the number, size, technology, products, and prices of firms.

The interpretation of deterrence could be so broad as to include any context jeopardizing the profitability of an incumbent, but studies focus on the asymmetry between an established incumbent and a potential entrant who must incur sunk costs to enter. These costs represent the unfavorable outcome for an entrant whose maneuver fails and who is

forced to exit or to sell out to an incumbent. Such costs are unrecoverable either because they are dissipated in administrative and operating expenses or because they are invested irreversibly in specialized equipment or knowledge with limited resale possibilities. Unsuccessful entry can be expensive for an incumbent too, if driving out the entrant entails costly actions, such as a price war, and in any case the incumbent usually experiences a temporarily reduced market share. The consequences of successful entry are continuing market share and profits for the entrant, and resulting reductions for the incumbents. The ensuing sustained competition typically entails lower prices, so aggregate profits in the industry decrease; but market penetration, consumers' benefits, and total surplus increase -- which is the reason why competition generally and entry in particular are socially condoned.

The means of deterrence vary greatly: pre-emptive investments in plant sites, equipment, production technologies, and product designs; signaling via 'limit pricing' (as explained later); and threats of price wars. Durable investments that alter irreversibly the incumbent's technology and costs are means of commitment. Pricing and other actions (e.g., advertising) having less durable effects are interpreted partly as signals. The role of signaling derives from asymmetries in firms' information about each others' technologies and costs. In dynamic contexts, reputation effects reflect repeated signaling. A firm invests in costly signals in order to build or maintain a reputation that it might have superior technology or resources; this is called the 'demonstration effect'. The payoff from an investment in reputation is the anticipation

of a reduced chance later of further incursions. The Appendix describes some hypothetical examples of entry deterrence, and the role of commitments, signaling, and reputations.

Failed deterrence may result in accomodation, meaning 'normal' competition for market shares and profits in which each firm accepts the continuing presence of the other. 'War' is a term usually reserved for battles for survival. In a war of attrition, the incumbent and the entrant battle to determine whether the entrant's costs are sufficiently low (and its financial resources sufficiently large), or the reverse for the incumbent, for the entrant to gain accomodation from the incumbent; otherwise the entrant exits after a duration sufficiently long to conclude that the chances of eventual success are small. Essentially, such continuing games of 'chicken' are a protracted negotiation over a division of the spoils from monopoly power. Anticipation of a war of attrition may itself deter entry. The incumbent can credibly threaten a costly price war if such a battle would reduce the chance of successful entry now; but even if it would not, the demonstration effect on other firms with later opportunities to enter might deter subsequent entries.

Other more symmetric wars of attrition occur in natural monopolies and declining industries when the firms are too numerous for all to recover their fixed costs of operation and their opportunity costs of redeploying assets into other markets. Competitive battles for market shares can also take this form: the net effect is to reveal which firms are stronger in terms of costs and products and can therefore sustain claims to larger shares.

Wars of the above kinds are predictable features of the competitive process. In theories that construct equilibrium strategies, such wars are part of the sorting process that selects the more efficient firms for survival or larger market shares. Their occurrence in equilibrium stems from private information: models without informational asymmetries typically predict immediate capitulation by the weaker firm. One can interpret competitive battles as akin to bargaining under incomplete information in which the only credible communication is persistence in the struggle. In an economic context, the sorting process selects efficient firms and promotes efficient production and pricing to the benefit of consumers. There is no evident analog in a military or political context because there are no third-party beneficiaries.

Also possible are roughly two kinds of disequilibrium wars, possibly triggered by 'mistaken' entry. In one version, an incumbent firm can, in equilibrium, have an incentive to sustain its reputation for likely being 'strong' (having low costs, etc.) by imposing severe losses on an entrant, even if the incumbent incurs losses from the price war or other means used. Again, such losses are an investment whose payoff subsequently is a chance the entrant will exit or a reduced chance of further entry. Such anti-competitive aggressive behavior motivated by the prospect of inducing exit or deterring subsequent entry is often called 'predatory'. Although there is no presumed rapacious motive to 'consume' the prey, the successful incumbent often acquires the assets of the defeated entrant.

In another version, the prospect of price wars and other noncooperative behavior is the credible threat that sustains equilibrium behavior that is either explicitly or implicitly collusive. Wars that police such equilibria by punishing defectors can be triggered by deviant or errant behavior, or by noisy observations that allow an inference that collusive arrangements might have been breached.

Lesser punishments than war are integral parts of the disequilibrium behaviors in many theories of equilibrium among firms. Whenever the equilibrium of a repeated encounter does not induce equilibria in the constituent stages, it is sustained by the prospect of a 'less cooperative' punishment phase if some firm deviates. One such punishment is reversion to a less profitable equilibrium, and another is the familiar tit-for-tat strategy. The Appendix mentions examples.

Scherer [1980] provides a superb exposition of the basic issues regarding deterrence in monopolistic and oligopolistic markets. Recent summaries of the current state of the theory are by Fudenberg and Tirole [1986, 1987] and by Roberts [1985], and various examples are described in Wilson [1985a, 1985b]. The experimental study by Isaac and Smith [1985] is notable for not finding predatory pricing in situations that theoretical studies indicate are conducive.

2. Methodology

The analytical methodology is invariably based on game theory, which was employed in rudimentary forms even by 19th century authors. By modern standards much of the early work was incomplete or based on

overly simplified models. Recent work focuses on models replete with dynamics, private information, and other realistic complicating features. The game-theoretic view emphasizes that the outcome of the competitive process results from an equilibrium among firms' strategies (customers are passive in most models), and possibly occasionally from disequilibrium.

