THREE ESSAYS IN INDUSTRIAL ORGANIZATION

by

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ABSTRACT

Three essays exploring the sources of uniformity and
diversity in economic systems use game-theoretic
approaches. The first chapter analyzes the difficulties
faced by consumers who care about choosing the same
products as other buyers (in order to exploit economies
of scale in consumption). The result is a "bandwagon
effect" in which early adopters of new technology have a
disproportionate impact on the market outcome.

The second chapter provides an explanation for observed
variations in firms' management structures in particular
industries. In equilibrium, firms benefit from
identifying profitable projects in states of the world
where their rivals do not. This desire to reduce
correlations in judgment produces managerial diversity.

The final chapter looks at a historical case of consumer
ambivalence about new technology--quadriphonic sound in
the 1970s. The analysis concludes that the existence of
two incompatible, proprietary quad technologies hindered
its market acceptance.

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INTRODUCTION

The essays that constitute this thesis each stand alone. Yet they are linked by a common theme whose variations permeate economic life, if not economic theory. That theme is the balance between homogeneity and diversity, between motives for agreement and motives for disagreement. Looked at in one way, economic choices possess a high degree of homogeneity. Consumers cluster around only a few of the many possible technical standards for products like videocassette recorders and personal computers. Firms practice certain policies almost universally, such as increasing employee compensation with seniority; other forms of conformity are industry specific, such as geographic clumping of headquarters or offering the same product mix as competitiors.

From another point of view, the economy is almost bewilderingly diverse. Firms with the same product pursue different sorts of customers, while those in the same market frequently use different techniques and sell varied products. In some industries, no two firms seem alike in organization or strategy. How do these differences manage to persist, and under what circumstances should diversity be expected?

The approach I take to answering questions like this is fundamentally strategic. By modeling agents as players in a plausibly-specified game, I look at how their mutual interactions provide incentives to agree or disagree. The equilibrium of the game can then be solved in terms of the exogenous variables in the model,

so that the conditions leading to homogeneity or heterogeneity can be characterized.

The first essay considers whether or not users of a standardized good that possesses increasing returns to consumption can noncooperatively "agree" to switch to a better, new standard if they are unsure of one another's preferences. This coordination problem turns out to reduce to a "bandwagon" equilibrium, in which the distribution of user preferences for the new over the old determines the extent of switching. The main feature of such an equilibrium is that users eager for the new standard will take the plunge first; if there are enough of them, they may stimulate slightly less eager users to switch also, and so on down the scale. "Gaps" in the preference distribution can lead to only some of the users adopting the new standard, so that heterogeneity will be the outcome.

The next essay examines disagreements among direct competitors about the value of investment projects, and tries to tie this phenomenon to the observation that managerial diversity among rivals is common. The basic concept is that a management structure acts as a filter for data about projects. If there are design tradeoffs between the different types of signals to which the filter can be sensitive, the question is whether or not rivals will choose to observe the same things.

It turns out that knowledge of a given signal is less valuable when other firms also have it, because if one firm decides to invest based on that data, so will others, leading to competition that reduces profits. When firms observe different signals, they are less

likely to simultaneously invest in the same projects, thereby avoiding competition and raising profits. Thus, firms learn the same signal only when its value relative to other signals is very high; rivalry generates management diversity whenever the signals have similar values.

The final essay is a case study of quadriphonic sound in the 1970s. Quad was billed as the natural successor to stereo, yet it failed to attract a significant number of adherents among consumers, retailers, or artists, and was dropped by its sponsors. Because quad, like other audio technologies, was subject to demand-side economies of scale--the more units of hardware sold, the more compatible software likely to be available, leading in turn to more hardware sales--the key issue in its history is why consumers failed to agree on adopting it, even though studies showed that listeners generally preferred it to stereo.

My analysis focuses on the fact that two incompatible quadriphonic systems were introduced by rival firms. There is considerable evidence that this hurt the new technology's chances of superseding stereo. The battle between the rival systems led to premature introduction of the products, diverted sales efforts into "knocking" the opposing system, and, by splitting the quad user base, reduced the incentive for producing compatible software. The forces promoting consumer disagreement led, paradoxically, to perpetuating the universal stereo standard.

<u>Chapter 1</u>

BANDWAGONS AND THE COORDINATION
OF STANDARDIZED BEHAVIOR

I. INTRODUCTION

Many industrial products supplied by different firms are standardized, so that components from different sources will function together. Nuts and bolts come in standard sizes in the United States (although there is a different standard in Europe); so do light bulbs and the lamp sockets into which they must fit. Railroad gauges were standardized in the U.S., for the most part, by the end of the nineteenth century, so that any train could run on any track. There are many examples of this sort, and one might wonder why.

Generally, compatibility allows consumers to take advantage of important "demand-side" economies of scale. I benefit from your possession of a telephone only if my telephone can talk to yours; I may want to play someone else's cassette tape on my tape deck. Sometimes the network externality is more indirect, as when standardization makes it easier to buy spare parts or expendable complementary goods (such as ammunition for a gun).[1]

At a more abstract level, there are forms of behavior that exhibit some of the characteristics of standardization in order to gain these economies of scale, sometimes called "network externalities." Conformity to various social norms, such as using words to mean the same thing that everyone else does, or using the same units of measurement as others, or adhering to the hypothesis of profit-maximization in the construction of economic models, is valuable largely because of the network externality involved in being

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[1]The gasoline-engine owner benefits from this effect in the U.S., since sources of gasoline are widely available. The smaller population of diesel-engine vehicles is more constrained by fuel availability.

able to communicate with more people. Having the same minimum
drinking age in neighboring states may reduce the flow of young drunk
drivers coming back form a binge across the state line. And stores
of a particular type may benefit from locating near each other so
that consumers can shop more easily. (This is a possible explanation
for the high concentration of modern wood furniture stores near
Harvard Square, for example). These examples show that network
externalities, and standardization intended to exploit them, are
fairly common. There is often an advantage to agreement.

Most of the literature dealing with network externalities has
focused on technological standardization. Arthur (1985) examines the
question of how standards get extablished in the first place when
there is more than one possible standard; he finds that "small
events" will tend to determine which competing standard gets an early
lead, and that network externalities will tend to "lock in" that lead
permanently. In a historical example of such locking-in, David
(1985) studies how typewriter keyboards became standardized on the
inefficient QWERTY format, and points out the difficulties faced by
the (apparently superior) Dvorak format in gaining acceptance.

Katz and Shapiro (1985) study an oligopoly model in which firms
can choose to make their products comptible or not. They find that
the private incentives for compatibility may diverge from the social
incentives, so that firms end up with too much or too little
compatiblity. For example, a large firm may want to make its product
incompatible with those of smaller firms, so as to avoid close
competition with them.

In two recent papers, Farrell and Saloner analyze the problems
associated with switching from an existing standard to a new,

possibly superior standard. In their (1986) work, they focus on the
importance of an existing installed base for perpetuating an existing
standard. A new user deciding between joining an established old
network of relatively large size or a new network of smaller size
must guess which network future users will join, and also assess the
net present value of waiting for the new network to grow assuming
that future users do join it. The result can be that everyone sticks
with the old network even though all would have preferrred the new.
It is also possible that too many users will join the new network,
relative to the social optimum, since these users do not consider the
externality that their decisions impole on users in the installe base
of the old network. Furthermore, if these networks are produced by
firms with market power, then the firms may be able to practice
socially inefficient predation by devices such as product
preannouncements and underpricing.

Farrell and Saloner (1985) presents two models that are closely
related to this paper. In the first, f rms contemplate a shift from
an existing technology to a new one, where the technologies are
incompatible with one another, and where firms have complete
information about one another's preferences. Unlike the installed
base model, here payoffs depend only on who switches, not when they
switch. With complete information, it turns out that there can never
be symmetric excess inertia in switching to the new technology, i.e.
if all firms would favor a unanimous switch, then every firm will
switch. In the more realistic and interesting case of incomplete
information, this result disappears. Instead, a "bandwagon
equilibrium" results: If one firm is relatively eager to see the new

technology become the standard, it will switch right away and hope that the other firm follows. If the other firm does not follow a switch, some early adopters will regret their decision. Types that are less eager to switch will wait for the other firm to start the bandwagon rolling; if the other firm switches, they will follow. Finally, there are some types who will never switch, even if the other firm leads the way.[2]

In this incomplete information model, symmetric excess inertia exists when both firms are fence-sitters, hoping that the other user will switch but unwilling to take the lead themselves. There is always a positive probability that this occurs. In addition, there can be asymmetric excess inertia, where one firm is happy that no switching takes place and the other unhappy, but where the sum of the payoffs to the firms is higher under the new technology than under the old.

Bandwagon equilibria of the kind described by Farrell and Saloner have interesting implications and seem intuitively reasonable. Unfortunately, the incomplete information model used to generate them is only specified for two users, and Farrell and Saloner prove the existence of a symmetric bandwagon equilibrium only for the two-user case.

This paper extends the incomplete information model to the case of N users. In Section II, I give a constructive proof of the existence of a unique symmetric bandwagon equlibrium for an arbitrary

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[2]Rohlfs (1974) examines the demand of users for the services of a communications network. He allows users to join and leave the network at will and describes disequilibrium adjustment processes that sometimes have the bandwagon feature.

number of players. The basic idea of the proof is to show that there exists a type of player who is just indifferent between waiting for k-1 others to switch before jumping on the bandwagon and waiting for k others to switch first. By establishing this for every k, I divide the types into N+1 intervals, where types in the first interval lead a switch, types in the second interval wait for one other user to switch before jumping on bandwagon, and so on. Except for types in the first interval, and intransigents who will never switch, the users are all fence-sitters who won't switch until the network of the new technology gets large enough; lower types simply wait longer than higher types.

In Section III, I show that as in Farrell and Saloner's model, in each interval there are some types who switch only because they hope to induce others to follow them. If the bandwagon fails to keep rolling after they switch, these types are worse off thabn if they had not jumped on themselves. In addition, there is excess inertia of the symmetric and asymmetric varieties; symmetric when all the users would prefer a unanimous switch to the new standard, but none will make the first move, and asymmetric when some of the users are happy to be stuck on the old standard, but the sum of the payoffs to the users would be greater with the new standard.

Besides the kinds of inertia just described, which are directly analogous to those found in Farrell and Saloner, the N-user model has something new, which I call conditional excess inertia. This occurs when given that some players have already switched, the remaining players would benefit if they could coordinate unanimous jumping on the bandwagon, but none will lead the process. Conditional excess

inertia can also be symmetric or asymmetric, and there is always a positive probability that the realizations of player types will generate such inertia.

Excess momentum, where players jump on the bandwagon to avoid being stranded but wish it had never started rolling is a possibility in both the two-user and N-user models. Excess momentum is characterized by the losses to those "forced" to swich exceeding the gains to those eager to switch. In the N-user model, it is even possible to have excess momentum and conditional excess inertia at the same time!

If it is known that the private incentive to adopt a new standard is too small for social efficiency, and adoption appears to be suboptimal, it is natural to consider policy interventions aimed at stimulating switching. I analyze the effect of paying a fixed subsidy to any user that switches, and find that this unambiguously increases the expected number of users moving to the new standard. The subsidy has both direct and indirect effects working in the direction of making switching more likely. Similarly, "pump-priming" by the government, where it imitates an eager-to-switch user, can overcome symmetric excess inertia. This suggests applying the model to analyze Keynesian underemployment equilibrium, where firms will be able to sell additional output only if other firms choose to hire more workers, and everyone is waiting for everyone else to be the first to increase employment. I also discuss pump-priming as a way to lower the price of a new input whose production id subject to large scale economies; if the government goes ahead and buys some of the input, it will drive down its average cost, and perhaps start a bandwagon rolling among potential users of the input.

The organization of the paper is as follows: Section II presents the model and proves the existence of a unique symmetric bandwagon equilibrium. Section III discusses the properties of the equilibrium and the effects of policy interventions. In Section IV, I present some general conclusions and suggest potentially interesting extensions of the model.

II. THE MODEL

My focus in this paper is purely on the coordination problem involved in moving from one standard to another, given that each user would like other users to agree with its decision. I therefore construct a model (and find an equilibrium of that model) where all that matters are the final sizes of the two networks, and not the timing of switches or the growth paths of the networks. The only reason for putting dynamics in the model is to sort the users according to their eagerness for the new standard; more eager types switch earlier because they are more willing to gamble that they will be followed.

The essence of the model presented in this paper is that a user facing a network externality and trying to decide whether or not to switch from an old standard to a new one is very interested in how many others will follow its lead if it switches; but the user is unable to predict exactly the number of followers it actually will have in the event it does switch. As in Farrell and Saloner (1985), this uncertainty is represented as incomplete information about the preferences of the other users, and a user is allowed to switch to the new standard in any period. Switches are assumed to be irreversible once made, so that some binding commitment such as investment in specialized equipment or signature of a contract is implicit in this formulation. The game has a countably infinite number of periods, but a finite time horizon T, normalized so that T=1. The first period begins at time 1/2, the second at 2/3, and the Nth at N/N+1. This rather artificial time structure is necessary to

maintain subgame perfection off the equilibrium path that I construct; on the equilibrium path, only N periods are needed.[3]

More formally, there are two standards: X, which is the initial standard for all N users, and Y, which is the proposed new standard. Users differ in their preferences over X and Y, and these preferences are indexed by i, where higher values of i are more favorable toward Y. For convenience, i is restricted to interval [0,1] and all types are assumed equally probable ex ante; that is, i is distributed uniformly on the unit interval.

The payoff to a user of type i of being on standard Z with a network size of m is denoted by $B(i,m,Z)$, where Z is either X or Y. Benefits to being on standard Y are normalized to be net of switching costs.

The structure of the game among the users is the following: At time 0, each user's type is realized. A user's own type is private information, but the distribution of i is common knowledge. Initially, all players are using X. Starting from time 1/2 and thereafter until time 1, a user can decide in any period to switch from X to Y. In each period, all switches take place simultaneously. Switches are public and irreversible; the status of each user's standard is always common knowledge. After time 1, no further

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[3]With a finite number of periods, there will be a final period in which switching is possible. If a player switches just before this period, other players may not get an opportunity to follow his switch, which means that players will have to condition their switching behavior on what period it is. By introducing a countably infinite number of periods, I avoid the possibility that players will be denied an opportunity to react to switches, since there is no last period. Thus, the timing setup allows a stationary equilibrium to be sustained. For more discussion of this issue, see part (2) of the proof of Proposition 1.

switching is allowed, and the users receive their payoffs; the interpretation here is that the game among the users takes a short time relative to the time over which the benefits will be received.

I make the following assumptions about the benefit functions:

(A1) $B(i,j,Z) < B(i,k,Z)$ for $j<k$, $Z=X$ or y, for any i.

(A2) $B(i,k,Y) - B(i,j,X)$ is strictly increasing in i for any k and any j.

(A3) $B(i,j,Z)$ is everywhere differentiable in i.

(A4) $B(0,N,Y) < B(0,1,X)$ and $B(1,1,Y) > B(1,N,X)$.

The first assumption says that networks are beneficial; <u>ceteris paribus</u>, users would rather be on a bigger network. A2 gives a formal meaning to user type. A higher value of i has a greater preference for Y over X with any fixed network sizes. A3 is purely a mathematical convenience. The last assumption ensures that there are low types who are "intransigent" and prefer being alone on standard X to being with everyone else on Y. It also means that there are high types who are "trailblazers" and prefer being the only switching player to staying with everyone else at the <u>status quo</u>. The existence of both classes of types, combined with A2, in turn ensures that there are at least some types who care about how many others switch, which is necessary to make the model non-trivial. The shapes of the benefit functions are common knowledge.

At any moment after Period 0, a user knows its own type, the benefit functions, the density from which the other users' types are drawn and how many others have switched. Trivially, it also knows if it has itself switched; if it has, then it has no more decisions to make. The only information that changes over the course of periods 1/2, 2/3,... is the number who have switched. It follows, then, that at time 0 a user could specify wherther or not it would switch as a function of the number of others who have switched, when the others switched, their identities, and time. I call such a function an action rule; it completely describes what the user wants to do in the course of the game. Presumably, a low-type user would want to specify a different action rule from a high-type user. A strategy, then, is a mapping from the set of types to the set of action rules; it assigns a unique action rule to each type i. Before time 0, the moment when types are realized, a user can choose its strategy. After it learns its type, the user's strategy tells it which action rule to employ.

I look for a stationary equilibrium of this game, where all the action rules chosen by the users are of the form "switch if at least m others have switched already." Action rules of this form make the user's behavior depend only on how many others switch, and not on when they switch, who switches, or the number of the current period. Since the number of others who switch is the only factor that is directly payoff-relevant in this game, such an equilibrium is intuitively appealing.[4]

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[4]Restricting strategies to be conditioned only on variables that are directly payoff-relevant is an application of the Markov Perfect Equilibrium concept defined in Maskin and Tirole (1986). The only difference is that here I apply it to a game of incomplete information.

Define a_k to be the action rule "switch if at least k-1 others have switched already." Then there are N+1 possible action rules, ranging from a_1 - "switch unilaterally" through a_{N+1} - "never switch." Generalizing Farrell and Saloner (1985), I define a bandwagon strategy to be a vector $(i_1,\ldots,i_N)$ with all elements in [0,1], where $i_1 > i_2 > \ldots > i_N$ such that a type in the interval $(i_k,i_{k-1}]$ plays a_k. This strategy implies that a higher type is more aggressive about switching, while a lower type will wait for a larger Y network to form before switching. A type in $(i_1,1]$ switches without waiting for anyone, while a type in $[0,i_N]$ never switches.