Game theory offers an impressively flexible methodology, but it imposes severe limitations. Besides the evident assumption of consistent maximizing behavior, the most important is the requirement that the rules of the game are common knowledge. An event is common knowledge if each player in the game knows it, each knows that the other knows it, and so on ad infinitum. For example, a fact could become common knowledge if it were announced publicly to the assembled players, so that each could observe that the others heard the same announcement, as in some experimental settings. The results of studies that assume that each protagonist's actions, information, and preferences are common knowledge are often not robust to variations that allow some features to be privately known.

It is unclear to what extent these limitations are peculiar to the special methodology of game theory and to what extent they reflect conundrums inherent in oligopolistic competition. That is, possibly the game-theoretic models represent the only (and unrealistic) contexts that oligopoly problems are solvable, whereas in reality most situations are fundamentally indeterminate, depending in each instance on the peculiarities of attitudes and behavior. In any case, the fundamental

difficulties in employing game theory to study oligopolistic competition raise questions about whether game-theoretic models can possibly be accurate descriptions of firms' decision processes. In the absence of descriptive validity, and verification of the super-rationality and common-knowledge assumptions, there are few normative prescriptions.

The Game-Theoretic Apparatus

The theoretical constructions are based on a few key principles. Of course, one is that players are 'unitary' and thoroughly rational according to the axioms of decision theory. What other disciplines might interpret as irrational or non-rational behavior, is here explained explicitly by preferences (e.g., risk aversion, impatience), limitations of information or memory, or complicated implications of equilibrium.

Peculiar to game theory is the requirement that a model must encompass all that is common knowledge among the participants; indeed, the formal rules of the game are equivalent to the body of common knowledge. Relevant information is rarely common knowledge in practice, but the assumption of common knowledge is often invoked as a modeling device to obtain a tractable approximation. (However, as an approximation this tactic fails in the many models that are quite sensitive to common knowledge assumptions: several of these models are included in the Appendix.) The models used are therefore invariably afflicted by strong assumptions as to what is common knowledge. For example, models with private information typically assume that the probability

distribution of this information is common knowledge. A major trend of the theory is progressively to weaken the assumed base of common knowledge -- but the regress is potentially infinite.

The raison d'etre of the theory is to construct an equilibrium; that is, a strategy for each player that is optimal against the others' strategies. (Some predictions weaker than equilibria have been proposed; e.g., equilibria in correlated strategies, and 'rationalizable strategies'.) Unlike equilibria and strategies in some other disciplines, here a strategy must specify the player's action in every possible contingency, even those unexpected in equilibrium, since equilibria are sustained by expectations about the consequences of deviant behavior.

Major mileposts of the theory are largely identified with discoveries of practically interesting games that have unique equilibria, or unique equilibria subject to plausible selection criteria. Often these equilibria reveal important aspects of strategic behavior.

Finitely repeated games pose paradoxes in some examples, however, because 'subgame-perfect' equilibria can fail to manifest intuitively plausible behavior. A subgame-perfect equilibrium has the stronger property that each player's strategy remains optimal in every subgame. For example, in the penultimate stage of a repeated game, players' actions must be optimal given that each player anticipates optimal play by himself as well as others in the final stage. The culprit in such examples is usually an overly strong common-knowledge assumption: this allows a backward induction that taxes credibility. A familiar example

is the finitely repeated Prisoners' Dilemma game, for which the unique subgame-perfect equilibrium precludes cooperation regardless of the number of repetitions. Several additional examples are described in the Appendix.

A major failing (some say strength ^{1/}) of the theory is that often there are multiple equilibria: selecting among these is a winnowing process in which plausible criteria are invoked to exclude equilibria deemed deficient. Some of these criteria invoke behavioral features, but mainly criteria are justified by an extended interpretation of rationality. Some of these criteria have considerable generality; others are peculiar to the context in which the model is interpreted. One general criterion aims to exclude implicit incredible threats: a strategy must be optimal in every subgame; or stronger, a strategy must be justified by probability assessments that are consistent with Bayes' rule for inference via conditional probability, and such that in every contingency the strategy is optimal for the remainder of the game. These probability assessments are subject to further criteria of plausibility based on signaling interpretations of other players' observed actions. Related criteria exclude weakly or iteratively dominated strategies. A second criterion enforces minimal memory requirements, and ideally prefers strategies that depend only on those parts of prior history that are payoff-relevant for the future (e.g., stationary or Markovian strategies in a stationary environment). Additional criteria invoke various kinds of stability, robustness under perturbations and related continuity considerations, and invariance to embeddings in

larger games. These selection criteria are highly vulnerable to the requirement of game theory that the equilibrium selected must itself be common knowledge among the players. An exception is the 'forward induction' criterion: as the players move in sequence, each is assumed to signal by his actions the equilibrium continuation he has selected to serve his own interests.

The empirical ramifications of game theory are exhausted by the joint implications of common knowledge of the rules, expected utility maximization, and (a selection of an) equilibrium. It is less a 'theory', therefore, than a method. Properly, theories are constructed on a game-theoretic foundation by formulating and testing models. The theory of oligopolistic competition presently comprises mostly its collection of models and the assorted facts used to motivate and test them.

In the formulation of models, game theory brings the special advantage that it elicits the implications of a precise and complete specification of 'who knows what when' and each player's possible actions in each contingency.^{2/} The recent theory has emphasized particularly the implications of dispersed private information among the players, and the consequences of repeated encounters among the same players. Analyses of these features provide reasoned explanations of the role of credible commitments, threats, signaling, and reputations. The interesting results focus on two extremes: explanations of severely non-cooperative behavior; and alternatively, maintenance of cooperative behavior in the absence of enforceable contracts. Interpreting equilibria in familiar

terms (price wars, implicit collusion, etc.) is occasionally problematic, but artistic license is allowed.

The implications of game-theoretic models for empirical studies are distressing. The range of possible phenomena in or out of equilibria can be extreme, and no realistic model provides a simple regression for estimation -- at the very least, a complicated time-series structure is implied, usually with many omitted explanatory variables. Matters are better regarding experimental studies: some simple experimental designs admit specific predictions about a few key measures.

For matters of public policy, the variety and complexity of phenomena predicted by game-theoretic models are useful to justify what might happen, and equally discouraging of attempts to justify exclusion of what might not happen. Adversarial protagonists of a policy can construct models to justify nearly any prediction. There is therefore considerable emphasis on identifying general features whose predictions have wide applicability.

3. Main Conclusions of the Theoretical Models

In the field of industrial organization, models and their predictions are presented as deductive exercises of the 'if M then P' variety. Actually, scholars search for plausible Ms that yield Ps approximating observations or stylized facts. Thus, the field's research is mostly a summary of what observations can be approximated by the predictions of plausible models. A more general enterprise seeks to

identify the ingredients of models that produce consistently interesting predictions. There seem to be few predictions that can not be derived from some model; therefore, there is an understandable interest in finding plausible ingredients whose predictions have wide validity. I mention several ingredients here; the Appendix provides more details. I assume that the interesting predictions are those that entail severe competitive battles, and those that entail sustained cooperation.

As mentioned previously, one important ingredient is an equilibrium selection criterion that enforces some version of sequential rationality. That is, each player's equilibrium strategy is in every contingency optimal for the remainder of the game. Moreover, it is usually necessary to impose plausibility restrictions on a player's probability assessments entertained after observation of an event deemed to have zero probability according to the equilibrium strategies. Without such criteria, there are often many equilibria that are vulnerable to the criticism that they reflect implicit commitments, incredible threats, unenforceable contracts, or 'threatening with (absurd) beliefs'.

It is important to model commitment explicitly via irreversible investments in durable equipment, etc. But too-strong commitments can be noxious as well; e.g., ignoring the time phasing of incremental investments precludes implicitly cooperative equilibria that depend on mutual expectations of restraint. Similarly, opportunities to pre-empt must be modeled explicitly (who moves first, etc.), or the several equilibria will reflect the several possibilities of who pre-empts first (or a collision).

Ideally, a model and its accompanying equilibrium-selection criterion admit a single equilibrium. But as mentioned previously, this is a disadvantage if uniqueness hinges on an incredible backward induction. Multiple equilibria have fundamental importance in dynamic games, moreover. Monopoly power or cooperation in an oligopoly is sometimes sustained by expectations that deviations will result in reversion to a less profitable equilibrium, at least for a duration sufficient to deter deviations.

Repeated encounters, and dynamic games generally, often provide an embarrassing wealth of equilibria. Finite repetition of a single stage-game need not add equilibria (e.g., the Prisoners' Dilemma), but in some cases the effects are appreciable, especially if the stage-game itself has multiple equilibria. Generally, repeated encounters add new possibilities for cooperation sustained by mutual expectations of punishments for deviations. In the extreme case of a single stage-game repeated infinitely often, essentially all feasible average payoffs are possible equilibrium outcomes.

Policing deviations from cooperative behavior can be problematic in the theory as well as in real life. In some equilibria, the incentives that motivate 'punishers' depend on further punishments for noncompliance.

Equilibria can be greatly restricted by confining strategies to plausible behaviors, such as stationarity or dependence only on payoff-relevant history, bounded memory, etc. Conversely, seemingly small

powers of commitment added to a dynamic game can sustain cooperative behavior even with narrowly restricted strategies.

Limitations on the players' common knowledge, and particularly possession of private information, can have dramatic effects in dynamic games. A main effect in finite games is to obviate the possibility of paradoxical backward inductions. Signaling and reputation effects can be the paramount motivation for limit pricing, wars of attrition, predatory price wars, bargaining delays and strikes, and presumably a host of other costly or dissipative behaviors that are inexplicable otherwise. Sometimes the only effect is the need to signal accurately to forestall reactions that are mutually unprofitable. A recurrent feature is that a small dose of incomplete information allows commitment or credibility to be attached to behaviors that otherwise could not be optimal in equilibrium; moreover, these effects escalate as the number of repeated encounters increases. In repeated encounters, whenever a player's preferences (motivations, intentions) are privately known, there is an incentive to maintain a reputation (for reckless or benign intent) via behaviors that sustain opponents' beliefs or suggest misleading inferences: offsetting the cost of reputation building via myopically non-optimal behavior is the prospect that it will engender favorable reactions in the future, or set the stage for exploitation of a more profitable opportunity later. In many models, private information is eventually revealed by the players' actions as the game unfolds, but in the interim private information is a major source of profitability.

On the other hand, limited common knowledge can also necessitate cooperation through reputation effects that engender imitative behavior, most notably in the Prisoners' Dilemma and related coordination games. In these games, each player has an incentive to cooperate if there is a chance others will reciprocate, and to reciprocate if it will sustain others' beliefs that there is such a chance of reciprocity.

4. Remarks

Oligopolistic competition has been a main proving ground for development of game-theoretic methods and models -- more so than military and political deterrence, to my knowledge. Game theory has been enriched by the encounter with difficult problems, while the subject has been enriched with models that offer explanations of puzzling phenomena. That the explanations center on the role of repeated encounters and private information offers prospects of an eventual synthesis.

On the other hand, game theory suffers from extreme rationality and informational assumptions, and little has been done to establish an empirical basis for these assumptions. The actual decision processes and behaviors of the firms it purports to describe have rarely been examined closely, and few inferences from case studies can claim transferability or generality. The substantive empirical basis of the theory still depends mainly on traditional statistical studies of industries and close examination of legal and regulatory cases. Experimental methods offer one route to examine behavior in greater depth; and one

can hope that new econometric methods will provide more direct tests of the predictions derived from game-theoretic models.