A bandwagon equilibrium is then defined to the a perfect Bayesian Nash equilibrium in which each user plays a bandwagon strategy. I will focus only on symmetric bandwagon equilibria, those where $(i_1,\ldots,i_N)$ is the same for each user. I'm not sure what conditions on the benefit functions, if any, allow an asymmetric bandwagon equilibrium to exist. If one does exist, it can't be unique, since the players are ex ante symmetric and could always swap roles. It's hard to see how such an equilibrium could be focal.

On a symmetric bandwagon equilibrium path, the beliefs of a player about the types of the other players follow a simple trajectory. If k players have switched by the end of Period t, then player j's posterior about the types of players who have not switched by the end of Period t+1 has support $[0,i_{k+1}]$. To see this, note that on the equilibrium path, if a player m is in $(i_{k+1},1]$ and k players (not including m) switch by the end of Period t, then m will switch in Period t+1. Hence, any player who has not switched by the end of t+1 must lie in $[0,i_{k+1}]$.

If the players are in a symmetric bandwagon equilibrium, their strategies are easily described by $i_1,\ldots,i_N$; however, their actual behavior is fairly complicated. Suppose a player's type falls into $(i_k,i_{k-1}]$ so that he plays a_k, which means that he switches iff at least k-1 others switch before him. For a player j to switch before him, j must use an action rule more aggressive than a_k, one of $a_1,\ldots,a_{k-1}$. Therefore, someone playing a_k switches only if there are at least k-1 others choosing form $a_1,\ldots,a_{k-1}$. This condition is necessary, but not sufficient; each of the players using actions a_1 through a_{k-1} faces the same necessary condition for switching. In general, the necessary and sufficient condition to get someone playing a_k to switch is that at least k-1 others choose from $a_1,\ldots,a_{k-1}$ and at least k-2 others choose from $a_1,\ldots,a_{k-2}$ and...and at least 1 other chooses a_1. If we call $(i_1,1]$ the first interval and $[0,i_N]$ the last interval, this means that someone in the kth interval switches iff there is at least one player in the first interval, at least two in the first two intervals,...,and at least k-1 in the first k-1 intervals. If $(i_1,1]$ is empty, no one switches.

Now that I have described the stationary strategies and the equilibrium trajectories of beliefs associated with a symmetric bandwagon equilibrium, I can show that if N-1 players are employing symmetric bandwagon strategies, then the Nth player will find it optimal to choose a stationary action rule.

Lemma 1: Suppose players $(1,\ldots,N-1)$ are each using the same bandwagon strategy $(i_1,\ldots,i_N)$. Then player N will find it optimal to choose a stationary action rule from the set $(a_1,\ldots,a_{N+1})$.

Proof: (1) Since all payoffs occur at time 1, after the game is played, the timing of player N's switch has no direct effect on N's payoff. The only effect it could have is through influencing the behavior of the other players. But the other players are employing bandwagon strategies, which map types into stationary action rules only, so players 1,...,N-1 will ignore the timing of N's switch. Since there is an infinite number of opportunities for switching, player N need not fear that other players won't have a chance to follow his switch. Hence, player N can gain nothing by choosing an action that makes his switching behavior contingent on what period it is.

(2) Since the addition of any user to a network has the same effect on the benefits associated with that network, regardless of the user's name (or type), the identity of players who switch has no direct effect on payoffs. And because player N is equally informed about the types of all players who have not yet switched, he can make no inference about how many others will follow if he switches based on the names of the players who have already switched. Hence, player N can gain nothing by choosing an action that conditions his switching behavior on the names of those who switch.

(3) The timing of other players' switches has no direct effect on the payoff of player N. However, the timing of switches does convey some information about the types of other players. Since switching is irreversible, information about the types of players who have already switched should have no effect on N's decision to switch. Therefore, if the timing of switches is relevant to N's optimal behavior, it must be because the timing of switches allows

useful inferences to be made about the types of those who haven't yet switched.

With the other players pursuing bandwagon strategies, the longer it takes for a given number of users to switch to the Y standard, the less weight N's posterior puts on high (i.e. pro-Y) types among the remaining members of the X network. If k-1 players switch in the first period, then N's posterior about the types of the remaining N-k+1 players is uniform on $[0,i_1]$; if one player switches in each of the first k-1 periods, N's posterior on the remaining N-k players has their types uniformly distributed on $[0,i_{k-1}]$. Since i_{k-1} is less than i_1, having the firms switch early increases the probability that a switch by N would be followed by other players.

Suppose a_k is optimal for player N in the class of stationary action rules. For a non-stationary action rule to be superior to a_k, it must involve switching when fewer than k-1 others switch if they move fast enough, or it must involve not switching when k-1 others switch if they move slowly enough.

Player N's switching decision can be reduced to two bases: How many of the other players will switch regardless of whether he does, and how many will switch if and only if he does. A policy that conditions N's behavior on the timing of other players' switches only helps if that timing sheds light on either of these quantities. But it never makes sense to guess how many will switch independently of N's behavior; waiting until all the other players have stopped switching reveals that number costlessly. Furthermore, N's posterior beliefs about the players who have not yet switched, and hence about how many will join Y if and only if N joins Y, is unaffected by the

timing of switches, given that all independent switching has stopped. Costless waiting thus eliminates the rationale for using timing information. (The optimal rule a_k does not involve waiting because its rationale is that if <u>at least</u> k-1 switch, then joining the Y network is desirable. A non-stationary action rule, however, only makes sense if guessing makes sense.)

(1), (2), and (3) together imply that player N's optimal action rule is sta ionary if the other N-1 players follow symmetric bandwagon strategies.

As one considers more players in a bandwagon equilibrium, the number of possible distributions of players into intervals grows explosively: In fact, with N users, there are 2N choose N possible sequences.[5] As a result, calculations of the probabilities of having different numbers of players switch become intractable. In the proof of equilibrium that I provide, I avoid explicitly calculating these probabilities in terms of $i_1, \ldots, i_N$. Not having a general formula for these probabilities is awkward when trying to predict the behavior of the users but does not affect one's general understanding of bandwagon equilibria.[6]

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[5]A bandwagon equilibrium with N players divides the unit interval into N+1 subintervals. The number of distinguishable allocations of the N players into the N+1 cells is just the number of selections (with repetitions) of N objects from N+1 types of objects. The expression for this number is C(N+1+N-1,N)=C(2N,N). See Tucker (1980).

[6]The work of Granovetter and Soong (1986) looks at the dynamics of bandwagons with a continuum of users. They consider the effects of changing prices, as well as "reverse" bandwagons where consumption externalities are negative. When both positive and negative externalities are present at different levels of aggregate consumption, they show that chaotic demand dynamics can result.

To establish the existence of a symmetric bandwagon equilibrium under A1-A4, I show that for a user f facing other users who play an appropriately constructed bandwagon strategy, f's best response is the same bandwagon strategy. The construction is accomplished first in a lemma, and I then go on to prove that the desired equilibrium results in Proposition 1.

Suppose that the other players are employing the symmetric bandwagon strategy $(i_1,\ldots,i_N)$. Depending on his type, each of the other N-1 players falls into one of three groups: Those who will switch regardless of what f does, those who will switch if and only if f does, and those who will never switch. Player f has prior probabilities on the size of these three groups. Note that these are equilibrium outcome probabilities; they are the probabilities that when the game is over at time 1, some number of players will have switched even if f doesn't switch, some number of players will have switched only if f does switch, and some number will not have switched even if f does switch. These equilibrium outcome probabilities are calculated before switching starts under the assumption that the other users are all playing the bandwagon strategy $(i_1,\ldots,i_N)$.

Since his optimal action rule is stationary by Lemma 1, f can commit himself to an action drawn from the list $a_1,\ldots,a_{N+1}$ as soon as he learns his type, without reduction in his payoff. This decision depends on the priors discussed above. Define P(k) to be the probability that exactly k out of the N-1 other users switch, even if f does not switch, given that all N-1 play the bandwagon strategy. P(k) depends only on $i_1,\ldots,i_{k+1}$; it is the probability

that exactly k of the <u>other</u> users lie in $(i_k,1]$ <u>and</u> at least k-1

others lie in $(i_{k-1},1]$ <u>and</u>...<u>and</u> at least one other user lies in

$(i_1,1]$ <u>and</u> none lie in $(i_{k+1},i_k]$.

Now define $P(m|j)$ as the probability that exactly m <u>others</u>

switch after f switches, given that exactly j switched independently

of f, and given that all N-1 other users play $i_1,\ldots,i_N$ as a

bandwagon strategy. If exactly j switched independently, then as

described above there is at least one user in $(i_1,1]$ <u>and</u> at least two

users in $(i_2,1]$ <u>and</u>...<u>and</u> at least j-1 users in $(i_{j-1},1]$ <u>and</u> exactly

j users in $(i_j,1]$ <u>and</u> no users in $(i_{j+1},i_j]$. Anyone who follows a

switch by f but did not switch independently of f must have a type

lying in $[0,i_{j+1}]$; for exactly m to follow f's switch, there must be

at least one user in $(i_{j+2},i_{j+1}]$ <u>and</u> at least two users in

$(i_{j+3},i_{j+1}]$ <u>and</u>...<u>and</u> at least m-1 users in $(i_{j+m},i_{j+1}]$ <u>and</u> exactly m

users in $(i_{j+m+1},i_{j+1}]$ <u>and</u> no users in $(i_{j+m+2},i_{j+m+1}]$. So $P(m|j)$

depends only on $i_{j+1},\ldots,i_N$ at most. In particular, note that

$$P(0|j) = (i_{j+2}/i_{j+1})^{N-j}$$

and that

$$P(0|j) + P(1|j) +\ldots+ P(N-j-1|j) = 1.$$

The bandwagon equilibrium will be constructed by starting with

the problem facing a player who is the last on the X network, then

considering the decision problem faced by two remaining members of X,

then applying mathematical induction for X populations of sizes

ranging up to N.

Let i_N be defined by $B(i_N,1,X) = B(i_N,N,Y)$. The existence of

i_N is guaranteed by A2 and A4. From this definition it follows that

all $i \leq i_N$ are intransigent--they will never switch. If N-1 have already switched, the $i > i_N$ will follow the move to Y. Note that if users are playing bandwagon strategies, i_N is independent of $i_1, \ldots, i_{N-1}$.

Having solved the decision problem facing a lone holdout on the old network, I now look at the game between two players still on X if the other N-2 have switched to Y. Define i^* to be an arbitrary (symmetric) cutoff such that all types below i^* choose a_N over a_{N-1} and all types above i^* choose a_{N-1} over a_N. Now define

$$g^{N-1}(i, i^*) = P(N-2)[\ P(0|N-2)B(i,N-1,Y) + P(1|N-2)B(i,N,Y)$$
$$- B(i,2,X)\ ].$$

This expression is just the difference in expected payoff between a_{N-1} and a_N for a user of type i, given that both players observe the i^* cutoff; the cutoff enters g^{N-1} through $P(0|N-2)$ and $P(1|N-2)$. The two action rules a_{N-1} and a_N have the same payoff except in the case where exactly N-2 others have already switched. (I establish this fact in the proof of Proposition 1.) Lemma 2 shows that there exists a unique value i_{N-1} in $(i_N, 1)$ such that $i^* = i_{N-1}$ is a perfect Bayesian equilibrium of the two-player subgame.

Lemma 2: There exists a unique value i_{N-1} of i^* in $(i_N, 1)$ such that $g^{N-1}(i, i_{N-1})$ has the sign of $i - i_{N-1}$, i.e. such that $i^* = i_{N-1}$ is the unique symmetric Bayesian equilibrium of the two-player subgame. This value is determined independently of $i_1, \ldots, i_{N-2}$.

Proof: (1) $P(0|N-2) + P(1|N-2) = 1$

$B(i,N-1,Y) < B(i,N,Y)$ by A1

Therefore

$g^{N-1}(i_N,i_N) < P(N-2)[\ B(i_N,N,Y) - B(i_N,2,X)\ ]$

But $B(i_N,N,Y) = B(i_N,1,X) < B(i_N,2,X)$

So $B(i_N,N,Y) - B(i_N,2,X) < 0$, and since $P(N-2)>0$,

$P(N-2)[\ B(i_N,N,Y) - B(i_N,2,X) < 0.$

Therefore, $g^{N-1}(i_N,i_N) < 0$.

(2) $g^{N-1}(1,1) = P(N-2)[\ P(0|N-2)B(1,N-1,Y)$

$+ P(1|N-2)B(1,N,Y) - B(1,2,X)\ ]$

$> P(N-2)[\ B(1,N-1,Y) - B(1,2,X)\ ]$

But $B(1,N-1,Y) > B(1,1,Y) > B(1,N,X) > B(1,2,X)$.

(The middle inequality is just A4.)

So $g^{N-1}(1,1) > 0$.

(3) Impose $i=i^*$. Let $D_iF(i,i^*)$ be the first derivative

with respect to i (and hence i^*) of the function F.

$P(N-2)$ does not depend on i^*; $P(0|N-2) = i_N/i^*$ and

$P(1|N-2) = (i^*-i_N)/i^* = 1 - P(0|N-2)$. Therefore,

$D_i g^{N-1}(i,i^*) = P(N-2)[\ D_iP(0|N-2)B(i,N-1,Y)$

$+ D_iP(1|N-2)B(i,N,Y)$

$+ P(0|N-2)D_iB(i,N-1,Y)$

$+ P(1|N-2)D_iB(i,N,Y)$

$- D_iB(i,2,X)\ ]$

$> P(N-2)[\ (D_iP(0|N-2)+D_iP(1|N-2)) * B(i,N-1,Y)$

$+ (P(0|N-2)+P(1|N-2))$

$$* \text{Min} \{ D_i B(i,N-1,Y), D_i B(i,N,Y) \}$$

$$- D_i B(i,2,X) \ ]$$

$$- P(N-2)[\ \text{Min} \{ D_i B(i,N-1,Y), D_i B(i,N,Y) \}$$

$$- D_i B(i,2,X) \ ]$$

which is strictly positive by A2.

(4) Since $g^{N-1}(i_N, i_N) < 0$, $g^{N-1}(1,1) > 0$, and $g^{N-1}(i,i)$ is continuous and strictly increasing on $(i_N, 1]$, there exists a unique i_{N-1} in $(i_N, 1)$ such that $g^{N-1}(i_{N-1}, i_{N-1}) = 0$. This construction depended only on i_N and the benefit functions, so $i_1, \ldots, i_{N-2}$ could have any arbitrary value.

This completes the proof.

Now I show that if one can find $i_{N-1}, \ldots, i_{k+1}$ such that $g^{N-1}(i_{N-1}, i_{N-1}) = 0$, $g^{N-2}(i_{N-2}, i_{N-2}) = 0, \ldots,$ $g^{k+1}(i_{k+1}, i_{k+1}) = 0$, then there exists i_k such that $g^k(i_k, i_k) = 0$. Thus, if the subgames with up to N-k players remaining on the old network admit unique fixed-point solutions, then the problem for N-k+1 on X does also; Lemma 3 demonstrates that there exists a type in $(i_{k+1}, 1)$ who is just indifferent between a_{k+1} and a_k. In Proposition 1, I will establish that $g^k(i,i)$ is just the difference in expected payoff between a_k and a_{k+1} for a player of type i, given that the other players all use symmetric bandwagon strategies.

Lemma 3: Suppose we are able to construct $i_{N-2}, \ldots, i_{k+1}$ all with analogous properties to i_{N-1}. Then we can find an analogous i_k,

i.e. then there exists a unique i_k in $(i_{k+1},1)$ such that

$g^k(i_k,i_k) = 0$, $g^k(i,i_k)$ has the sign of $i-i_k$, and the value of i_k is

independent of the $i_{k-1},\ldots,i_1$ chosen by the k-1 who switch to Y.

Proof: Define i^* as an arbitrary symmetric cutoff between

players who choose a_k and a_{k+1}. Then

$$g^k(i,i^*) = P(k-1)[\ P(0|k-1)B(i,k,Y)$$

$$+\ldots+P(N-k|k-1)B(i,N,Y)$$

$$-B(i,N-k+1,X) \ ]$$

(1) $P(0|k-1) = (i_{k+1}/i^*)^{N-k}$, so when $i^* = i_{k+1}$, $P(0|k-1) = 1$.

This means that for $i^* = i_{k+1}$, $P(1|k-1)+\ldots+P(N-k|k-1) = 0$.

Now $g^k(i_{k+1},i_{k+1}) < P(k-1)[\ P(0|k-1)B(i_{k+1},k,Y)$

$$+ \ (P(1|k-1)+\ldots+P(N-k|k-1))B(i_{k+1},N,Y)$$

$$- \ B(i_{k+1},N-k+1,X) \ ]$$

$$= P(k-1)[\ B(i_{k+1},k,Y) - B(i_{k+1},N-k+1,X) \ ]$$

But we know that $g^{k+1}(i_{k+1},i_{k+1}) = 0$, and

$g^{k+1}(i_{k+1},i_{k+1}) = P(k)[\ P(0|k)B(i_{k+1},k+1,Y)$

$$+\ldots+ \ P(N-k-1|k)B(i_{k+1},N,Y)$$

$$- \ B(i_{k+1},N-k,X) \ ].$$

$$> P(k)[\ (P(0|k)+\ldots+P(N-k-1))B(i_{k+1},k+1,Y)$$

$$- \ B(i_{k+1},N-k,X) \ ]$$

$$= P(k)[\ B(i_{k+1},k+1,Y) - B(i_{k+1},N-k,X) \ ]$$

So now we know that the last square bracketed term is negative.

Since it is larger than $[B(i_{k+1},k,Y) - B(i_{k+1},N-k+1,X)]$, we

have $g^k(i_{k+1},i_{k+1}) < 0$.

(2) $g^k(1,1) = P(k-1)[\ P(0|k-1)B(1,k,Y) +\ldots+ P(N-k|k-1)B(1,N,Y)$

$$- B(1,N-k+1,X)]$$

$$> P(k-1)[B(1,k,Y) - B(1,N\cdot k+1,X)]$$

But $B(1,k,Y) > B(1,1,Y) > B(1,N,X) > B(1,N-k-1,X)$

So $g^k(1,1) > 0$.

(3) Constrain $i = i^*$. Then for $i > i_{k+1}$,

$$D_i g^k(i,i) = P(k)[D_i P(0|k-1)B(i,k,Y) +...+ D_i P(N-k|k-1)B(i,N,Y)$$

$$+ P(0|k-1)D_i B(i,k,Y) +...+ P(N-k|k-1)D_i B(i,N,Y)$$

$$-D_i B(i,N-k+1)]$$

$$> P(k)[(D_i P(0|k-1)+...+D_i(P(N-k|k-1))B(i,k,Y)$$

$$+ (P(0|k-1)+...+P(N-k|k-1))*$$

$$Min\{D_i B(i,k,Y),...,D_i B(i,N,Y)\}$$

$$- D_i B(i,N-k+1,X)]$$

Since $P(0|k-1)+...+P(N-k|k-1)$ is identically one, the last

expression is just

$$P(k)[Min\{D_i B(i,k,Y),...,D_i B(i,N,Y)\} - D_i B(i,N-k+1,X)]$$

which is strictly positive by A2.

Therefore $D_i g^k(i,i) > 0$.

(4) Since $g^k(i_{k+1},i_{k+1}) < 0$, $g^k(1,1) > 0$, and $g^k(i,i)$ is

continuous and strictly increasing in i, there exists a unique

i_k in $(i_{k+1},1)$ such that $g^k(i_k,i_k) = 0$, and $g^k(i,i_k)$ has the

sign of $i-i_k$. The construction of i_k depended only on

$i_N,...,i_{k+1}$ and the benefit functions, so i_k is independent of

$i_{k-1},...,i_1$. This establishes the Lemma.

Lemma 2 and Lemma 3 together provide a proof by mathematical

induction that it is possible to construct a vector $i_{N-1},...,i_1$ such

that $g^{N-1}(i_{N-1}, i_{N-1}) = 0, \ldots, g^1(i_1, i_1) = 0$. Now I can establish the main result.

Proposition 1: With $i_N, \ldots, i_1$ as defined above, a unique symmetric bandwagon equilibrium exists.

Proof: Let $u(i, a_k)$ be the expected benefit to a user of type i when it chooses a_k and all other users play the bandwagon strategy $i_1, \ldots, i_N$. Let $Pr(j, Y|a_k)$ be the probability of ending up in a Y network of size j if you choose a_k, and $Pr(j, X|a_k)$ the analogous probability for an X network of size j.

(1) Note that if i plays a_k, the smallest possible Y network i can be a part of has size k. The smallest possible X network that i can be a part of has size N-k+2, which occurs when exactly k-2 other players switch. With these facts in mind, I can write

$$u(i, a_k) = Pr(k, Y|a_k)B(i, k, Y) + \ldots + Pr(N, Y|a_k)B(i, N, Y)$$
$$+ Pr(N-k+2, X|a_k)B(i, N-k+2) + \ldots + Pr(N, X|a_k)B(i, N, X)$$

It also follows that
$$Pr(k+r, Y|a_k) = P(k+r-1)P(0|k+r-1) + \ldots + P(k-1)P(r|k-1)$$

So $Pr(k+r, Y|a_k) - Pr(k+r, Y|a_{k+1})$
$$= [P(k+r-1)P(0|k+r-1) - P(k+r-1)P(0|k+r-1)]$$
$$+ [P(k+r-2)P(1|k+r-2) - P(k+r-2)P(1|k+r-2)]$$
$$+ \ldots + [P(k)P(r-1|k) - P(k)P(r-1|k)]$$
$$+ [P(k-1)P(r|k-1) - 0]$$

$$= P(k-1)P(r|k-1)$$

The only case when playing a_k instead of a_{k+1} matters to a user's probability of switching to Y occurs when exactly k-1 others switch independently of the given user. Intuitively, if k or more others switch independently, then the user switches under either a_k or a_{k+1}, while if k-2 or fewer switch independently, then the user stays with X under a_k or a_{k+1}.

Now note that $\Pr(k+r, X|a_k) = P(N-k-r)$ for $k+r \geq N-k+2$

$$= 0 \qquad \text{for } k+r < N-k+2$$

It follows that

$$
\begin{aligned}
u(i,a_k) - u(i,a_{k+1}) = \ & [\Pr(k,Y|a_k) - 0]B(i,k,Y) \\
& + [\Pr(k+1,Y|a_k) - \Pr(k+1,Y|a_{k+1})]B(i,k+1,Y) \\
& +\ldots+ [\Pr(N,Y|a_k) - \Pr(N,Y|a_{k+1})]B(i,N,Y) \\
& + [0 - \Pr(N-k+1,X|a_{k+1})]B(i,N-k+1,X) \\
& + [\Pr(N-k+2,X|a_k) - \Pr(N-k+2,X|a_{k+1})]B(i,N-k+2,X) \\
& +\ldots+ [\Pr(N,X|a_k) - \Pr(N,X|a_{k+1})]B(i,N,X) \\
= \ & P(k-1)P(0|k-1)B(i,k,Y) + P(k-1)P(1|k-1)B(i,k+1,Y) \\
& +\ldots+ P(k-1)P(N-k|k-1)B(i,N,Y) \\
& - P(k-1)B(i,N-k+1,X) \\
& + [P(k-2) - P(k-2)]B(i,N-k+2,X) \\
& +\ldots+[P(0) - P(0)]B(i,N,X) \\
= \ & P(k-1)[P(0|k-1)B(i,k,Y) +\ldots+ P(N-k|k-1)B(i,N,Y) \\
& \qquad - B(i,N-k+1,X)] \\
= \ & g^k(i,i)
\end{aligned}
$$

This shows that $u(i,a_k) - u(i,a_{k+1}) = g^k(i,i)$. Now the rest of the proof is straightforward. From Lemma 2, $u(i,a_k) - u(i,a_{k+1})$ has

the sign of $i - i_k$. Therefore, any type higher than i_k prefers a_k to a_{k+1}. So now it follows that

If $i > i_N$, then $u(i,a_N) > u(i,a_{N+1})$

If $i > i_{N-1}$, then $u(i,a_{N-1}) > u(i,a_N)$

...

If $i > i_1$, then $u(i,a_1) > u(i,a_2)$

Therefore the bandwagon strategy $i_1,\ldots,i_N$ is the unique best response to the bandwagon strategy $i_1,\ldots,i_N$ played by everyone else.

(2) The argument up to now has established that the bandwagon strategy $i_1,\ldots,i_N$ is a Bayesian Nash equilibrium, in that along the equilibrium path, if everyone else uses this strategy in every period of the game, then so should the last player. However, the definition of bandwagon equilibrium included the requirement of subgame perfection, which means that the bandwagon strategy must be the optimal response even if someone else deviates from it. The deviation is an event of zero prior probability; in a bandwagon equilibrium it is never rational to deviate.

Deviations from the equilibrium path are important only insofar as other players are aware of them. In a bandwagon equilibrium, switches take place for a finite number of periods (perhaps zero) starting in the first period, and then stop forever. Any behavior consistent with this pattern will not be interpreted as a deviation by any other player. A deviation from the equilibrium path can only be observed if it induces a player to switch after a period in which there was no switching. Resumption of switching after a hiatus is always off the equilibrium path, and all deviations take this form.

What is the optimal response to such a deviation? Since switching is irreversible, the type of the deviant who switched after a hiatus is not directly payoff-relevant to any player. And since the types of the players represent independent draws from a distribution, whether the deviant is seen as someone who should have switched earlier, or as someone who should not have switched at all has no effect on inferences about the players who have not yet switched. Hence beliefs about those who have not yet switched are updated in the equilibrium manner.

With equilibrium beliefs in the face of a delayed switch, the bandwagon strategy must be optimal, unless the delay prevents some players from pursuing their optimal actions. With a finite number of periods, this would be a problem, since a switch delayed until the penultimate period, for example, might not leave other players enough time to carry out a chain of switches called for by their bandwagon strategies. To be specific, with three users and three periods, suppose f's optimal action under his bandwagon strategy is a_2, because he hopes to be followed by the third player if he follows a switch by the first player. If no one switches in the first period, but then one of the other players switches in the second period (a deviation), f knows that if he follows in the third period, the game will end without the third player having an opportunity to follow him. So a_2 might not be the optimal response to a delayed switch. Since the model in this paper actually has an infinite number of periods, the problem can never occur. Therefore, the equilibrium bandwagon strategy is the best response to a deviation.

(3) Any symmetric equilibrium must have $g^{N-1}(i_{N-1}, i_{N-1}) = 0$, $g^{N-2}(i_{N-2}, i_{N-2}) = 0, \ldots, g^1(i_1, i_1) = 0$. But then Lemmas 1 and 2 imply that the symmetric bandwagon equilibrium is unique.

(1), (2), and (3) together imply that there exists a unique symmetric bandwagon equilibrium. This proves Proposition 1.

Corollary 1: The unique symmetric bandwagon equilibrium is the unique symmetric stationary-strategy equilibrium.

Proof: A stationary strategy is a mapping from the set of types to the set of stationary action rules $a_1, \ldots, a_{N+1}$. No matter what profile of stationary action rules the other players choose, the Nth player will always find that if his optimal strategy says to choose a_k when his type is i', then it says to choose an action from $a_k, \ldots, a_{N+1}$ when his type is i < i'. This follows directly from A2; a higher type will always be at least as eager to switch as a lower type, since a higher type values standard Y more, relative to standard X, than does a lower type. Since the benefit functions are continuous in i, there will always be a level of i that makes a player indifferent between a_k and a_{k+1}, no matter what stationary strategies the other players employ. Thus, every optimal stationary strategy is a bandwagon strategy. But Proposition 1 establishes that there exists a unique symmetric bandwagon equilibrium, so it must also be the unique symmetric stationary strategy equilibrium.

III. DISCUSSION OF EQUILIBRIUM

The bandwagon equilibrium constructed in the previous section has several interesting features. First, note that the equation $g^k(i_k, i_k) = 0$, which implicitly defines i_k, looks like

(*) $\quad P(0|k-1)B(i_k,k,Y) + \ldots + P(N-k|k-1)B(i_k,N,Y) = B(i_k,N-k+1,X)$.

Therefore, $[P(0|k-1) + \ldots + P(N-k|k-1)]B(i_k,N,Y) < B(i_k,N-k+1,X)$. So $B(i_k,k,Y) < B(i_k,N-k+1,X)$. This implies that in every interval k there are some types who switch after k-1 others have switched only because they hope that others will follow; if no one follows their switch to Y, they will regret their decision ex post. In particular, some of the "early adopters" in the first interval $(i_1,1]$ are not "trailblazers" as described in the discussion of A4; they switch only in hopes of getting the bandwagon rolling.

In the two-user case, Farrell and Saloner (1985) define symmetric excess inertia to be the situation where both users would prefer a unanimous switch from X to Y, but neither is willing to switch first and risk not being followed. They show that there is always a positive probability that such inertia exists with two users. Extending this definition to the N-user case, let i^u be defined by $B(i^u,N,Y) = B(i^u,N,X)$. Then any type above i^u would prefer a unanimous switch to Y, and there is symmetric excess inertia whenever every user's type falls in the interval (i^u,i_1). To show that this happens with positive probability, it suffices to demonstrate that

$i^u < i_1$, and this is easy to see from the defining equation
$g^1(i_1,i_1) = 0$:

$$P(0|0)B(i_1,1,Y) +...+ P(N-1|0)B(i_1,N,Y) = B(i_1,N,X)$$

Since $P(0|0)+...+P(N-1|0) = 1$, A1 implies that
$B(i_1,N,Y) > B(i_1,N,X)$, so $i^u < i_1$ by A2. Thus, there is always a
positive probability of symmetric excess inertia.

In the N-user model, one can further define <u>conditional
symmetric excess inertia</u>. Let $i^{c(k)}$ be defined by
$B(i^{c(k)},N,Y) = B(i^{c(k)},N-k+1,X)$. Then given that k-1 users have
already switched, a type above $i^{c(k)}$ would prefer that all of the
remaining users switch to Y, while a type below $i^{c(k)}$ would prefer
that the remaining N-k+1 users stay with standard X. Conditional
symmetric excess inertia occurs when k-1 users switch and the N-k+1
others all lie in the interval $(i^{c(k)},i_k)$. All the holdouts would
prefer a unanimous switch to Y, but none will take the risk of not
being followed. There is always a positive probability of such
inertia, because equation (*) implies that $B(i_k,N,Y) > B(i_k,N-k+1,X)$,
and then A2 tells us that $i^{c(k)} < i_k$.

<u>Asymmetric excess inertia</u> occurs when even though all users
would not prefer a unanimous move to Y, the sum of the benefit
functions B(i,N,Y) over all users exceeds B(i,N,X) summed over all
users.[7] This kind of inertia always exists with positive probability,
since starting with symmetric excess inertia and changing the type of

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[7]Note that the implicit assumption of cardinal, transferrable
utilities is needed only for asymmetric excess inertia; the usual
Pareto-optimality rules are sufficient for symmetric excess inertia.

one or more players to be below i_u can generate the asymmetric

variety. <u>Conditional asymmetric excess inertia</u> is defined and

constructed analogously.

There is also a possibility of <u>excess momentum</u>--k users switch

to Y but the sum of the benefits is less than the sum over $B(i,N,X)$

for all the switching users. However, only some specifications of the

benefit functions allow excess momentum to occur. In general, if any

user switches whose type is less than i^u, that user will wish that no

one had started switching. Excess momentum occurs when the losses

suffered by such users exceed the gains to those above i^u who switch.

For i^u sufficiently low (it can't be lower than i_N), and for benefit

functions where low types are nearly indifferent between X and Y, this

will be impossible.

It is always possible to have inefficiently large amounts of

switching, even when there is no excess momentum. To see this, note

that it is possible for all the users but one to be "intransigents" in

the last interval, while the remaining user is in the first interval

but is not a "trailblazer." Then the early adopter will switch,

hoping to be followed, but no one will; he will regret his switch <u>ex</u>

<u>post</u>. The intransigents will also be worse off because of the switch,

since the X network will be smaller by one. No user below i^u has been

stampeded onto the Y network, but there is still too much switching.

This model of bandwagon equilibrium with N users also offers

some insights into the role and effects of various promotional

policies. For example, suppose a fixed subsidy of v is paid to any

user switching from X to Y. The effect of this is to raise the

benefits to a user of type i from joining a Y network of size k to

$B(i,k,Y) + v$. There are two channels through which this intervention affects the equilibrium. First, there is a direct effect on each i_k. Since i_k without subsidy is defined by (*), adding v to the left-hand side of the equation while holding the right-hand side unchanged makes forces an adjustment in the cutoffs between the intervals. Holding $i_N, \ldots, i_{k+1}$ fixed then requires that i_k fall, since A2 says that the difference between the left and right sides of (*) is increasing in i. So the subsidy has the direct effect of lowering each i_k.

But given this direct effect, there is a second, indirect consequence of subsidizing Y. Because the conditional probabilities in (*) are functions of $i_N, \ldots, i_{k+1}$, the reduction of these interval boundaries due to the direct effect changes the level of i_k that solves the equation. Specifically, when i_{k+1} is reduced, the probability that there is no one in k+1st interval falls, which lowers $P(0|k-1)$ and raises the conditional probabilities of achieving higher network sizes of Y if the user switches. Similarly, reducing i_{k+2} lowers $P(1|k-1)$ and raises $P(2|k-1), \ldots, P(N-k|k-1)$. This shift of probability mass to the larger network sizes raises the left-hand side of (*), so that i_k must fall to maintain equality. Therefore, i_k is driven down by two forces: The direct effect of the subsidy on the benefit functions for Y, and the indirect effect of reduced $i_N, \ldots, i_{k+1}$ on the conditional probabilities of other users following a switch.

Of course, such subsidies could be provided by the government, but a private actor might have an incentive to do so. If technology Y is being sold to the players in the game be a monopolist, the monopolist can effectively choose v by altering the price. The

effects of lowering each of $i_1, \ldots, i_N$ is always to increase the expected size of the Y network, so in the case of a monopolist the behavior of the users is like a downward-sloping (expected) demand curve; as the price falls, the expected number of Y-purchasers increases.

Another interesting policy intervention to consider is "pump-priming." Here the government steps in and imitates a user choosing Y, in hopes of starting the bandwagon rolling to eliminate excess inertia. A possible example of when such pump-priming could be desirable would be a situation of Keynesian underemployment equilibrium where insufficient aggregate demand makes firms reluctant to hire workers, but where if all firms were to hire there would be sufficient aggregate demand to justify the increased employment. Firms will differ in their eagerness to hire, a difference which corresponds to a firm's type. X would be the standard "not hire," while Y would be "hire," and a larger value of i would have a greater preference for hiring. Pump-priming would entail the government employing workers in order to influence the high types to follow, and so start a chain of hiring.

Another example of pump-priming is the suggestion by some advocates of solar energy that the federal government make large purchases of photovoltaic cells, with the rationale that private firms won't buy the cells because their price is too high, but that if enough firms bought them, then scale economies would tend to lower the price of the cells. These advocates hope that government purchases would induce enough of a cost decrease to stimulate the more eager-to-buy customers to make their own purchases, inducing further reductions in costs, and so on.

In general, intervention in bandwagon situations may be able to achieve large results with relatively small resources. Just as a small shock or even a loud noise can trigger a large avalanche, a single extra switch can turn a stalled bandwagon into an unstoppable juggernaut.