For studies of deterrence in military and political spheres, there may be useful lessons that can be drawn from studies of oligopolistic competition. The game-theoretic models mostly verify features that are easily perceived directly by any serious student of the subject; nevertheless, the models enable analytical studies to be conducted within a consistent logical framework. For example, in an ongoing relationship between two parties, each with private information, the extant models verify the variety of competitive regimes that can occur, including stable competition, dissipative battles for entry or shares of the spoils, or 'predatory' attempts to acquire or maintain dominance via credible threats motivated by reputational effects. And as well, they verify possibilities for sustained cooperation by self-enforcing collusive agreements, and by mutual incentives to sustain incentives for reciprocity. Because these features depend subtly on the 'rules of the game', and particularly on the structure of information and rewards, and the dynamics of the parties' interaction, reliance on a systematic methodology is apparently essential for analytical studies. The likely consequences are a more thorough understanding of the process of competition and cooperation. Novel policy recommendations seem unlikely, since studies can at most add further substance to conclusions derived from centuries of military engagements, diplomatic history and political science.

APPENDIX

Illustrative Game-Theoretic Models and Results

This appendix provides a selection of some of the models and results about oligopolistic competition among firms, all derived by the methods of non-cooperative game theory. Section A.1 examines only the case that there is no private information among the firms: all information is common knowledge. In this context, an equilibrium is assumed to be a subgame-perfect equilibrium: the equilibrium induces an equilibrium in every subgame. This restriction is intended to exclude implicit incredible threats. Section A.2 allows that some of the participants have private information; however, it is still restricted by a common knowledge assumption; e.g., the probability distribution of private information is usually assumed to be common knowledge. In this context, an equilibrium is assumed to be (at least) a sequential equilibrium: every action is part of an optimal strategy for the remainder of the game, based on probability assessments that are consistent with the rules of conditional probability and the structure of the game.

A.1 Games with Complete Information

Strategic Substitutes and Complements

The recent literature on oligopolistic competition emphasizes the distinction between strategic substitutes and complements. This distinction may explain the qualitative differences between deterrence

models in economic and military contexts. Two firms' outputs, for example, are (roughly speaking) strategic substitutes if an increase in one's output reduces the other's optimal output in response; that is, the static reaction function is downward sloping. Strategic complements are analogous: the reaction function slopes upward. Of course, it is possible that one firm's reaction function slopes downward, and the other's, upward; or that, a reaction function slopes upward initially and then downward, etc. In economic models it is fairly natural to specify that firms' outputs are strategic substitutes, and in some contexts that their prices are strategic complements. The recent literature indicates that these specifications account substantially for the qualitative nature of the results obtained from dynamic models of oligopolistic competition. In particular, several authors assume that outputs are strategic substitutes in the course of deriving the prediction that, in equilibrium, firms will not install excess durable capacity. On the other hand, examples have been given in which outputs are strategic complements and firms are predicted to install excess capacity in order to deter entry of other firms.

The analogy between excess capacity and armaments that are unused in equilibrium, but exist to deter invasions, is inexact. However, it is probable that realistic models of arms races would naturally assume that armaments are strategic complements: one's optimal defensive capability is an increasing function of the other's capability. One would expect, therefore, that the predictions derived would correspond

more closely to those derived from economic models that similarly assume strategic complementarity. Such models are rare, however.

• References: Bulow, Geanakoplos, and Klemperer [1985a, 1985b], Dixit [1979, 1980], Eaton and Ware [1986], Fudenberg and Tirole [1986, §2; 1987].

'Exceptional' Equilibria of Dynamic Expansion Games

Continuing with the imperfect analogy between economic capacity and war-making capability, I mention a result that reveals some of the potential for implicit cooperation afforded by dynamic interactions. Consider the game between two firms competing for shares of a new market by installing durable capacity.^{3/} Assume that capacity costs and long-run profits are such that the firms' capacities are strategic substitutes. Each firm can continuously install capacity at a bounded rate. In one equilibrium the firms install capacity until they reach one of the reaction functions; if firm 1 has a lead on firm 2 then it stops expansion early to induce 2 to stop at 1's optimal point on 2's reaction function. This equilibrium corresponds essentially to the result of the static game in which firms choose directly their final capacities (but recognizing the advantage of the leader). The dynamic game, however, has other equilibria resulting in smaller capacities and larger profits. These equilibria are sustained by mutual expectations about each other's retaliatory strategy. Both firms expand up to a mutually anticipated point; thereafter, each expands further up to one of the reaction functions if and only if the other continues expansion. These other

equilibria are possible only in the dynamic formulation that admits the possibility of contingent retaliation. Other than direct communication, it is unclear how firms might coordinate on these equilibria.

The implication of these results is that incremental commitments offer more potential for cooperation by admitting a role for retaliation to police defections from mutually expected actions.

• References: Fudenberg and Tirole [1983, 1986], Spence [1979].

Cooperative Outcomes Sustained by Expectations of Retaliation

A basic result in game theory is the 'folk theorem' for infinite repetition of a single stage game. For the case in which each of two players is interested in his average payoff, this theorem asserts that: any pair of feasible stage-game payoffs, provided they give each player at least what he could guarantee for himself (by a maximin strategy), are the average payoffs from some equilibrium. Indeed, such payoffs are approximated by an equilibrium of a sufficiently long finite repetition, provided that in the stage game the worst and best each player could get from equilibria of the stage game are not the same. These equilibria are sustained by expectations of more or less credible retaliatory punishment phases ('trigger strategies', 'three-phase punishments'). Or, more dramatically, efficient payoffs can be approximated, provided (among other conditions) that the stage game has three equilibria for which the players' preferences are in reverse order, in which case tit-for-tat strategies suffice and retaliation is not costly to the retaliator. (The provisos exclude the repeated Prisoners' Dilemma stage

game). Also, for some games (including the repeated Prisoners' Dilemma) ϵ -equilibria achieve superior outcomes.

These results highlight the cooperative possibilities enabled by repetitive interactions, but they also admit inefficient outcomes.

• References: Abreu [1983], Benoit and Krishna [1985]; Friedman [1977]; Fudenberg and Maskin [1986]; Moreaux, Ponsard, and Rey [1986]; Radner [1980]; Rubinstein [1977, 1979].

The special structure of particular games affords further insight. I illustrate with a simple example in which in the stage game the players move sequentially as follows: the seller names a price, then the buyer accepts or rejects, then the seller chooses the quality to be high or low. Assume a positive interest rate and suppose that high quality costs the seller more but is valued even more by the buyer; thus, high quality is efficient. In the only equilibrium of the stage game, the seller provides low quality, so expecting this the buyer is willing to pay only for low quality. In the infinitely repeated game the interesting equilibria can be interpreted in terms of the length of the buyer's memory. If the buyer has no memory, then the stage-game equilibrium results. If the buyer remembers only the previous quality then there is an additional equilibrium in which the buyer plays tit-for-tat: he expects today the quality provided yesterday, and therefore the seller provides high quality continually. Each additional bit of memory adds an additional efficient equilibrium: among all these, the one-bit memory is best for the buyer, since he pays the least price for

high quality. This example gives only a flavor of a newly flourishing approach to game theory that models players as finite automata having memory or information processing capability that is limited. One genre of results shows that such limitations enforce a selection among the many possible equilibria.

Outside the realm of repeated games there are other interesting models of sustained cooperation. I mention one in which a small degree of commitment suffices. Consider a duopoly in which each firm, in alternating periods, picks a price (from a finite set) to which it is committed for two periods. In a wide class of examples, the unique Markov^{4/} equilibrium predicts the monopoly price. This is sustained by the prospect that if one firm lowers its price then the other follows suit, resulting in a spiralling price war that ends only when one firm returns to the monopoly price; the duration of the price war is random because the return decision is randomized, but the expected duration is sufficient to deter deviations. Interestingly, after a price war starts, neither player prefers to return to the monopoly price until the price hits bottom one step above marginal cost; thus, there is a positive minimum duration. An implication of this kind of example is that in continuing encounters with retaliatory possibilities, a small degree of commitment can sustain cooperative outcomes.

• References: Fudenberg and Tirole [1985, §5], Maskin and Tirole [1985, Part II].

Contestability of Markets

The literature on contestability studies competition for the incumbent's role in a natural monopoly, in which potential profits are sufficient to cover the fixed costs of operation for one firm, but not two. In one model, in alternating periods each of two firms commits for two periods either to exit or to entry and a production level. In the unique Markov equilibrium, a firm with an initial monopoly chooses a production level large enough (and therefore a price low enough) to deter entry that (in equilibrium) would result in his own subsequent exit. Starting from a duopoly, however, a competitive battle ensues that may take several periods to induce one or the other to exit. When fixed costs are small, the persistent threat of entry, even of the hit-and-run variety, keeps the incumbent monopolist's price and profit low.

These results are closely akin to limit pricing: the persistent threat of entry erodes monopoly power.

• References: Maskin and Tirole [1985, Part I].

A variation of this theme has been called 'judo economics', and I am tempted to add 'guerilla warfare' or 'terrorism'. An incumbent monopolist may have an incentive to engage an entrant in a competitive battle (e.g., price cuts) only if the scale of entry is sufficiently large; hence, small-scale entry can be profitable and not elicit a competitive response. An illustration refers to a large resort hotel beside which a small pension is built: since the hotel gets the overflow from the pension in any case, the hotel prefers to retain monopoly

pricing for its residual demand. More cleverly, the pension could sell advance reservation coupons for rooms at a stated price, which (if the price were above the hotel's marginal cost) the hotel would want to honor.^{5/} Indeed, with this form of 'blackmail', the pension can in principle extract all of the profit from entry via its revenues from coupons and never needs to serve a customer -- although of course it must stand ready to serve to make the coupons credible.

These results are indicative of a general apprehension that the full panoply of competitive tactics has yet to be catalogued. Are monopoly profits subject to 'blackmail'?

• References: Gelman and Salop [1983].

The Coase Conjecture

Coase [1972] offered the conjecture that a monopolist selling a durable good produced (or stored) at constant marginal cost would have little ability to price-discriminate intertemporally if customers were quite patient. It has been shown recently that this conjecture is true of the 'stationary' subgame-perfect equilibria of the game among the seller and the buyers; moreover, if the seller's cost is less than all the buyer's valuations, then all subgame-perfect equilibria are stationary in the required sense that the buyers use a reservation price strategy. This result, that monopoly power is eroded by the buyers' patience, carries over to bargaining games between a seller and a buyer whose valuation is privately known, but it is sure that there are gains from trade: in a stationary sequential equilibrium, the seller is

unable to screen profitably among the buyer's types (cf. 'Bargaining' below).

This result indicates that customary notions of monopoly power that depend on intertemporal discrimination must be strongly qualified. When customers are included among the players in the game, and they are patient (they use a small interest rate to discount gains from trade), then intertemporal discrimination is not credible. Customers anticipate (correctly) that the seller's prices will decline, and therefore they wait for favorable terms. Interestingly, this analysis does not apply to oligopolies, since the expectation of price wars in response to price cutting can sustain high prices that effectively discriminate.