CONCLUSION

Bandwagon equilibria among many users can easily lead to excess inertia or excess momentum; there is no analogue to perfect competition in the theory of standard choice with network externalities and incomplete information. Hence, the phenomena of insufficient and excessive innovation found in Farrell and Saloner's (1985) model were not artifacts of their assuming only two users. What is different with N users, in this regard, is the possibility of suffering from conditional excess inertia and excess momentum at the same time. This unhappy state is reached when, given that a certain number of users have already switched, the remaining users would prefer that they all switch as well, but none of the holdouts will make the first move; and at the same time, the holdouts all devoutly wish that no one had switched in the first place.

Looking at N users also focuses attention on the importance of early adopters to the process of innovation in cases of network externality. A potentially vast benefit--when added up across users-- may never be gained because no organization is willing to gamble on going first. In such cases, government policy to overcome the coordination problem might be called for; but distinguishing genuine cases of excess inertia from the special pleading of those supplying unwanted technology is not a trivial task. The possibility of excess momentum should be another dampening influence on enthusiasm for pro-innovation policies of the sort described in this paper.

Difficulties of coordinating agreement on behavior among decentralized decision makers when agreement is valuable are

widespread in economic and political life. The elements of the model presented in this paper--types, benefit functions, and standards-- are sufficiently flexible to capture at least some of the features of these difficulties. Decisions to produce goods that are compatible with new standards, decisions to buy commodities whose production involves large scale economies, decisions to switch from the English to the metric system of measurement, and many similar group choice problems appear amenable to analysis in this spirit.

Interesting extensions of the bandwagon model abound. One involves giving the users different weights, so that a large user creates larger network externalities that a small user. The goal would be to understand how the size distribution of users affects an industry's innovative behavior, and whether concentrations of market power exacerbate or alleviate inefficiencies. Another possibility is to look at what Arthur (1985) refers to as "sponsored" technologies, where the new technology is supplied by a monopoly or oligopoly. Again, whether excess momentum or inertia is more or less troublesome with sponsorship than without is an open question. In addition, the optimal policy of a sponsor would be useful to know.

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Chapter 2.

CULTIVATING DISAGREEMENT:
MANAGERIAL INPUT CHOICE UNDER OLIGOPOLY

I. INTRODUCTION

One of the most important features of a market economy is divergence of beliefs about investment opportunities. Everyday discussion in the business press largely consists of arguments among analysts and executives about the appropriate allocation of firms' resources. Should American steel firms spend millions of dollars to modernize their plants? Is it necessary for minicomputer firms to jump into microcomputers, or is this a poor strategy? How much money should oil companies be putting into exploration? The answers given by firms in the same industry frequently differ--at least in the short run.

In my view, disagreements like these are central to the functioning of a private-enterprise economy, and understanding them is a prerequisite for a realistic account of how such economies allocate resources, let alone for an intelligent normative evaluation. If everyone always agreed about which investment projects would generate positive returns, then who actually controlled the disposition of assets would matter little; a centrally planned effort to "pick winners" would do at least as well as private capital markets in fostering economic efficiency, provided that the planning process could be insulated from political forces.

Furthermore, the history of our economy is laden with new ventures whose eventual success was predicted by few but the entrepreneurs responsible: Federal Express, MCI, and Digital Equipment are among the recent examples. Many successful products were controversial among business analysts when launched, such as instant photography, stainless steel razor blades, jet engines, and alternating-current electrical equipment. Also significant are new products, widely expected to earn

large profits, that turn out to be disappointing: quadriphonic stereo,
videodisk technology, fluidic control systems, Corfam artificial
leather, pizza parlor/puppet theaters, and rotary engines comprise an
incomplete list of recent "undera .evers." While it is possible to
assert that such "surprising" results are merely the low-probability
outcomes of stochastic processes, and that all individuals agree ex ante
on the probabilities of all outcomes, this assertion seems implausible
in the extreme, and appears to be inconsistent with the expressed
diversity of opinions among business observers and participants.[1]

Not only do firms differ in their assessments of particular
projects, but they also display significant variation in the managerial
mechanisms used to generate those assessments, even across direct
competitors in the same industry. IBM is typically dominated at the top
by salesmen, Digital Equipment by engineers; Merck, Sharp and Dohme has
a stronger emphasis on research scientists in management than do its
rivals in the pharmaceutical industry; General Motors has historically
operated on a committee basis, as opposed to the more centralized
approach at Ford and Chrysler[2]. Even if these managerial designs were

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[1]The two leading minicomputer firms of the 1970s and 1980s, Digital
Equipment and Hewlett-Packard, took completely different views of the
emergence of microcomputers. Digital's chief executive scorned personal
computers in 1984, saying "Businesses don't want a computer on a table
to run the business. They want a real computer and disk drive that stand
on the floor...People were misled into thinking a PC would solve
problems and are now learning that it won't." Hewlett-Packard's
electronic products chief at the time said, "In the past, if you were
not a minicomputer supplier, you are now obsolete. In the future it will
be the same with personal computers....[The PC market] will be the
center of attention for years to come." See McClellan (1984), p.171.

[2]The general point is made by Rumelt (1986): "The systematic study of
business strategy, as practiced in schools of business and management,
had its beginnings in case studies of several firms within an industry.
These investigations revealed that firms in the same industry often
differed markedly from one another. Although operating in the same basic
competitive environment... they were observed to use different
organizational structures."

not chosen rationally by optimizing agents at some earlier date, it is puzzling that such differences could persist over time, especially if they can be ranked in terms of efficiency or profitability.

The diversity of organizational structures among close competitors presents a challenge to both team theory and incentive theory, the two main approaches in economics to modelling the internal arrangements of firms, since these theories explain the structure of any particular firm as the optimal solution to problems of imperfect and asymmetric information. Both perspectives thus posit a causal relationship between the information structure of the firm (that is, who knows what) and the types of decision rules, authority relations, and compensation schemes found in the firm. But why, then, will firms in the same industry, evaluating the same projects and producing similar goods, differ in their internal organization?

As Arrow (1985) points out, team theory and incentive theory have tended to take the firm's information structure as given exogenously. To generate organizational diversity within industries, these theories require that information structures be diverse. If such diversity cannot be rationalized, the alternatives are unappealing: One can argue that in some "essential" way, the underlying internal structure of firms in a given industry is homogeneous, despite appearances; perhaps product differentiation or differences in asset composition are responsible for diversity in information structures; or team and incentive theory can be treated as purely normative inquiries into optimal firm structure, with actual organizational forms accounted for by various evolutionary processes, as in Hannan and Freeman (1977, 1984) or Nelson and Winter (1982).

The agenda of this paper is therefore to show that both divergent project assessment and heterogeneity of managerial structures can be derived from rivalrous, profit-maximizing behavior. In order to do this, I construct a simple model of investment choice under uncertainty in a duopoly, in which firms can choose what type of information to observe about a project. In equilibrium, firms may differ in what aspects of their environment they observe, leading to ex post disagreement about the project. This differential observation also has a natural interpretation as variation in managerial structures.

The model's basic structure is that two firms must decide whether or not to make an investment in a project whose payoff depends on two independent random variables, as well as on the number of firms that actually invest. The firms have common priors over the random variables. For expository purposes, the project is described as a new product, and the two random variables as customers' reservation price and the level of production cost.

The game can be divided into two phases. First, firms decide which of the random variables to observe. Then, based on their information (and what they know and can infer about others' information) they decide whether or not to enter the market for the new product.

I make two assumptions about the technology of learning. First, in order to focus on game-theoretic, rather than decision-theoretic, considerations, observations are assumed noiseless; a firm either observes a random variable's realization perfectly, or not at all. Second, for most of the paper, firms are faced with an either-or choice between observing price and observing cost. The motivation for this restriction is that "learning" is not simply a matter of collecting

data, but also one of possessing the organizational aptitude and experience needed to interpret data. Since the choice of managerial structure involves tradeoffs between different sorts of capabilities, omnicompetence is generally not a feasible option. Here, the firm selects between a marketing orientation and a manufacturing (or engineering) focus.[3]

The main result of the paper is that for a wide range of parameter values, the perfect Bayesian Nash equilibrium of the game entails one firm learning price and the other cost. Consequently, prior to any investment actually being made, the firms will, with positive probability, disagree about whether investing is a good idea. Heterogeneous beliefs are thus an endogenously generated phenomenon, not an assumption of the model. Furthermore, diversity of organizational structures in a given industry need not reflect management incompetence; in a heterogeneous-learning equilibrium, no firm desires to reorganize its management even if it is earning lower profits than a rival.[4]

Heterogeneous learning, when it occurs, does not result simply from cooperation between the firms to ensure that no good projects are missed. The real incentive to cultivate disagreement is that each firm would rather be alone in knowing that a project is good; by observing a

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[3]The notion that either marketing or manufacturing tends to dominate the outlook of firms is commonplace (see, for example, Hickson et al. [1986], p.64). A specific instance is the contrast between Xerox and its Japanese rivals in the photocopier industry before the 1980s; Xerox was a marketing-driven company that set price targets and tended to let production adjust, while its rivals were manufacturing-oriented, setting unit-cost goals and allowing price to take up the slack. See Jacobson and Hillkirk (1986), p.286.

[4]If firms are assumed to choose their management structures at different times, then the leader will be able to preempt the more favorable niche. This bears some resemblance to the theory of strategic groups and mobility barriers in Caves and Porter (1977).

signal uncorrelated with its rival's information, a firm increases its chances of reaching that position. This incentive operates because of the key assumption that favorable news about either one of the random variables by itself guarantees that investment is profitable.

Homogeneous-learning equilibria, in which both firms observe the same variable, are also possible. For this to occur, the parameters must be such that one of the two signals has a much higher value than the other. Thus, there is a negative association between symmetry of the firms and symmetry of the parameters: When knowing one random variable is not too much more or less valuable than knowing the other, the firms make asymmetric choices of information. When the random variables are of significantly unequal value, the firms learn the same thing.

The relationship between the social and private incentives for managerial diversity can also be described. Generally, even assuming that the firms can appropriate all consumer surplus, rivalry need not generate Pareto-optimal learning strategies. As in Dasgupta's and Maskin's (1986) work on research portfolios, firms ignore the impact of their information choices on their rival's profits. As a result, homogeneous-learning equilibria occur in some cases where heterogeneous learning would maximize industry profits.

Extending the model to allow more than two firms the possibility of entering the market does not change the fundamental character of the results. The incentive for heterogeneity still exists, and the value of learning a particular random variable is decreasing in the number of other firms that also learn it. As a result, if the two signals are sufficiently close in value (where "close" is much less stringent than

for getting heterogeneous learning with two firms), then adding firms to the industry will always guarantee that price and cost are each observed by at least one firm.

I also consider the two-firm case where learning really can be reduced to data collection. In this context, firms can make cash outlays in order to observe the random variables, and the either-or restriction is relaxed. Hence, the information-choice strategy space is expanded to include the possibilities of learning both price and cost or neither one. Heterogeneous-learning equilibria again appear with great frequency, but now they may also take on the form of one firm's information being a proper subset of the other's.

The external effects of one firm's information on the other's profits are especially obvious in this version of the model. An observation hurts a rival in states of the world where the rival would otherwise be the only firm to consider investing in a project. An observation helps a rival when it reveals the profitability of a project that the rival would otherwise miss, or when it reveals the unprofitability of a project in which the rival would otherwise invest.

When resources are expended in order to acquire information, and firms choose the amount of observation, rather than simply its direction, the relationship between social and private incentives for learning becomes important. If consumer surplus is ignored, then the firms may engage in excessive learning. One reason for this result is that in any state of the world where both firms are aware that the project is profitable, the learning expenditure of one of the firms is redundant ex post. The other reason is the "business-stealing" effect alluded to in the restricted model: Firms ignore the negative effect of their knowledge on their rivals' profits.

Because of the positive spillovers that information may bestow on another firm, suboptimal learning can also take place. For this to occur, the cost of information must be high compared to the gain from learning first, rather than second, that the project is good. The situation is analagous to the problem of research effort when patents provide less than complete appropriability of the gains from invention; firms have an incentive to free-ride, and research is less than the socially efficient level.

Both the negative and positive externalities imply that coordinated learning through cooperative mechanisms (say, by means of research joint ventures or trade association marketing studies) may increase overall social efficiency. One must be careful, however, about the degree to which firms can appropriate consumer surplus; if appropriability is less than perfect, then eliminating "excessive" learning (in order to maximize industry profits) may reduce social welfare by preventing investment in some state of the world where it would be efficient.

Comparisons of the duopoly with a monopoly reveal that rivalry tends to promote learning. When a monopolist learns only price or only cost, it is possible that the two duopolists together will learn both price and cost in a heterogeneous-learning equilibrium. When a monopolist finds it optimal to learn both price and cost, the duopolists will never both learn price alone or both learn cost alone. As a result, duopoly is at least as likely to induce entry when the project is profitable as is monopoly. However, the welfare implications depend on whether or not there is consumer surplus from the launching of the product. If not, then monopoly will be Pareto-superior to duopoly.

Changing the model to have a leader in the first period, the information choice stage, gives a possible explanation for persistent interfirm differences in profitability. The leader in the first period may be able to pre-emptively occupy the most desirable information niche, forcing the follower to settle for lower profits. The result is that an informational "mobility barrier" is created.

Related Work

Little effort seems to have been expended in understanding the nature of divergences in project assessment between similarly situated firms. Furthermore, the possible source of these disagreements in managerial diversity has not been previously identified. In fact, industrial organization's tradition is to assume maximal homogeneity among an industry's members for tractability reasons--empirical tractability, in the case of "structure-conduct-performance" devotees, and theoretical tractability in the case of oligopoly theorists. The idea that organizations may have different managerial foci also runs up against the theorist's customary reluctance to probe the decision-making limitations of firms.

Dasgupta and Maskin's (1986) paper is probably closest in spirit to this one. They look at a pair of firms pursuing a particular invention, each firm selecting one research project from a continuum of such projects. The correlation of success between the two firms is inversely related to the "distance" between their projects. Under the assumption that picking a "far-out" research strategy is more costly (either directly or in terms of a lower success probability), they show

that the symmetric Nash equilibrium of the project-choice game entails socially excessive correlation between the firms' projects. Firms ignore the effect of their success on their rival's profits.

In this paper, firms seek out information about a known investment project. Instead of assuming that correlation between signals is a freely chosen variable, the model specifies a well-defined set of information alternatives, and derives the conditions on project payoffs needed to give homogeneous or heterogeneous decisions. In addition, the unrestricted version of the model allows firms to choose the number of signals they will observe, and not only the interfirm correlation of knowledge.

Stiglitz and Sah (1985) interpret "noise" as human fallibility in their model of project selection under uncertainty. They assume that the errors of decision makers are independent and compare the efficiency of what they label "hierarchies" and "polyarchies." The firms in this paper look like one of their polyarchies in the case where the first-mover advantage of entry into the new-product market is small. Their model, however, ignores the effects of rivalry and imitation on optimal project screening rules, and does not consider the possibility that heterogeneous beliefs could be the outcome of optimizing behavior.

Roll and Cornell (1981) employ the concept of an evolutionary stable strategy to derive a security market equilibrium in which informed and uninformed traders coexist. While their setup is completely different from the one here, and they do not look ɛt choices of correlation between traders, their equilibrium has the same property as some of the examples in this paper: Specialized information strategies can coexist even when the payoffs between the strategies are asymmetric.

Most work that deals with differences in beliefs among economic actors tends to assume that these differences are due to random sampling errors. In this "noisy signal" approach, each agent's knowledge is imagined to be the result of a statistical sample of reality. While the agents are sometimes allowed to choose the precision of their estimates, the degree of correlation between their signals is usually taken as exogenous (and fixed at zero). As a result, disagreements can come from only two sources: chance variations in noise or differences in prior beliefs. Since the latter usually seem ungrounded and arbitrary in the context of a particular model, theorists are reluctant to vary from the assumption of common priors.[5]

For example, heterogeneous information is assumed in the formal literature that studies whether market prices will fully reveal private information. Usually, the distribution of information across agents is exogenous, although sometimes traders are allowed to allocate resources to improving the accuracy of what they know. Similarly, in models of auctions, the bidders are frequently assumed to have only imperfect information about the object up for sale, with different bidders possessing different estimates of its value. The main application of this literature has been to auctions of offshore oil leases, as in the work of Hendricks, Porter, and Gertler (1986). Here, too, the norm is to assume that bidders' valuations differ solely because of measurement error, with no consideration given to whether or not the agents prefer to disagree.

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[5]An exception to this rule is Varian (1985), which considers the importance of "differences of opinion" in generating trading volume on securities markets. Opinion is operationally defined to be a belief whose disclosure to others has no effect on their beliefs, and is equivalent to Bayesian priors.

II. THE MODEL WITH ORGANIZATIONAL CHOICE

This section covers the restricted version of the model where firms are constrained to an either-or choice of learning price or learning cost. Part A lays out the assumptions on payoffs and timing. Part B calculates the entry continuation equilibrium after signals have been observed. In Part C, taking the entry behavior as given, the equilbrium in information choices is derived. Part D extends the model to the case of N firms in the industry.

IIA. Basic Structure

The model is a discrete-period, infinite horizon game between a pair of risk-neutral, profit-maximizing firms. They each must decide whether or not to undertake a risky investment project, and in addition choose what information to seek to aid them in their decisions. To make the situation more concrete, I suppose that the project is a new type of product that only the two firms involved can produce. Demand and production cost are uncertain in a way specified shortly.

The time structure is as follows: In Period 0, the firms become aware of the project, along with the probability distributions of the demand and cost parameters. All this is common knowledge, as is the mapping from price, cost, and number of entrants to firm profits.

In Period 1, firms simultaneously choose either to observe the true value of demand, or the true value of production cost. At the end of the period, the set of variables each firm has observed becomes common knowledge, but their actual values remain private information.

In Period 2, one of the firms randomly becomes the leader in developing

the product. This status is common knowledge, and means simply that one

firm's efforts in preliminary design and production engineering have had

more success and gone more quickly than have those of its rival. Each

firm has probability .5 of being leader. The assumption that one firm

gets a first crack at entry before its rival serves two purposes: First,

it eliminates the problem of finding a reasonable equilibrium when two

firms simultaneously decide whether to enter a market that will sustain

only one firm profitably. The assumption can therefore be thought of as

a random selection over the two pure-strategy Nash equilibria of such a

game. Allowing the simultaneous-move mixed-strategy equilibrium would

needlessly complicate the analysis. Second, it avoids the farfetched

assumption that firms always enter in mutual ignorance of one another's

decisions.

The leader has the option of entering in Period 3. Entry means

that the production cost, which is fixed and sunk, is incurred. If the

leader enters, then the true value of demand and cost become public

information. The assumption here is similar to the one in the limit-

pricing model of Milgrom and Roberts (1982b) that entry leads to

revelation of unknown parameters. It means that the leader need not

worry about adjusting his behavior in order to influence the beliefs of

the follower, as it must in Milgrom-Roberts (1982a) or Gal-Or (1985).

The leader will earn monopoly revenue in Period 3 and all subsequent

periods until the follower enters, if entry occurs in Period 3. In

Period 4, and in all subsequent periods, any firm that has not yet

entered may do so. The first time anyone enters, the true values of

demand and cost become public. For each period in which a firm is alone

in the market, it earns monopoly revenue; for each period in which both firms are in the market, they earn duopoly revenues.

The demand parameter, P, can take on two values, P^H and P^L, $P^H > P^L$. P is high when demand is strong and low when demand is weak. To produce the new good requires a fixed, sunk investment. The cost of this investment, C, is also a Bernoulli random variable that can take on the values C^H or C^L, $C^H > C^L$. P and C are independently distributed; $P = P^H$ with probability x and $C = C^L$ with probability y. Variable costs are assumed to be certain and convex in output, and are suppressed throughout.

Define $S(j,k)$ to be the present discounted value of entering now given that the other firm has already entered, when $P = P^j$ and $C = C^k$. Define $Z(j,k)$ to be the present value of entering now given that no one has yet entered. To avoid semantic confusion, I shall refer to the firm that gets the first opportunity to enter as "the leader" and to the firm that must wait until Period 4 as "the follower"; the firm that actually enters first will be called "the initial entrant," while a firm that enters after the other has done so will be called "the second entrant". Hence, Z is the payoff to an initial entrant and S is the payoff to a second entrant, regardless of who is the leader and who the follower. Note that $Z(j,k)$ is not independent of $S(j,k)$: If $S(j,k) \leq 0$, then $Z(j,k)$ is just the present value of monopoly profits forever net of the sunk cost, while if $S(j,k) > 0$, then $Z(j,k)$ is the net present value of one period of monopoly profits followed by duopoly profits forever (I assume no asymmetry between firms after both firms have entered).

The simplest structural specification of these payoffs is to assume N consumers each desiring to buy one unit of the new good each

period, with common reservation price P. Monopoly profit per period is then NP (the monopolist extracts all consumer surplus when facing perfectly inelastic demand), while each duopolist earns $N\theta P/2$ per period, θ a parameter lying in the unit interval. $\theta=1$ corresponds to post-entry collusion and $\theta=0$ to Bertrand behavior. In this framework,

$$S(j,k) = \theta NP^j/2(1-\delta) - c^k$$

and

$$Z(j,k) = NP^j + \delta S(j,k) - (1-\delta)c^k \quad \text{if } S(j,k)>0$$

$$NP^j/(1-\delta) - c^k \quad \text{if } S(j,k)\leq0$$

In the analysis that follows, I work entirely with the "reduced form" Z and S functions. All of the results therefore apply to any type of investment project whose return is a function of two independent signals and the number of firms that undertake it. The new product example is interesting because it is a commonplace that either marketing or manufacturing tends to dominate the outlook of firms (see, for example, Hickson <u>et al</u>, 1986, p.64), and this fundamental choice of emphasis is highlighted by thinking about the launch of a new product.

I make five assumptions about the Z functions. These are:

A1) $Z(j,k) > S(j,k)$

A2) $Z(H,H) \geq Z(L,H)$, $Z(L,L) \geq Z(L,H)$

$$S(H,L) \geq S(H,H), \ S(H,L) \geq S(L,L)$$

$$S(H,H) \geq S(L,H), \ S(L,L) \geq S(L,H)$$

A3) $Z(H,H) > 0, \ Z(L,L) > 0, \ Z(H,L) > 0$

A4) $yZ(L,L) + (1-y)Z(L,H) < 0$

$$xZ(H,H) + (1-x)Z(L,H) < 0$$

A1 says that for any configuration of price and cost there is a first-mover advantage in the entry game. Note that $S(j,k)$ can be negative, so that the project may admit only one firm. A2 simply states that profits are higher when the first argument (demand) is high and the second argument (cost) is low. I do not assume that $Z(H,L)$ exceeds $Z(H,H)$ and $Z(L,L)$, because if $S(H,L)$ is positive and $S(H,H)$ or $S(L,L)$ is not, then in the structural model, a second entrant will cut into profits when $P=P^H$ and $C=C^L$, but not otherwise. A3 is the only substantive assumption, in the sense of putting a real restriction on the applicability of the results. It, together with $Z>S$, says that if a firm knows that exactly one of the two signals is favorable, while the other is unfavorable, then initiating entry is profitable. This assumption plays a large role in deriving the equilibrium and in generating the heterogeneous learning results. A4 is needed to ensure that the signals are relevant to a firm's decision: If a firm knows only that the news is bad about one of the parameters, then initiating entry has a negative expected value. A3 and A4 together imply that $Z(L,H)<0$.

Firm strategies can be divided into two parts: the Period 1 information choice and the decisions about entry from Period 3 on. Let

s_i represent firm i's choice of information in Period 1. s_i can take on one of two values:

s_i = M (marketing-based); learn P

E (engineering-based); learn C

In this model, the s_i can best be interpreted as a choice of managerial composition or structure. Strategy M, for example, might entail hiring executives with marketing experience for jobs that involve decisions about new-product introductions. Alternatively, this strategy might be thought of as setting up an organizational design that is oriented to gathering and bringing together information about demand, perhaps by creating divisions organized by customer group instead of by technology base. As noted in the introduction, there is reason to believe that such managerial tradeoffs are inherent in organization design.

To describe the entry decisions of firms, more notation is needed. Let P_i represent i's private information, directly obtained, about P. P_i can take on the values P^H, P^L, or P^O, where P^O means that only prior information about P is known. Parallel notation is used for C_i, i's private information about C. I shall refer to finding out that price is high or cost is low as "good news", the reverse as "bad news". If a firm knows that one of the random variables is good news and the other bad news, then the result is "mixed news". Let $A_{it}(P_i, C_i, s_j)$ represent i's decision about entry in Period t, given that no one has yet entered, and $B_{it}(P, C)$ represent i's entry decision in Period t given that the

other firm has already entered. These variables equal one for entry, and zero for non-entry.

IIB. <u>Entry Equilibrium</u>

As is usual in a multiperiod game, perfect equilibrium is not found by starting at the beginning, in this case at the choice of information. Instead, I prove a number of lemmas about the game from Period 3 on, and then establish the perfect Bayesian entry equilibrium in Proposition 1. It is then straightforward to "fold back" the payoffs in each Period 3 subgame to Period 1 and then to find the Nash equilibrium information choices.

<u>Lemma 0</u>: Once a firm enters the market, it never exits.

<u>Proof</u>: Entry requires a sunk cost to be incurred, but no further outlays are needed to stay in the market. Once the cost has been sunk, exit would only eliminate a non-negative revenue stream which comes to the firm by virtue of its remaining in the market. Hence exit would reduce profits.

The next lemma completely characterizes secondary entry, that is, the B_{it}s.

<u>Lemma 1</u>: If the other firm has already entered in Period t-1, revealing $P=P^j$ and $C=C^k$, then $B_{it}=1$ iff $S(j,k)>0$ is a dominant strategy for firm i.

<u>Proof</u>: Since entry by the other firm always reveals the true value of P and C, the remaining firm enters iff the net present value of entry

is positive. By definition, that NPV is $S(j,k)$, since Lemma 0 establishes that the other firm will never exit. Furthermore, for $\delta<1$, if $S(j,k)>0$, then waiting T periods to enter, for $T>0$, will have a lower NPV than immediate entry, since $\delta^T S(j,k)<S(j,k)$. Therefore, entry takes place in Period t.

Now the leader's behavior is addressed.

Lemma 2: If the leader knows, at the beginning of Period 3, that $P=P^H$ or that $C=C^L$, then it is an iterated dominant strategy for the leader to enter in Period 3.

Proof: By A3, $Z(H,L)$, $Z(H,H)$, and $Z(L,L)$ are all positive. Given Lemma 1 and A1, then, knowing that $P=P^H$ or that $C=C^L$ guarantees positive profits to the initial entrant for any undominated strategy by the follower in later periods. Furthermore, since $\delta<1$, delay can only reduce the net present value of profits, so entry takes place in Period 3.

The following result establishes that bad news deters entry.

Lemma 3: If no one has yet entered at the beginning of Period t, $t>2$, and a firm's private information is bad news, then entry in Period t is dominated in expected value by waiting for the other firm to enter first.

Proof: By waiting for the other firm to enter first, a firm can always guarantee itself of zero profits. A4 says that the expected value of initiating entry conditional on $P=P^L$ or on $C=C^H$ is negative,

even if it could be guaranteed that the other firm will not also enter in Period t. Hence, a firm with the postulated knowledge will never enter in Period t.

Now it is possible to describe the inferences firms will draw from the actions of their rivals. First, I look at the follower's inferences, then the leader's. Because entry reveals the true values of P and C, the non-trivial inferences are those that follow non-entry by the other firm.

Lemma 4: If the leader, say firm 1, without loss of generality, chooses not to enter in Period 3, then the follower's inference at the beginning of Period 4, ignoring its own private information, is that the variable observed by the leader is bad news; no inference is drawn about the other variable.

Proof: By Lemma 2, if the leader had good news, then entry in Period 3 would have been an iterated dominant strategy. Since entry did not occur, the leader must have had bad news.

Lemma 4 establishes that the leader's private information is always revealed after Period 3, and if the leader does not enter in Period 3, then his information must have been unfavorable. Now I specify, for completeness, the leader's inferences from the follower's behavior.

Lemma 5: If the leader, say firm 1, without loss of generality, chooses not to enter in Period 3, and the follower chooses not to enter

in Period 4, then the leader's inference at the beginning of Period 5, ignoring its own private information, is that the variable observed by the follower is bad news; no inference is drawn about the other variable.

Proof: As in Lemma 4.

Note that Lemma 2, which is the key to establishing equilibrium inferences in Lemmas 4 and 5, is based on a dominant strategy argument. The inferences derived, therefore, are particularly compelling. Suppose, however, that the other firm's behavior leads to inferences that contradict private information. In this situation, one can adopt the convention that firms always believe their private information, which is directly gathered, over conflicting inferences. As the proof of the continuation equilibrium described below demonstrates, however, any specification of out-of-equilibrium beliefs leads to the same results.

The following lemma accomplishes a vast reduction in the number of entry strategies that must be considered.

Lemma 6: Both of the following statements hold:

(1) If the leader does not initiate entry in Period 3, then it never will.

(2) If the leader does not initiate entry in Period 3, and neither does the follower in Period 4, then neither firm will ever enter.

Proof: Suppose, without loss of generality, that firm 1 is the designated leader. If firm 1 fails to enter in Period 3, then the argument of Lemma 4 shows that firm 1's private information can only

have been bad news, i.e. that $P=P^L$ or $C=C^H$. Since no new information is gained by firm 1 in Period 3, it will not initiate entry in Period 4. If firm 2 initiates entry in Period 4, then of course firm 1 can no longer be the first to enter. If firm 2 stays out in Period 4, then Lemma 5 establishes that firm 1 makes only pessimistic inferences, if any, about firm 2's private information. Therefore, firm 1 will not initiate entry in Period 5 or thereafter. This completes the proof of (1).

Suppose firm 1 does not enter in Period 3. If firm 2 fails to initiate entry in Period 4, then Lemma 5 demonstrates that firm 2's private information can only have been bad news about the project. Since it was just established that firm 1 will never initiate entry after Period 3, and since firm 2 learns nothing new after Period 4, neither firm will ever enter. This establishes (2).

Lemma 6, together with Lemma 1, shows that if only undominated strategies are allowed, then Periods 3, 4, and 5 are the only ones that need to be considered in describing entry decisions. Furthermore, the above lemma proves that the A_{it}'s, the initiating entry decisions, can only equal one for t=3 or 4.

Define $W_{it}(P_i, C_i, s_j)$ to be i's beliefs in Period t about P and C, given i's private information P_i and C_i, the type of information learned by j, and the fact that no firm has yet entered. Recall that $A_{it}(P_i, C_i, s_j)$ is i's decision about initiating entry in Period t, and that $B_{it}(P, C)$ is i's decision about entering in Period t given that j entered in Period t-1. Setting the entry decision variables to one signifies entry, zero signifies staying out. With this notation, the equilibrium can now be described.

Proposition 1: Given A1-A4, there exists a perfect Bayesian Nash equilibrium to the continuation game starting in Period 3 with the following properties on the equilibrium path. Furthermore, any perfect Bayesian Nash equilibrium shares this equilibrium path.

(1) $B_{it}(P^j, C^k) = 1$ iff $S(j,k) > 0$

(2) Assume that 1 denotes the leader and 2 the follower. Then W_{13} is just the leader's private information in Period 3, and A_{13} is given by (2.1)-(2.4).

    (2.1) $A_{13}(P^H, C^0, s_2) = 1$ for any s_2

    (2.2) $A_{13}(P^L, C^0, s_2) = 0$ for any s_2

    (2.3) $A_{13}(P^0, C^H, s_2) = 0$ for any s_2

    (2.4) $A_{13}(P^0, C^L, s_2) = 1$ for any s_2

(3) Following the convention that firm 1 is the designated leader, if firm 1 failed to initiate entry in Period 3, then equilibrium-path strategies and beliefs for Period 4 are given by (3.1)-(3.2).

    (3.1) If homogeneous information ($s_1 = s_2$), then firm 2 does not enter. Its private information and its inference are that the variable observed by both

firms is bad news.

(3.2) If heterogeneous information ($s_1 \neq s_2$), then firm 2

enters if and only if its private information is good

news. Its inference about the variable observed by

firm 1 is that it is bad news.

(4) After Period 4, entry is never initiated. Beliefs

are the same as W_{i4}. Of course, if entry was

initiated in Period 4, then the behavior described in

(1) occurs in Period 5, and the true values of P and

C are known.

Proof: See Appendix 1.

The equilibrium path is straightforward. Following Lemmas 1

through 6, it gives firms the following simple rules: If ever the other

firm initiates entry, enter if and only if the perfectly known profits

from doing so are positive. If the leader has favorable private

information, then it should enter in Period 3; if the leader's private

information is unfavorable, then the leader should not initiate entry.

If the leader has not entered in Period 3, then the follower should

enter in Period 4 if it has favorable private information; otherwise,

neither firm ever enters.

There are a number of features of the equilibrium that deserve

comment. First, the equilibrium path is the result of iteratively

eliminating dominated strategies. Lemma 2 establishes that in Period 3,

entry is a dominant behavior if $P=P^H$ or $C=C^L$. Hence, part (3) of the

proposition excludes subgames in which the leader has favorable private information, since (3) assumes that entry has not occurred in Period 3. Furthermore, the follower can safely ignore the possibility that the leader will initiate entry in Period 4, since Lemma 6 shows that either initiating entry in Period 3 or never initiating entry dominate this alternative for the leader.

Second, part (1) of the proposition is just Lemma 1 restated. Third, the follower's beliefs W_{24} in Period 4 are determined by the logic given in Lemma 5; if the leader has private information and chose not to enter in Period 3, then it must have had bad news.

Finally, the subgames that can motivate heterogeneous learning are those where the leader's private information is unfavorable, while the follower's is favorable. These represent chances for the follower to seize opportunities missed by the leader, which is why assumption A3 is so important.

IIC. Information Equilibrium

Given the continuation equilibrium for Period 3 and thereafter, I can now calculate the payoffs for the various choices of information in Period 1. Recall that the probability in Period 2 of firm i being designated the leader is .5, and define $F_i(s_1,s_2)$ to be firm i's expected payoff divided by δ^2 when firm 1 chooses s_1 and firm 2 chooses s_2, conditional on i being designated the follower. Let $L_i(s_1,s_2)$ be the equivalent expected payoff, conditional on i being designated the leader. Finally, define $V_i(s_1,s_2)$ as i's unconditional expected payoff, divided by δ^2, when s_1 and s_2 are the firm's choices of information. Then

$$V_i(s_1,s_2) = .5L_i(s_1,s_2) + .5F_i(s_1,s_2)$$

By using Proposition 1, it is straightforward to write down $F_i(s_1,s_2)$, $L_i(s_1,s_2)$, and hence $V_i(s_1,s_2)$, for all possible choices of information:

$$F_1(M,M)=F_2(M,M)=\delta xyMax\{S(H,L),0\} + \delta x(1-y)Max\{S(H,H),0\}$$

$$L_1(M,M)=L_2(M,M)=xyZ(H,L) + x(1-y)Z(H,H)$$

$$F_1(M,E)=F_2(E,M)=\delta xyMax\{S(H,L),0\} + \delta x(1-y)Z(H,H)$$
$$+ \delta(1-x)yMax\{S(L,L),0\}$$

$$L_1(M,E)=L_2(E,M)=xyZ(H,L) + x(1-y)Z(H,H)$$
$$+ \delta^2(1-x)yMax\{S(L,L),0\}$$

$$F_1(E,M)=F_2(M,E)=\delta xyMax\{S(H,L),0\} + \delta x(1-y)Max\{S(H,H),0\}$$
$$+ \delta(1-x)yZ(L,L)$$

$$L_1(E,M)=L_2(M,E)=xyZ(H,L) + \delta^2 x(1-y)Max\{S(H,H),0\}$$
$$+ (1-x)yZ(L,L)$$

$$F_1(E,E)=F_2(E,E)=\delta xyMax\{S(H,L),0\} + \delta(1-x)yMax\{S(L,L)\}$$

$$L_1(E,E)=L_2(E,E=xyZ(H,L) + (1-x)yZ(L,L)$$

With these expressions in hand, it is possible to characterize the Period 1 Nash equilibrium information choices. The informational equilibrium turns out to hinge on the relative sizes of the expected net gains of learning price versus learning cost. If $x(1-y)Z(H,H)$ and $(1-x)yZ(L,L)$ are not too far from equality, in a sense that will presently be made precise, then the only pure-strategy Nash equilibria will have one firm choosing M and the other E. If $x(1-y)Z(H,H)$ is sufficiently larger than $(1-x)yZ(L,L)$, then M is a dominant strategy for both firms; if the difference goes the other way, then E is dominant for both firms.