• References: Bulow [1982]; Coase [1972]; Gul, Sonnenschein, and Wilson [1986].

A.2. Games with Private Information

Communication and Signaling

Little of the literature deals directly with communication, since the prevailing view is that actions, which 'speak louder than words', are the principle credible signals. There are, however, several results to report.

The first considers a game in which one player (the sender) first observes privately the realization of a real-valued random variable (the signal) and then chooses a real-valued action (the message) that is

observed by the other player (the receiver), who then chooses an action. Assume that the players' payoffs depend only on the signal and the receiver's action, but differently for the two players so that given any signal they prefer different actions; and for each, the optimal action is a monotone function of the signal. There are many equilibria of this game but surprisingly they are ordered by the fineness or accuracy of the message; moreover, one that is finer than another yields Pareto-superior outcomes. The unique finest equilibrium still yields imperfect communication: the sender's message enables the receiver to locate the signal only within an interval of positive length. Precise communication is precluded by the difference in the players' preferences.

The second considers more general models in which the sender can make statements to the receiver. It has been argued (not deduced) that among the many equilibria it is plausible to select those that satisfy the following criterion: the receiver should believe a statement such that, if it is believed, then the subsequent action benefits the sender if the statement is true and harms the sender if it is false. Several similar criteria have been invoked to select among equilibria of games involving signaling. A typical example involves bargaining between a seller and a buyer whose valuation of the item might be high or low. Suppose that the buyer is impatient and chooses to delay making a counteroffer so long as to make its acceptance unprofitable (compared to accepting immediately the seller's initial offer) if and only if the buyer's valuation is high: then the seller concludes that the buyer's valuation is low.

This literature emphasizes on the one hand that costless signals must meet severe tests to be credible, and on the other, that one can select among equilibria on the basis of the plausibility of the inferences drawn from observations that have potential signaling content. However, one recent result shows that costless signals (communication) in a pre-play stage of a bargaining game can substantially alter the equilibrium of the subsequent negotiation process if they affect the parties' estimates of the chance that gains from trade exist; cf. Farrell and Gibbons [1986].

• References: Bernheim [1984], Crawford and Sobel [1982]; Farrell [1984]; Farrell and Gibbons [1986]; Kreps [1985]; Cho [1985]; Cho and Kreps [1985]; Grossman and Perry [1986a].

One example of reputation effects in communication might be called the George Smiley game. A spymaster (George) repeatedly receives reports from a spy with privileged information who might be loyal but might possibly be a mole. A loyal spy shares George's interests, whereas a mole's interests are directly opposed. In equilibrium, the mole's (randomized) strategy is to send accurate reports until a sufficiently important opportunity arrives to deceive George. Recognizing this, George's actions reflect probability assessments that his agent is a mole that decrease with the length of the history of accurate reports, weighted by the magnitude of the gain a mole could obtain from deception. If George ever discovers a deception, however,

then he immediately concludes that the agent is a mole and acts accordingly thereafter.

- References: Sobel [1985].

Limit Pricing

Limit pricing refers to the practice by an incumbent monopolist of keeping its price low in order to deter subsequent entry. Assuming that the current price has no effect on the profit an entrant might earn subsequently (e.g., it does not constrain the incumbent's future choices), one supposes that pre-entry pricing is mainly a means of communication: a credible signal to warn potential entrants against entry that would be unprofitable for both parties. The signal is credible because it is costly (a low price reduces the incumbent's present profits); but it is worthwhile to signal if it reduces the chance of entry.

An illustrative model assumes that both firms have private information about their costs of production. A potential entrant infers the incumbent's cost from observation of the incumbent's price and then enters if the inferred cost is sufficiently high to enable the entrant to reap a profit. Thus, in a separating equilibrium it can be that entry occurs under precisely the same cost conditions as it would if the entrant knew the incumbent's costs. The advantage of limit pricing for the incumbent is to prevent entry by a firm with costs too high to make it profitable, yet whose very presence in the market would affect the incumbent's profits adversely.

A main conclusion from this literature is that limit pricing has a kind of inevitability. Were the incumbent to ignore the threat of entry and choose the ordinary monopoly price corresponding to his true costs, then an entrant would likely conclude that the incumbent's costs are higher than they really are, and this could precipitate uneconomical entry that would be costly for the incumbent. Similarly, the entrant can not ignore the possibility that the price he observes reflects limit pricing, since he can anticipate that were he naively to assume that the price he observes is the incumbent's ordinary monopoly price then the incumbent would find it advantageous to cut his price in order to stave off entry that would be profitable for the entrant. Thus, whenever the incumbent has private information relevant to the profitability of entry, one must expect that his observable interim actions, such as prices, have a substantial signaling motivation.

• References: Milgrom and Roberts [1982a].

Bargaining

A prototype for communication is bargaining in which the language of negotiation consists only of offers. In the economics literature a 'standard' model considers bargaining between a buyer and a seller over the price of an item. The two parties alternate making offers until one accepts the other's offer, or there is no trade if offers continue forever. A central aspect of the formulation is that each party is impatient for an agreement; that is, each discount gains from trade at some positive interest rate. If the gains from trade are known to both

parties, then this game has a unique equilibrium: trade occurs immediately at a price that, if preferences are linear in the price, divides the gains approximately in inverse proportion to their interest rates. Matters are greatly different if one party's valuation of the item is privately known: there are many sequential equilibria, but all the stationary ones have the property that if the interest rates are small or the interval between offers is short, then the informed party captures most of those gains in excess of the minimal possible gain, and again trade occurs quickly. This 'quick trade' result disappears if the informed party can choose his delay in responding with a counteroffer, in which case delay retains its signaling role.

The principle conclusion from this literature is that patience and private information are major advantages in negotiations. For example, a plausible extrapolation is that in negotiations between a union and a firm, one party (especially one with inferior information) might elect a strike or lockout in order to impose delay costs on the other to make it relatively more impatient for an agreement.

• References: Admati and Perry [1986]; Rubinstein [1982]; Grossman and Perry [1986b]; Gul and Sonnenschein [1985]; Gul, Sonnenschein, and Wilson [1986].

Wars of Attrition

A war of attrition is another mode of implicit bargaining in which costly persistence in the struggle is the only credible signal. Wars of attrition are contests for a prize (such as survival in a market) in

which the struggle reveals which of the contestants is stronger (having lower costs or greater financial resources, etc.). Typically each side has private information about its own strength but is uncertain about the other's. The fight continues until one party infers that its chance of winning the prize is insufficient to justify further expense in the quest.

The main result of this literature is that costly battles are a predictable consequence of mutual uncertainties about each other's competitive strength. The outcome of the struggle reveals which contestant is stronger, and can therefore claim the prize, but much of the value of the prize is dissipated in the process. Essentially the prize is sold at auction, but each contestant pays the second highest bid (namely, the cumulative costs incurred until capitulation) whether he wins or not. In an economic context, this double payment is the source of the benefits to consumers from competition; in a military context, presumably, there are no third-party winners.

- References: Fudenberg and Tirole [1986].

Predation and Price Wars

Predation usually refers to competitive tactics (e.g., a price war) whose advantages depend on increasing the likelihood that an entrant will exit; that is, they are anti-competitive to the extent they are designed to recoup monopoly power. The alternative to predation is accomodation: the normal pricing and other tactics based on an assumption that the entrant will persist if it has a viable technology.

Predation is not applied to ordinary wars of attrition fought to determine which firm has the superior technology to be the surviving firm in a natural monopoly. It is more usually applied in the context that predation is the threat used to deter or defeat entry. In this context the main issue is whether predation is a credible threat: can it be in the interest of an incumbent to incur losses battling a firm whose entry is a fait accompli? This issue is particularly complex when there is no chance that the battle will induce the entrant to exit.

One strand in the analysis examines the so-called 'deep pocket' hypothesis; namely, that an incumbent with greater financial resources can drive an entrant to exit, and indeed, thereby prevent entry initially. A simple model supposes that initially the entrant can sustain losses for at most, say, ten periods, whereas the incumbent is willing to impose these losses for one period if the reward is the entrant's exit. Then the entrant foregoes entry; or if it enters then it exits immediately! The argument is by backward induction: With one period's reserves remaining, the entrant anticipates that the incumbent will fight, after which the entrant will be forced to exit, so the entrant exits immediately. But anticipating this, with two periods' reserves remaining, the entrant expects the incumbent to fight because it will induce exit next period, so again the entrant exits immediately. And so on: regardless of the reserves remaining, the entrant exits immediately; or better, never enters initially. This kind of conclusion is often called paradoxical, presumably because it precludes entry by an entrant with vast but finite financial reserves. The source of the

conclusion is the reasoning by backward induction. The inductive steps can be invalidated by introducing some incomplete information into the model (as will be illustrated for a related model below) with the result that the entrant may gain accomodation from the incumbent.

Some argue that clobbering an entrant must be irrational if it is costly and there is no chance that the entrant will exit. The counter-argument is that the costs incurred are merely an investment in deterring subsequent entrants: this is the so-called 'demonstration effect'. The prototypical paradoxical example runs as follows. An incumbent operating in several product markets anticipates the possibility of entry into each of its markets. Assume that these entry opportunities occur sequentially. Moreover, assume that in each market separately the incumbent prefers no entry, but given entry he prefers to accomodate, although he has available a (predatory) tactic that would make entry unprofitable for the entrant and himself. The unique equilibrium of this game predicts that the incumbent will acquiesce to entry in every market, and therefore every entrant will enter: again the argument is by backward induction. This conclusion affronts intuition, at least if the number of markets is very large: the counter-argument, appealing vaguely to the demonstration effect, is that clobbering a few of the early entrants might induce sufficiently many of the later ones to forego entry to make it worthwhile for the incumbent to incur the necessary losses early on.

To give substance to the demonstration effect, and to invalidate the backward induction, it suffices to remove the hidden assumption that

the model as postulated is common knowledge. Consider just two entrants and assume that individually each entrant and the incumbent know the facts stated above. However, suppose that the incumbent is unsure whether the second entrant knows that the incumbent's best response to entry is accomodation rather than predation. Now it is possible that in equilibrium the incumbent will clobber the hapless first entrant if he enters (so he won't), simply on the chance that this will sustain the second entrant's belief that the incumbent might prefer predation and therefore deter its entry -- although in fact the second entrant knows that accomodation can be expected and will therefore enter.

The gist of this example is that predation is a credible threat if it might sustain the incumbent's reputation (in the mind of the second entrant, were he to be uncertain about the incumbent's preferences) that he might prefer predation. Moreover, predation could occur even though both the predator and the prey know that it is unprofitable for both, and the prey knows that actually it is ineffective in deterring the second entrant. All of this illustrates that informational effects due to limited common knowledge can be very complicated.