One way of viewing the tendency toward heterogeneous learning is to consider the degree of first-mover advantage in the entry game. Suppose only one firm can earn positive profits selling the new product. In this model, battles over which firm gets to be the ex post monopolist are resolved randomly and exogenously; if both firms desire to enter, then the designated leader will end up as the monopolist. However, even with a simultaneous-move game at the entry stage, any symmetric equilibrium would lead to the same result: If only one firm "fits" in the market when news is mixed, then the value of knowing that entry is profitable is higher when the other firm does not know, because the informed firm can seize the market unopposed. The situation is similar to Dasgupta and Maskin's (1986) model, where a firm would rather have its research project succeed when its rival's fails than succeed at the same time; there, the reward to sole success is a patent, here a monopoly position.

On the other hand, suppose there is no first-mover advantage at all in this game, so that a firm is just as happy to let its rival enter first. Then it is both individually rational and Pareto-optimal for a

firm to seek different information from that of its rival, because such a strategy guarantees that no favorable projects will be missed; if either signal is favorable, entry will occur, and both firms benefit.

The above statements are formalized in the following proposition.

Proposition 2: In the game where M and E are the only possible values of s_i and s_j, the parameter space can be divided into three regions:

(1) $V_1(M,E) > V_1(E,E)$ and $V_1(E,M) > V_1(M,M)$. The only pure-strategy Nash equilibria are $s_1=E, s_2=M$ and $s_1=M, s_2=E$.

(2) $V_1(M,M) \geq V_1(E,M)$ and $V_1(M,E) \geq V_1(E,E)$. $s_1=s_2=M$ is the dominant strategy equilibrium.

(3) $V_1(E,E) \geq V_1(M,E)$ and $V_1(E,M) \geq V_1(M,M)$. $s_1=s_2=E$ is the dominant strategy equilibrium.

Figure 1 shows the three regions in expected-profits-from-mixed-news space for the case where all S terms are negative.

Region (1) is defined by the following two conditions:

(i) $.5x(1-y)Z(H,H) < .5(1+\delta)(1-x)yZ(L,L)$
$$+.5\delta^2 x(1-y)\text{Max}(S(H,H),0)$$

This says that $V_1(M,M) < V_1(E,M)$.

(ii) $.5(1-x)yZ(L,L) < .5(1+\delta)x(1-y)Z(H,H)$
$$+.5\delta^2(1-x)y\text{Max}(S(L,L),0)$$

This says that $V_1(E,E) < V_1(M,E)$.

Figure One

$$\frac{x(1-y)\, Z(H,H)}{(1-x)y\, Z(L,L)} = 1 + \delta$$

Region (2) Both learn P

Region (1) Heterogeneous learning

Region (3) Both learn C

$$\frac{x(1-y)\, Z(H,H)}{(1-y)x\, Z(L,L)} = \frac{1}{1+\delta}$$

$x(1-y)Z(H,H)$

$(1-x)y\, Z(L,L)$
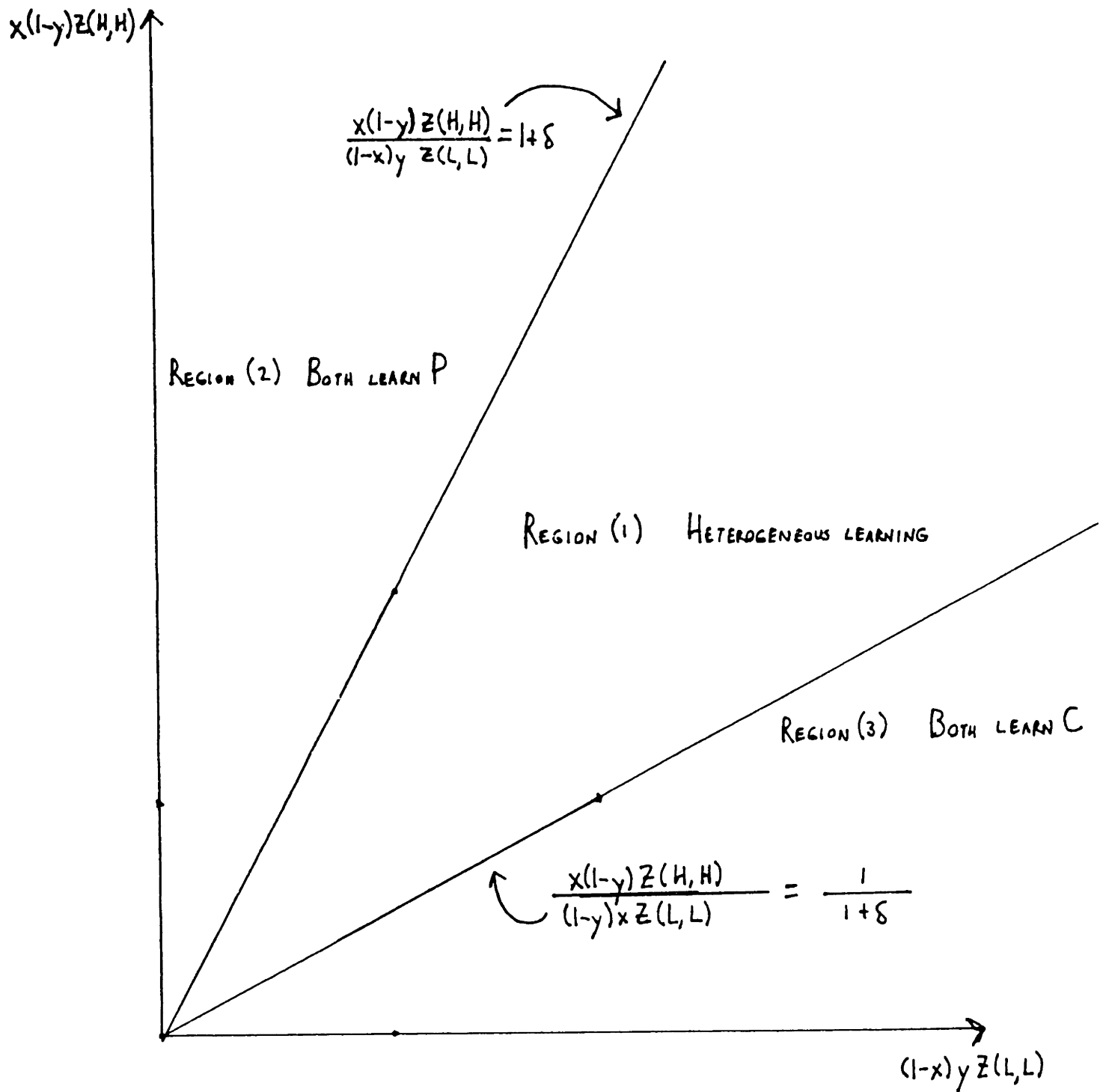
Region (2) is defined by the reverse of (i) and by (ii).

Region (3) is defined by the reverse of (ii) and by (i).

Proof: For there to be a Nash equilibrium with heterogeneous learning, it is necessary and sufficient that if firm 2 is playing M, firm 1 prefers to play E, and that if firm 2 is playing E, then firm 1 prefers to play M. (Since the payoffs are symmetrical with respect to the firms' identities, there is no loss of generality in holding fixed firm 2's information choice and looking at firm 1's best response). But this is just a restatement of the description of region (1). Derivation of (i) and (ii) then follows directly from the expressions for the F_is and L_is and from the definition of the V_is. To show that region (1) exists, i.e. that (i) and (ii) can hold under A1-A4, it suffices to show that there exists a set of parameter values that satisfies the inequalities. Such a set is described by $S(H,H)=S(L,L)=0$ and $x(1-y)Z(H,H)=(1-x)yZ(L,L)=G>0$.

For $s_1=s_2=M$ to be a dominant strategy equilibrium, it is necessary and sufficient that for any choice of s_2, firm 1 prefers to play M. This is just a restatement of the definition of Region (2).

For $s_1=s_2=E$ to be a dominant strategy equilibrium, it is necessary and sufficient that for any choice of s_2, firm 1 prefers to play E. Again, this is the definition of Region (3).

It remains only to show that it is impossible for $V_1(M,M)>V_1(E,M)$ and $V_1(E,E)>V_1(M,E)$ to hold simultaneously. Starting with the reverse of inequality (i) and rearranging gives

(*) $Z(H,H) > [(1+\delta)(1-x)y/x(1-\gamma)]Z(L,L)$

$\qquad + \delta^2 Max\{S(H,H),0\}$

Rearranging the condition $V_1(E,E) > V_1(M,E)$, which is the reverse of inequality of (ii), yields

(**) $Z(H,H) < [(1-x)y/x(1-y)(1+\delta)][Z(L,L) -$

$\qquad\qquad\qquad\qquad \delta^2 Max\{Z(L,L),0\}]$

But the right-hand side of (*) is larger than the right-hand side of (**), since $(1+\delta)>1$, $\delta^2 Max\{S(L,L),0\} \geq 0$, and $\delta^2 Max\{S(H,H),0\} \geq 0$. Thus, (*) and (**) cannot be true simultaneously. This completes the proof.

As noted above, if $x(1-y)Z(H,H)$ and $(1-x)yZ(L,L)$ are equal, then regardless of the gains to entering second, the heterogeneous-learning equilibrium will prevail in the restricted game. In fact, $x(1-y)Z(H,H)$ and $(1-x)yZ(L,L)$ need only be within a factor of $(1+\delta)$ of one another to guarantee this outcome. Therefore, reducing the time between periods, hence driving δ closer to one, enlarges the scope of heterogeneous learning. So does raising the payoff to the second entrant.

To get some intuition about the game, consider the following numerical example:

Example 1

$N=100$, $\delta=.9$, $P^H=3$, $P^L=1$, $C^H=1200$, $C^L=400$, $x=.08$, $y=.24$

These "structural" parameters give the following values for the Z and S terms as a function of θ:

$$S(H,L)=1500\theta-400 \qquad Z(H,L)=3625 \qquad \theta\leq 4/15$$
$$S(H,H)=1500\theta-1200 \qquad\quad =1350\theta-75 \qquad \theta>4/15$$
$$S(L,L)= 500\theta-400 \qquad Z(H,H)=1800 \qquad \theta\leq 4/5$$
$$Z(L,H)=-200 \qquad\qquad\quad 1350\theta-900 \qquad \theta>4/5$$
$$Z(L,L)=625 \qquad \theta\leq 4/5$$
$$450\theta-275 \qquad \theta>4/5$$

The resulting normal form is:

	M	E
M	$90,90$ $\theta\leq 4/15$ $26\theta+51,26\theta+51$ $4/15<\theta\leq 4/5$ $108\theta-64,108\theta-64$ $4/5\leq\theta$	$139,166$ $\theta\leq 4/15$ $26\theta+100,26\theta+127$ $4/15<\theta\leq 4/5$ $198\theta-132,198\theta-124$ $4/5\leq\theta$ *
E	$139,166$ $\theta\leq 4/15$ $26\theta+127,26\theta+100$ $4/15<\theta\leq 4/5$ $198\theta-124,198\theta-132$ $4/5\leq\theta$ *	$104,104$ $\theta\leq 4/15$ $26\theta+65,26\theta+65$ $4/15<\theta\leq 4/5$ $125\theta-74,125\theta-74$ $4/5\leq\theta$

The first entry in each cell gives $V_1(s_1,s_2)$, the second $V_2(s_1,s_2)$. Several features should be noted. First, the payoffs are symmetric between players, since the game is symmetric as of Period 1. Second, the cells with asterisks represent the pure-strategy Nash equilibria of the game. Third, it is apparent that heterogeneous learning is generated regardless of the degree of first-mover advantage obtained by an initial entrant. In this example, for all θ in the unit interval, heterogeneous learning is the equilibrium. When θ is low, so that post-entry competition is stiff (at $\theta=0$, it makes the duopoly game repeated Bertrand), the S terms are all negative and there is no

cooperative motive. The advantage of learning something different from one's opponent is that sole knowledge that the project is good has more value than shared knowledge; in the event of becoming the follower, having the same information as the leader is useless. When θ is high, so that first-mover advantages are small for the initial entrant, the cooperative motive takes over, and the firms simply split up the responsibility for identifying good projects.

It is not true, however, that firms will always choose heterogeneous learning strategies when such strategies maximize industry profits. As in Dasgupta and Maskin (1986), since firms ignore the effect of their signal choice on their rival's profits, excessive correlation is possible. The conditions for both firms to learn price, for example, when heterogeneous learning maximizes industry profits, are that $V_1(M,M) > V_1(E,M)$ (implying also that $V_1(M,E) > V_1(E,E)$) and that $V_1(M,E) + V_2(M,E) > 2V_1(M,M)$. Structural parameters consistent with such an outcome are $N=100$, $\delta=.9$, $P^H=5$, $P^L=1$, $c^H=3000$, $c^L=600$, $x=.177$, $y=.152$, $\theta=0$; they result in $V_1(M,E)=344$, $V_1(E,M)=107$, $V_1(M,M)=209$, and $V_1(E,E)=84$. Industry profits are maximized at 451 with a heterogeneous choice of signals, but the unique equilibrium is for both firms to learn price, jointly earning 418.

Note that if the probability of a firm's being designated the leader were altered, then incentives for learning would shift. Specifically, if a firm is relatively sure of becoming the leader, then heterogeneity of learning is of less value than in the standard model; a firm that is likely to be the follower, on the other hand, has an even stronger incentive to learn the opposite signal from its rival. When $x(1-y)Z(H,H)$ and $(1-x)yZ(L,L)$ differ in magnitude and the $S(.,.)$ terms

are negative, a firm that is certain of becoming the leader will always choose to observe the signal associated with the higher payoff, regardless of what the other firm does. A certain follower will then always choose the other signal.

IID. The N-Firm Game

The model is easily extended to handle an arbitrary number N of firms evaluating the project. Instead of a leader and follower, assume the firms to be randomly assigned positions in an entry queue after their choices of M or E. The first player in the queue has the opportunity to enter in Period 3 or thereafter, the second in Period 4, and so on. As before, if anyone initiates entry, then the true values of P and C become common knowledge.

Let $S(j,k,n,q)$ be the expected value of the continuation game for a firm eligible to enter when the demand parameter is P^j, cost is C^k, there are n profitable "slots" left in the industry, and q firms eligible to pursue them. If $q>n$, then $S(j,k,n,q)$ might be a mixed-strategy equilibrium payoff. It is not necessary to specify or solve this game to derive the results about signal choice. Note that the S function is allowed to be always zero, so that the project can be a natural monopoly.

Payoffs now have to be specified for initial entrants contingent on the number of firms eligible for secondary entry at the time the initial entry occurs. Define $Z(j,k,r)$ to be the payoff for an initial entrant when demand is P^j, cost is C^k, and the entrant is rth in the queue (which means that r firms will be eligible to enter in the next period). Note that these payoffs incorporate the equilibrium behavior

of secondary entrants, including the possibility that too many firms may enter in a mixed-strategy equilibrium.

The assumptions needed for the payoffs are directly analogous to A1-A4 in the two-firm case, and are listed in Appendix 4. They merely take into account queue position, but otherwise are unchanged. Under these assumptions, the continuation game after observations of P and C have been made is familiar from the two-firm model:

If at least one firm has already entered, then any firms that are eligible to enter in a given period will play a game for occupation of the remaining profitable industry slots, possibly entailing mixed strategies, as in Dixit and Shapiro (1986). If no one has yet entered, and an eligible firm has observed that $P=P^H$ or that $C=C^L$, then the firm enters at its first opportunity. If no one has yet entered, and a firm has observed bad news, then it will not enter when it becomes eligible. Anytime an eligible type M firm fails to enter, other firms will infer that $P=P^L$; when an eligible type E firm refuses to enter, then rivals will infer that $C=C^H$. Again, it can be assumed that if inference contradicts private information (off the equilibrium path) then inference gives way. In equilibrium, if a type M and a type E both turn down entry as they become eligible, then no firm will enter; if entry does not occur by Period N+2, then it will never occur. The proofs for these statements are trivial extensions of the proofs to Lemmas 1-6 and Proposition 1.

Given the entry behavior and inferences of the firms, it is possible to analyze equilibrium signal choices in the N- player, simultaneous-move game of Period 1. Consider a particular firm. Let m be the number of other firms choosing M. Now define V(M,m) as a firm's

expected payoff from choosing M when m others do the same; let $V(E,m)$ be a firm's expected payoff when it chooses E and m others choose M. The key result is the following:

Proposition 3: Given A1'-A4', $V(M,m)$ is strictly decreasing in m and $V(E,m)$ is strictly increasing in m.