Another example illustrates that the effects of limited common knowledge escalate as the number of encounters increases. For this example, assume that the entrants are unsure whether the incumbent's best response to entry is accomodation or predation; in particular, suppose that initially they all assess a very small probability p that he prefers predation, whereas acting in isolation each entrant would be willing to run the risk of entry if this probability were anything less

than some large probability q . The claim is that, in equilibrium, all but a few entrants will forego entry. That is, if there are many entrants then all but the last few (the number depending only on p and q) will pass up the opportunity to enter even though p is small relative to q . This claim derives from a demonstration that when there are many entrants remaining the incumbent who prefers accommodation will nevertheless want to meet entry with predation in order to sustain his reputation that he might prefer predation; indeed, if he were not to prey on an entrant then surely all the remaining entrants would enter. One method of proof is again a backward induction, this time showing that when n entrants remain the accommodating incumbent would nevertheless do best to meet entry with predation if $p > q^{n-1}$. Note that n need not be very large for it to be optimal for the accommodating incumbent to 'imitate' the behavior of a predatory one. His motive can be simply explained as an investment decision: the cost of predation now is fully recouped by deterring entry of some of the subsequent entrants; predation deters by sustaining his reputation, interpreted as the probability that he might profit from predation. Other interpretations come to mind; e.g., the predatory type of the incumbent might reflect the remote possibility that the incumbent is irrational or motivated by factors excluded from the model.

A sequence of entrants is used above only for expository purposes; the same result obtains if there is a single entrant with repeated opportunities to enter. In this case, it is of further interest to consider the case that also the incumbent is unsure whether the entrant

is hurt sufficiently by predation to make entry unprofitable. The equilibrium now assumes the form of a war of attrition or a game of 'chicken'. Following entry, the incumbent responds with predation and as this continues both parties revise their probability assessments: the incumbent becomes increasingly convinced that the entrant can sustain predation, and the entrant becomes increasingly convinced that the incumbent profits from predation. The incumbent, if he is accomodating and the entrant has not exited, is all the while incurring losses and so eventually he succumbs and stops preying on the entrant; or the entrant, if he is hurt by predation and the incumbent has not reverted to accomodation, is all the while incurring losses so eventually he succumbs and exits. If they are both 'strong' competitors, then they realize this after a limited duration; if only one is strong then he surely 'wins' the encounter; if both are weak then one or the other wins according to their (randomized) choices of stopping times for capitulation.

The thrust of these several examples is that, in repeated encounters affected by private information, costly competitive battles may be undertaken as an investment in sustaining one's reputation. The benefits of building or maintaining a reputation derive from the prospect of deterring future entry, inducing exit or accomodation from a competitor (if there is a probability that he is 'weak'), etc.

An important generalization of the folk theorem shows fairly generally that a small dose of incomplete information, added in appropriate ways to a model of a repeated game, can generate equilibria whose payoffs approximate any desired feasible outcome.

• References: Benoit [1984], Kreps and Wilson [1982a], Maskin and Fudenberg [1986], Milgrom and Roberts [1982b]. See Isaac and Smith [1985] for disconfirming experimental evidence.

Cooperation in the Finitely Repeated Prisoners' Dilemma

One of the more dramatic instances of reputation effects occurs in the finitely repeated Prisoners' Dilemma game. The claim is that if there is a small chance that one of the players (say player 2) is an automaton that mechanically plays the tit-for-tat strategy, then an equilibrium necessarily entails cooperative play for all but the last few periods. The proof relies on the fact that tit-for-tat guarantees its user that his payoff will differ from his opponent's payoff by no more than an amount that is independent of the number of periods; that is, tit-for-tat is a good second-best strategy -- which is one reason it fares well in tournaments. However, the intuition behind the result is plain. If he knew he was playing with an automaton, then player 1 would surely cooperate until near the end, since he would be assured that cooperation would be reciprocated. With many periods to go, therefore, player 1 wants to cooperate until 2 defects, just on the chance that he is playing with an automaton. The non-automaton player 2, moreover, wants to imitate the automaton's behavior (by scrupulous adherence to tit-for-tat) in order to promote this behavior by 1; indeed, were 2 ever to deviate from tit-for-tat his identity would be revealed and play would revert thereafter to strictly non-cooperative behavior.

Recent results indicate that the conclusion can be generalized. One version, so far proved only for finitely repeated games of coordination, shows a comparable result for the case that there is a chance that one player is possibly any finite automaton with bounded memory. The key feature of this result is that efficient outcomes during most of the game are a necessary implication of equilibrium.

The main implication of these results is that cooperative behavior can be 'bootstrapped' by adding some role for imitation of benign intention, provided it is reinforced by reputational effects. An important feature is that cooperation for most of the history is a necessary consequence of equilibrium. An ideal result would characterize situations in which even scoundrels find it advantageous to imitate angels.

• References: Aumann and Sorin [1986]; Kreps, Milgrom, Roberts, and Wilson [1982].

FOOTNOTES

- 1/ For example, one line of analysis demonstrates that the several equilibria are the 'shadows' cast by the equilibria of the various larger games in which the present game might be embedded. Multiple equilibria may therefore reflect realistically an inherent indeterminacy. Similarly, criteria that select among equilibria to find ones that are 'stable' depend on the class of perturbations of the game that are entertained. Indeed, all equilibria are stable in the strongest sense that they are limits of 'strict' equilibria in perturbed games obtained by modifying information sets.
- 2/ On the other hand, this is also why game theory is ill-adapted to analyze communication via natural language, particularly where it is subject to uncertain interpretation.
- 3/ Irreversible durable capacity is equivalent to a cost-reducing innovation. In both cases the effect is to enable production at costs no greater than and possibly less than previously. It is also formally equivalent in many contexts to an explicit observable irrevocable commitment.
- 4/ That is, each firm ignores prior history that is payoff-irrelevant for the future.
- 5/ Recall the coupon war among the major airlines: Eastern's coupons for transcontinental flights, issued on its eastern seaboard flights as part of its competitive battle with New York Air, were honored by the other major carriers, so in fact Eastern did not need to allocate many planes to the transcontinental routes.

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is often called paradoxical, presumably because it precludes entry by an entrant with vast but finite financial reserves. The source of the