Proof: See Appendix 4.

The logic behind Proposition 3 is familiar from the two-firm model. When more firms copy your knowledge, your chances of initiating entry go down; it becomes more and more likely that a firm with your information will precede you in the entry queue. If a simultaneous-move, mixed-strategy game were used instead of an entry queue, the idea would be the same: The more firms there are competing to achieve a profitable industry position, the lower the expected value of each participant. Hence, the more firms there are that observe the same signal, the lower the value of that signal. From this it follows that there is a pressure for heterogeneity in the N-firm model.

Corollary 3a: Suppose there exists $m>0$ such that $V(M,m) \geq V(E,m)$. Denote the maximum such m by m_0. Then Nash equilibrium in signal choices exists and, if $m_0<N$, has m_0+1 firms choose M and $N-m_0-1$ choose E. All firms choose M if $m_0 \geq N$. If there does not exist $m>0$ such that $V(M,m) \geq V(E,m)$, then all firms choose E.

Proof: See Appendix 4.

This corollary establishes the existence and basic nature of the signal choice equilibrium in the N-firm game. Heterogeneous learning occurs when one signal is not so large in expected value relative to the other that even if all firms choose that signal, no one has an incentive to switch. In general, the industry can be divided into two populations, with the larger population corresponding to the more valuable signal.

Corollary 3b: For any given set of Z and S payoff functions satisfying A1'-A4', and also satisfying conditions $(1-\delta)(1-x)yZ(L,L,r) < x(1-y)Z(H,H,1) < (1-x)yZ(L,L,r)/(1-\delta)$, there exists finite K such that in a K-firm game, each signal is observed by at least one firm in equilibrium.

Proof: See Appendix 4.

This corollary shows that in an N-firm version of the model, heterogeneity is the "normal" case. With a large number of firms studying the same project, one signal would have to be dwarfed in importance by the other to generate homogeneous learning. As firms are added to the industry, if they all learn the same information, then the competition to initiate entry when that signal is favorable becomes increasingly fierce.

These results suggest that the more firms there are evaluating a project, the more likely it is that all the relevant information will be observed by the industry as a whole. Hence, one of the benefits of an industry structure in which many firms have access to new projects is that investment decisions will be more informed. Heterogeneous learning

is socially desirable because it eliminates the possibility of Type I error, the rejection of good projects; Type II error, the acceptance of bad projects, never occurs in this model for any profile of signal observations.

Note that these results characterize any Nash equilibrium, but that there are still multiple equilibria. In particular, which firms are the type Ms and which the type Es is not uniquely determined. Since the payoffs to these types will generally differ, firms will care about their role in the equilibrium, and so selection among the possible equilibria may be considered an important issue. I will return to this subject in the context of "mobility barriers" in a two-firm model with expanded strategy space.

III. MODEL OF INFORMATION PURCHASE

So far, the discussion has been restricted to an either-or choice between learning about demand and learning about cost. For thinking about long-term choices of managerial structure, this focus seems like a useful abstraction, a way of capturing some of the essential tradeoffs involved in organizational design. In the context of evaluating a particular project, however, one might want to consider the possibility of buying information with an actual resource outlay, rather than relying only upon the non-tradeable assets of one's managerial competence to guide the entry decision. For example, a firm might hire outside consultants to perform market surveys, or to evaluate a technology. Such expenditures are optional on a case-by-case basis, unlike choices about managerial structure.

In Section IIIA, I modify the model to account for the possibility that a firm might choose to observe both demand and cost, or neither one. This corresponds to the interpretation given above, in which choice of signal(s) to observe is a short-term, project-by-project decision, rather than a commitment to long-term personnel or organizational policies. Section IIIB discusses some of the conclusions that can be drawn from such a model.

IIIA. Equilibrium With Expanded Strategy Space

Once again, the model assumes that two firms are considering whether or not to invest in a particular project, which I will interpret as a new product. Assumptions A1-A4 about the payoff functions are

maintained. What is changed is the Period 1 strategy space, which now contains the following choices of signal for firm i:

s_i = J (judgment-based); spend nothing on information

M (marketing-based); spend c(M) to learn P

E (engineering-based); spend c(E) to learn C

I (information-based); spend c(I) to learn P and C

Aside from the expansion of the strategy space to allow J and I, this formulation also differs in assuming a direct cost to obtaining any information. I will assume that c(I)$\geq$c(M)+c(E), so that there are no economies, and possibly diseconomies, to learning and assimilating both kinds of information jointly.

The continuation equilibrium, after signal choices have been made, is a straightforward extension of the results for the model with restricted signal choices. Lemmas 0-3 are completely unchanged. Lemma 4, which specifies the follower's inferences if the leader fails to initiate entry in Period 3, must be expanded to include the following: If the leader is type J, then the follower can draw no inferences about P and C, while if the leader is type I, then the follower knows that $P=P^L$ and $C=C^H$. Proof is obvious, and it remains true that the leader's private information is always revealed after Period 3. Lemma 5, which specifies the leader's inferences if no one has entered through Period 4, is extended analagously.

The main complication involved in this version of the model is the entry behavior of firms that are type J. Any of the other types always knows that it should initiate entry if and only if it has favorable

private information. A type-J firm, however, has only public, prior
information to guide its decisions. Even if initiating entry has a
positive expected payoff based on prior information, it is possible that
a type-J firm would be better off waiting for the other firm to make the
first move. If $s_1 = s_2 = J$, a waiting game might materialize.

Let $E(Z,J)$ denote the expected payoff to initiating entry given
only prior information, and let $E(S,J)$ represent the expected value of
having the other firm initiate entry next period given only prior
information. $E(S,J)$ incorporates the behavior in Lemma 1 about when to
become a second entrant. So

$$E(Z,J) = xyZ(H,L) + x(1-y)Z(H,H) + (1-x)yZ(L,L)$$
$$+ (1-x)(1-y)Z(L,H)$$

$$E(S,J) = \delta^2[xy\text{Max}(S(H,L),0) + x(1-y)\text{Max}(S(H,H),0)$$
$$+ (1-x)y\text{Max}(S(L,L),0)]$$

Now it is possible to characterize the continuation equilibrium
of the subgame in which $s_1 = s_2 = J$:

Lemma 7: Suppose $s_1 = s_2 = J$. If $E(Z,J) > E(S,J)$ and $E(Z,J) > 0$, then the
leader will initiate entry in Period 3. If $0 < E(Z,J) < E(S,J)$, then a war
of attrition results, with each firm preferring the other to initiate
entry. Multiple pure-strategy equilibria occur, including the
possibility that the leader gives in immediately in Period 3. If
$E(Z,J) < 0$, then neither firm will ever enter.

Proof: If $E(Z,J) > E(S,J)$ and $E(Z,J) > 0$, then immediate entry earns a
higher expected profit than does waiting, even in the most favorable

case for waiting where the other firm enters in the next period. If $0<E(Z,J)<E(S,J)$, then if the other firm would cooperate by initiating entry next period, waiting for the other firm to initiate entry earns more than initiating entry oneself. However, both firms face this incentive by hypothesis, so each will want the other firm to lead the way. The result will be a war of attrition with multiple equilibria. If $E(Z,J)<0$, then neither firm will ever find it rational to initiate entry, since each can guarantee itself zero profits by staying out.

Type-J firms present a similar complication when facing other types. Although no wars of attrition are generated, it is possible that a type-J leader will not initiate entry even if $E(Z,J)$ is positive, because letting its better-informed rival have the first crack at entry eliminates the possibility of entering when $P=P^L$ and $C=C^H$. Recall that $L_i(s_1,s_2)$ is the expected payoff to player i from being a leader, given equilibrium entry behavior, and $F_i(s_1,s_2)$ is the equivalent number for a follower. The F_i terms are easy to derive for type-J firms, from Lemmas 0-6. Lemma 8 characterizes the L_i terms.

Lemma 8: Suppose $s_1=J$ and s_2 differs from J. Then

$$L_1(J,s_2) = Max\{E(Z,J),\delta F_1(J,s_2)\} \qquad \text{and}$$

$$F_2(J,s_2) = E(S,J)/\delta \qquad \text{if } E(Z,J)>\delta F_1(J,s_2)$$

$$\delta L_2(J,s_2) \qquad \text{if } E(Z,J)<\delta F_1(J,s_2)$$

Proof: See Appendix 2.

An uninformed leader facing an informed follower compares the expected value of plunging ahead and initiating entry, risking investment when both signals are bad news, with the expected value of waiting for the informed firm to expose its private information. The informed follower is then either in the same position as an uninformed follower, or in the position of an informed leader with the game starting one period later.

The general expressions for the $F_i(s_1, s_2)$ and $L_i(s_1, s_2)$ are contained in Appendix 3. Note that

$$E(Z, J) = L_1(I, s_2) + (1-x)(1-y)Z(L, H)$$

and

$$E(S, J) = F_1(J, I)$$

Now it is possible to characterize the equilibrium of the game after signals are chosen. The version of Proposition 4 given here is informal; for a formal version and the proof, see Appendix 2.

Proposition 4: Given A1-A4 and the expanded strategy space, there exists a perfect Bayesian Nash equilibrium to the continuation game starting in Period 3 with the following properties along the equilibrium path. Furthermore, any perfect Bayesian Nash equilibrium shares this equilibrium path.

(1) If the other firm initiates entry, revealing P^j and C^k, then a firm enters if and only if $S(j, k)$ is positive.

(2) If both firms are type J, then they follow the behavior described in Lemma 7.

(3) In Period 3, the leader's beliefs about a parameter are just its private information, if any, or prior information if no private information is held. A type-J leader follows the rules described in Lemma 8 when facing a follower with some private information. A leader with private information enters in Period 3 if and only if some of that private information is favorable.

(4) If the leader does not initiate entry in Period 3, then in Period 4, then the follower infers that all the signals observed by the leader were unfavorable. The follower initiates entry in Period 4 if and only if it has some favorable private information.

(5) If entry has not been initiated by the end of Period 4, then no entry ever occurs. Beliefs are unchanged from Period 4 for the follower; the leader updates his beliefs to pessimism for any information observed by the follower alone.

Proof: See Appendix 2

There is no elegant characterization of the possible signal-choice equilibria in this game, unlike the model with a restricted strategy space. Equilibrium with one firm learning about demand and the other cost is still possible, but additional restrictions on the parameters are of course necessary to rule out the new deviations J and I. For example, to get $V_1(M,E)>V_1(I,E)$, so that deviation to I is unprofitable, it must be true that

$$.5(1-x)y[Z(L,L) - \delta^2 \text{Max}\{S(L,L),0\}] < c(I) - c(M)$$

The left-hand side of the inequality gives the expected marginal benefit to firm 1 of having cost information added to demand information when facing a type-E firm 2. Such additional information is valuable only when firm 1 is the leader, since firm 2 also has this knowledge, and will preempt opportunities to use it if firm 1 is the follower. Cost information on top of demand information is also only valuable when it lets firm 1 initiate entry in a state where it otherwise would not realize that entry is profitable, i.e. when P and C are both low. The right-hand side of the inequality gives the marginal cost of strategy I over strategy M.

In general, if a firm is designated the follower, then ex post, learning both variables is wasteful if the other firm has learned either one. Similarly, if the leader is of type I, then the follower is best off ex post choosing to be type J. For a follower, the only private information that is of any use is information not possessed by the leader.

Other equilibria may also occur in the unrestricted game.[6] If $c(M)$, $c(E)$, or $c(I)$ is pushed toward zero or infinity, then it is easy to make $s_1 = s_2 = J$, $s_1 = s_2 = M$, $s_1 = s_2 = E$, or $s_1 = s_2 = I$ a dominant-strategy equilibrium. More interesting is the possible existence of the Nash equilibria $(s_1, s_2) = (I, J)$, $(s_1, s_2) = (I, M)$, $(s_1, s_2) = (I, E)$, $(s_1, s_2) = (M, J)$, and $(s_1, s_2) = (E, J)$. In these equilibria, one of the firms is "more

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[6]It is possible that the game will have no pure-strategy Nash equilibrium in signal choices. Here we have a difference from the model with a restricted strategy space. The extra degrees of freedom created by the cost-of-information terms allows construction of examples that lack pure-strategy fixed points. Of course, mixed-strategy equilibria will always exist.

informed" thar. its rival, yet it does not pay either firm to close this gap. The firms fill different "information niches," and may well earn different expected profits, but the favorable niche supports only one firm. (The less-informed niche may be the favored one.)

To get a sense of some of the possibilities, consider the following game: Let $N=100$, $\theta=1$, $\delta=.9$, $x=y=.3$, $P^H=3$, $P^L=1$, $c^H=1300$, $c^L=200$, $c(M)=c(E)=50$ and $c(I)=100$. The resulting normal form for the signal choice stage is:

<u>Example 2</u>

	J	M	E	I
J	g,h 130<g,h<180	136.8, 151.9	153.9, 143.8	189.8, 163.6 *
M	151.9, 136.8	123.6, 123.6	191.6, 173.6 *	177.4, 143.4
E	143.8, 153.9	173.6, 191.6 *	133.0, 133.0	168.9, 152.8
I	163.6, 189.8 *	143.4, 177.4	152.8, 168.9	138.7, 138.7

Once again, cells with asterisks represent Nash equilibria. Just as in the restricted model, (M,E) and (E,M) are equilibria, but in addition, so are (I,J) and (J,I). In the case where one firm is uninformed and the other fully informed, the uninformed firm actually earns higher expected profits. The advantage of initiating entry, compared to entering second, is quite small in this example, so that the benefit of finding good projects largely spills over to the uninformed

firm while the cost is borne by the type-I firm. Note also that a type-M firm gains about 40 in payoff if its rival switches from type J to type E, as it picks up $\delta S(L,L)$ in a state where before it earned zero.

Information acquisition also creates negative externalities. These come from making a rival's information less valuable by preempting entry initiation in favorable states. Thus, a type I facing a type J earns 163.6, but only 143.4 against type M. The reduction of 20.2 is mostly due to the substitution of $\delta S(H,H)$ for $\delta Z(H,H)$ when the informed firm is the follower, demand is high, and cost is high. The probability of this compound event is $.5x(1-y)=.105$ and the net loss conditional on that event is $\delta[Z(H,H)-S(H,H)]=.9(150)=135$. The loss associated with this event is thus 14.2. The remainder of the negative spillover of the type M onto the type I is accounted for by the event where the fully-informed firm is the follower and the signals are both favorable; the type I loses $\delta[Z(H,L)-S(H,L)]=135$ with probability $.5xy=.045$ for an expected net loss of 6.1. Thus, if the other firm moves from being type J to type M, the fully-informed firm loses approximately 20.3 in payoff.

The payoffs when both firms choose to become type J are the result of a war of attrition in this case. Each firm can guarantee itself $E(Z,L)=130.5$ by initiating entry; the most it can get is $E(S,L)=179.8$. Depending on which equilibrium of this continuation game is chosen, the players may find themselves at any of the points in between. Any equilibrium in which some delay occurs in entry, that is, any equilibrium in which the leader does not immediately give in, will result in a joint diminution of payoff.

Finally, note that $(s_1,s_2)=(M,E)$ and (E,M) Pareto-dominate the (I,J) and (J,I) equilibria, even though in either case the project is

always undertaken if it's profitable, and c(M)+c(E) is the total amount spent on information gathering in both sets of equilibria. The efficiency loss is caused in the (I,J) and (J,I) equilibria by the uninformed firm finding it optimal not to initiate entry as a leader. The resulting delay in investment reduces joint profits.

IIIB. Externalities in Information Choice

As shown above, information choice, in this model, can lead to externalities across firms. It so happens, in Example 1, that the Pareto-optimal information choice is a Nash equilibrium, but this need not be so. By appropriately manipulating the costs c(M) and c(E), or the differences between Z and S terms, it is possible to construct examples in which price or cost is not observed even though such observation is socially efficient, or where the equilibrium features overinvestment in information.

When second entrants earn negative profits, anytime a firm acquires information that causes it to initiate entry in a particular state of the world, it reduces the expected profits of a rival who would also like to initiate entry in that state. It is important to realize that the externality is not restricted to firms that learn the same information (although it is more severe in such instances); it can occur even in a heterogeneous-learning equilibrium. The reason is that in the state where both price and cost are favorable, a firm learning either one desires to initiate entry, so that one firm will be kept out and its information wasted.

Example 3 shows this negative externality at work. The values used are $xyZ(H,L)=100$, $x(1-y)Z(H,H)=(1-x)yZ(L,L)=25$, $(1-x)(1-y)Z(L,H)=-200$, $c(M)=c(E)=50$, $c(I)=100$, and $\delta=.9$. The $S(.,.)$ terms are negative.

Example 3

	J	M	E	I
J	0, 0	0, 68.75	0, 68.75	0, 42.5
M	68.75, 0	12.5, 12.5	23.75, 23.75 *	12.5, -13.75
E	68.75, 0	23.75, 23.75 *	12.5, 12.5	12.5, -13.75
I	42.5, 0	-13.75, 12.5	-13.75, 12.5	-25, -25

Once again, asterisks denote the Nash equilibrium points, which are of the heterogeneous-learning variety. The cannibalization effect of one firm's information on the value of the other's is apparent; the equilibrium does not maximize industry profits, and the homogeneous-learning outcomes are even worse.

The cannibalization, or business-stealing, motive for information choice is similar to the cause of excessive homogeneity in the restricted model. A completely new issue in the unrestricted model is the possibility of insufficient learning from a social point of view. The phenomenon is caused by imperfect appropriability of the value of information, with either consumers or rivals receiving part of the gains to learning. Suppose, for example, that $E(Z|J)<0$ and $E(S|J)>0$, so uninformed firms never initiate entry, but would benefit if the other firm initiated entry. If $V_1(M,J)<0$, say because the cost of learning price is high, but $V_1(J,M)>0$, and a similar situation holds for learning

cost, then it is possible that no observations are made and no one
enters, even though industry profits would be maximized by a firm
learning one of the random variables.

A particular example of underinvestment in information is given in
Example 4 with $xyZ(H,L)=200$, $x(1-y)Z(H,H)=(1-x)yZ(L,L)=50$,
$(1-x)(1-y)Z(L,H)=-300$, $xyS(H,L)=100$, $X(1-y)S(H,H)=(1-x)yS(L,L)=20$,
$c(M)=c(E)=250$, $c(I)=500$, and $\delta=.9$. Then the normal form is

Example 4

	J	M	E	I
J	0 , 0 *	102.6,-12.5	102.6,-12.5	119.7,-215
M	-12.5,102.6	-71 , -71	-39.5,-39.5	-53,-273.5
E	-12.5,102.6	-39.5,-39.5	-71 , -71	-53,-273.5
I	-215,119.7	-273.5,-53	-273.5,-53	-287,-287

One firm observing either price or cost, and the other firm
remaining uninformed, constitutes the joint-profit-maximizing set of
signal choices. The unique dominant-strategy equilibrium, however, has
both firms remain uninformed. Whether or not firms appropriate all
consumer surplus, this equilibrium is Pareto-inferior to having one firm
learn price or cost; if consumers get some surplus in the event of
entry, then the social inefficiency is even worse, since the equilibrium
involves missing good projects.

The analysis suggests that coordinating information acquisition through research joint ventures or industry-association marketing studies may enhance social welfare. As long as the exchange of information does not become a facilitating device for collusion in the post-entry game, these cooperative approaches may improve the situation.

One must be careful, however, to distinguish between promotion of learning when it would otherwise not occur, as in Example 4, and control of excessive learning through joint mechanisms. The first of these objectives will always create benefits, because it not only maximizes industry profits, but also promotes entry which would otherwise not occur. Mechanisms to reduce expenditures on learning, however, may reduce social welfare even as they increase industry profits; in Example 3, for instance, forcing one of the firms to be uninformed increases joint profits, but eliminates entry in one of the mixed-news cases. If there is substantial unappropriated consumer surplus in the event of entry, then the loss of this investment can actually reduce overall welfare.[7]

IIIC. Comparison of Monopoly and Duopoly

Allowing firms to learn both signals, or neither one, makes it difficult to draw precise conclusions about the effect of raising the number of firms in the industry. However, the same logic applied to the restricted model operates here. The more rivals there are with a

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[7]Note also that a "cooperative" approach to restraining learning expenditures would involve the firms in rather heavy monitoring of one another's management practices. Even if the information is shared and the cost of acquisition split, if only one of the signals is jointly observed, each of the firms may have an incentive to cheat and research the other variable.

particular piece of information, the less valuable is that information. It is plausible that with a large number of players, and reasonably low learning costs, there will be a set of firms observing one variable, another set observing another, and some firms that choose to rely solely on their private information.

It is possible to be a bit more definite about the effect of increasing the number of industry participants from one to two, and the exercise gives additional insight into the role of rivalry in promoting learning. Certain requirements must be met in making this type of cross-model comparison. First, monopoly profits of entry in the various states must be calculated appropriately. The easiest way to do this is to assume that the S terms are all negative, so that monopoly profits are identical to the Z terms.[8] Of course, this expedient precludes discussing the public good aspects of information, but it avoids having to commit to a particular structural model of ex post competition. Second, the leader-follower structure must be interpreted in a monopoly setting. I choose to treat it as a probability of .5 that the monopolist is ready to invest in Period 3 and .5 that investment must wait until Period 4.

Example 3, for a monopolist, would have the following payoffs: $V(J)=0$, $V(M)=V(E)=68.75$, and $V(I)=47.5$. Either M or E will be chosen; J involves not entering for fear of a big loss if the news is bad on both fronts, while I costs 50 more than M or E, but only brings in an additional 21 in expected value terms. The net marginal value of a second observation is negative. In this example, the duopoly

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[8]If the S terms are positive, then the monopolist's gain to entry exceeds Z, since there is no secondary entry to dilute profits.

equilibrium guarantees that the project will be taken whenever it earns

positive profits, while the monopolist will fail to invest in some

favorable circumstances, since it learns only one piece of information.[9]

In situations like this one, the relative performance of the two market

structures is determined by how much surplus consumers get from facing a

post-investment monopoly. If no consumer surplus is gained, then a pre-

investment monopoly dominates a pre-investment duopoly, since industry

profits are higher under that structure in expected value terms. On the

other hand, if consumers actually get surplus when purchasing from a

post-investment monopoly, then a duopoly at the pre-investment stage may

be superior, since it ensures production in an additional state of the

world where production is socially desirable. Thus, the monopoly

position internalizes the externalities that lead to excessive learning.

Whenever second entrants earn negative profits, if a monopoly

chooses strategy I, then duopolists will not settle on an equilibrium in

which each learns price or each learns cost. For a monopolist, $V(I)-V(M)=.5(1+\delta)(1-x)yZ(L,L)-c(E)$. For a duopolist, $V_1(I,M)-V_1(M,M)=.5(1-x)yZ(L,L)+.5\delta(1-x)yZ(L,L)-c(E)=V(I)-V(M)$.

So if a monopolist would rather learn both price and cost than

price alone, then a duopolist would have an incentive to deviate from

learning price alone given that its rival learns only price. A parallel

argument works for cost information. This analysis maintains the

hypothesis that all S terms are negative, and leads to the following

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[9]In Sah-Stiglitz (1985), a "polyarchy" will invest in a project that
is accepted by any one of its multiple decision-makers, and so has a
lower probability of missing good projects than does a unitary decision-
maker. The differences in assessments are caused by random noise in the
evaluation process. Here, the duopolists are _better_ _informed_ (jointly)
than is the monopolist.

conclusion: when first-mover advantages are significant for an investment project, a pair of firms is at least as likely to undertake the project as is a single firm facing no rivals.

IIID. Asymmetries in Timing

The value of information to a duopolist is also affected by the likelihood that it will have an opportunity to enter first. Suppose that instead of being fixed at .5, the probability of a firm becoming leader is varied. Whenever a leader enters first and the follower would have liked to initiate entry based on its private information, that information is wasted. The leader's entry reveals the true value of price and cost, so the other firm regrets information purchases ex post. Information is therefore more valuable to a firm the more likely it is that the firm will be designated the leader in Period 2, and so the desirability of learning both price and cost rises. As in the restricted model, a firm that expects to be the follower will avoid duplication of its rival's information; if learning both signals is optimal for a certain leader, then the follower will not make any observations.

Another interesting variation of the model is created by changing the Period 1 information choice from a simultaneous-move game to a Stackelberg game that takes place in two subperiods, 1a and 1b. Designate the firm that moves in 1a "the pioneer" and the firm that moves in 1b "the latecomer". This formulation allows for a stylized sort of industry history to be considered. For simplicity, return to the assumption that the probability of either firm being designated the leader in Period 2 is .5, regardless of who is the pioneer in Period 1.

The pioneer will always choose an information strategy that maximizes its payoff over all best responses by the latecomer, assuming that the latecomer's arrival is foreseen.

In Example 2, the "information leader" will select M, when the follower's best response is E, so that the leader earns 191.6 and the follower 173.6. The asymmetry in profits can be thought of as resulting from a "mobility barrier," in the sense of Caves and Porter (1977). Only one firm can profitably occupy the marketing-strategy niche, so a first-mover advantage for one firm prevents the other from becoming a marketing-oriented firm. The second-mover finds it impossible to enter the more profitable segment of the industry.

Preemption of a favorable information niche can also occur where one firm's knowledge is a proper subset of the other. In Example 2, the firm moving in Period la could choose J and induce its rival to choose I, but this would be slightly inferior to the policy described above. However, consider Example 5, which comes from assuming that all S terms are negative, $xyZ(H,L)=100$, $x(1-y)Z(H,H)=(1-x)yZ(L,L)=50$, $(1-x)(1-y)Z(L,H)=-200$, $c(M)=20$, $c(E)=30$, and $\delta=.9$:

Example 5

	J	M	E	I
J	0, 0	0, 122.5	0, 112.5	0, 140
M	122.5, 0	55, 55	77.5, 67.5	55, 72.5 *
E	112.5, 0	67.5, 77.5	45, 45	45, 72.5

I	140, 0	72.5, 55 *	72.5, 45	50, 50

In the Stackelberg version of this game, the pioneer will choose I and the latecomer M. The equilibrium favors the firm whose information strictly contains the information of its rival. Because it is an equilibrium, the fact that one firm is more informed and is earning higher profits does not imply that its rival has made a mistake by gathering less information about the investment project. Rather, the appearance of "bad management" on the part of the latecomer is the result of the niche structure of the industry.[10]

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[10]Note that the equilibrium in Example 5, either with simultaneous choice of information or Stackelberg leadership, is inefficient. One firm learning cost and the other price maximizes industry profits; furthermore, such a set of information choices implies that the new-product market will always be entered when such entry is socially desirable, so that consumer surplus considerations cannot change the verdict that the market provides excessive learning expenditures. A collusive arrangement to share information would be agreed to by both firms only if the firm giving up the favorable position can receive side-payments of some kind.

IV. CONCLUSION

The model in this paper illustrates how the decentralized optimizing behavior of firms can lead to different beliefs about uncertain investment projects. Firms may "cultivate disagreement," focusing their attention on different parts of the environment and gathering different sorts of information. The degree of correlation of rivals' signals about project profitability flows endogenously from assumptions about technology and demand, unlike the usual noisy-signal approach in which the degree of correlation is taken as given.

Considering information choices in a rivalrous context also destroys the notion that there exists a single, optimal management structure for each industry. Rather, the optimal type of management team to construct is critically dependent on the decisions of other firms. Just because firms look different and display systematic differences in profits does not mean that the "losers" ought to emulate the "winners".

This model bears an interesting relationship to the growing literature on technology adoption in the presence of network externalities. In that work, such as the first essay of this thesis, Farrell and Saloner (1985 and 1986), and Katz and Shapiro (1985 and 1986), the key assumption is that a network of users yields its members greater value as its size grows. Here, if one thinks about one "network" of marketing-driven firms and another "network" of engineering-driven firms, the externalities are negative--the larger the network, the lower the value to each member. In the typical model with

positive consumption externalities, the equilibrium sizes of competing networks are not stable unless one network has swallowed up all the available users while the other shrinks or stagnates. With negative externalities, by contrast, the pressure for equality of network sizes is strong; this is particularly clear in the N-firm model.

The bandwagon-effect models of Farrell and Saloner (1985), and the first essay of this thesis, are related to this paper in another way. In the bandwagon papers, the players contemplate switching from an existing network to a new one; each player puts a different value on old and new networks of varying sizes, and these values are private information. If one thinks of "not investing" and "investing" as the old and new networks in the restricted version of the oligopoly investment game here, then the continuation game after signals are learned looks like a bandwagon model, but with common values for the two networks rather than private ones. Under assumption A3, this bandwagon is always efficient; whenever the project is good, some firm or firms switches from "not invest" to "invest". If A3 is voided, however, so that mixed news implies unprofitability of the investment (although both signals good still implies profitability), then the entry game exhibits "excess inertia": It is possible for each firm to observe good news but for neither firm to initiate entry, since the risk of a loss under mixed news may outweigh the expected gain with both parameters favorable.

Exploring the sources of firm disagreement also leads naturally to questions of great importance for the normative evaluation of a market economy: Does rivalrous behavior lead to optimally diversified learning about investment projects? If not, how serious are deviations, and in what direction do they go? Can anything be done about these deviations?

The model used here is obviously not rich enough to provide convincing answers to these questions. Some tentative conclusions can be advanced, however.

First, there should be no presumption that an oligopoly devotes resources optimally to learning about investment projects. Informational externalities across firms prevent incentives from lining up properly. If learning is seen as a choice of managerial structure rather than data collection, however, adding firms to the industry guarantees that no good projects will be missed. Second, these externalities can be either positive or negative, depending on how much of the surplus generated by a project is appropriated by the first mover, implying the possibility of both under- and overinvestment in information.

Third, pre-investment oligopolies will generally be at least as likely as monopolies are to undertake valuable but uncertain investment projects if post-investment profits are mostly captured by the first mover. When consumer surplus is generated by a project, therefore, ex ante monopolies may be less socially efficient than oligopolies. This point gives cause for concern about situations like that of the electric power industry, where there is little rivalrous incentive to seek out different sources of information about new investments.

Fourth, joint ventures for the purposes of evaluating new technologies or new products may be desirable ways to overcome free-rider problems in information acquisition when first movers are unable to appropriate a large fraction of project profits. Use of such mechanisms to restrict excessive learning is problematic, since in the absence of side-payments, and in a regime of pure-strategy equilibria, one firm will always refuse to cut back on learning.

Thinking about heterogeneous-learning equlilbria also leads to serious doubts about proposals to direct capital through industrial-planning boards in an effort to "pick winners" among industries and investment projects.[11] The board would need a sophisticated understanding of the nature of projects in all the various industries; specifically, it would need to know when the equivalent of Assumption 3 holds, so that a single positive signal implies that a project should go forward. Absent such competence, which seems the likely case, the board would be prone to direct investment capital into projects unanimously supported by industry members and away from those that provoke disagreement. Following unanimous advice would shield the board from criticism for pouring public money into bad projects; taking a flier on a controversial venture exposes the board to the risk that this is a case where Assumption 3 does not hold.

The result, even ignoring the incentive effects on what firms choose to tell the board, is that industries with homogeneous managements and common modes of assessment will have an edge in getting projects approved over heterogeneously-managed industries. Since it is plausible that there are systematic differences between these two types of industries (for example, that homogeneous industries tend to be mature in demand and technology), this could lead to serious distortion of investment.

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[11] I refer here to the various proposals floated in the United States to have a government body (a tripartite board of businessmen, union leaders, and government officials, in the classic formulations) allocate loan capital, and also coordinate regulatory policy, in order to "rationalize" the national portfolio of businesses. My criticism here is not directed to the seemingly inevitable substitution of political criteria for considerations of economic efficiency by such a board. Nor am I addressing the merits of French-style indicative planning, in which the government applies no coercion, at least in theory.

APPENDIX 1

Proof of Proposition 1: First I will show that the proposed

equilibrium path is consistent with the lemmas established in the text.

Then I will consider potential deviations and show that they do not

disturb the equilibrium for any off-the-equilibrium path behavior.

(1) The secondary entry behavior described is just a restatement

of Lemma 1.

(2) In Period 3, the leader's beliefs are determined solely by the

common prior information and by its private information; no inferences

can be drawn from the follower's actions because the follower has not

yet had a chance to move. The leader's entry initiation behavior as a

function of those beliefs obeys Lemmas 2 and 3. Note that given (1),

the behavior in (2) dominates other possible actions.

(3) If the leader fails to enter in Period 3, then the follower's

beliefs are a combination of common prior information, private

information, and inferences following the rules of Lemma 4. These

inferences are that the leader's private information is unfavorable to

the project. Given that the game is on the equilibrium path, if the two

firms have observed the same signal, then the follower's private

information must be unfavorable; otherwise, the leader, following the

behavior in (2) would have initiated entry. If the firms have observed

different signals, then the follower enters if its private information

is favorable, and stays out if its private information is unfavorable. This behavior is optimizing given equilibrium beliefs and assumptions A3 and A4.

(4) If no entry has occurred by Period 5, then it will never occur in equilibrium, by the logic of Lemma 6: if all private information is unfavorable, then A4 makes initiating entry an unprofitable choice.

To establish that a perfect Bayesian equilibrium with the above equilibrium path exists, it is not sufficient to demonstrate that the path is internally consistent. It is also necessary to show that unilateral deviations from the path are not profitable. In this model, deviations fall into two categories: Entry when the proposed equilibrium calls for non-entry, and non-entry or delayed entry when the proposed equilibrium calls for entry.

A) Secondary entry always is decided upon with full information. The proposition incorporates the behavior of Lemma 1, which simply says to enter if and only if secondary entry earns positive profits. Any strategy that fails to incorporate this rule is dominated by one that does. Hence, no deviation from (1) can possibly increase a firm's payoff.

If a leader initiates entry in Period 3 when its private information is unfavorable, thereby violating Lemma 3, A4 guarantees that it is engaging in an action with negative expected value. Such a move cannot cause the follower to behave in a manner that benefits the leader, because the follower will always obey Lemma 1, as just

explained. So this deviation is unprofitable. If a follower initiates entry in Period 4, despite having unfavorable private information, then its actions can't be optimal for the same reason.

B) is a bit more complicated. A number of subcases must be dealt with, corresponding to the different information sets a deviant's rival might hold.

B1) A firm initiates entry and the other firm fails to enter even though entry guarantees positive profits (i.e. Lemma 1 is violated): By Lemma 0, the firm which has entered will find it optimal to stay in the market, having already sunk the "entry fee". The deviant gains nothing (and in fact loses the S that is positive by assumption).

B2) A leader, facing a follower whose private information is identical to its own, fails to enter in Period 3, even though it knows that $P=P^H$ or that $C=C^L$ (i.e. the leader violates Lemma 2 in a situation where the follower is aware of the violation): Whatever beliefs the follower has as a result of the leader's failure to choose an apparently (iterated) dominant strategy, and whatever actions it takes as a result of those beliefs, the leader's profits from deviating are guaranteed to be strictly less than they would be from following Lemma 2. Hence, such a deviation can never upset the equilibrium behavior described in (1)-(4) of the proposition.

Note that it is not necessary to deal with the case of a partly or fully informed firm failing to enter, despite good news, when its rival's private information is different from its own. In that case, the rival will simply infer that the first firm observed bad news, since such a situation can occur on the equilibrium path. An implication of

this point is that in a heterogeneous-learning equilibrium of the
restricted game, all behavior appears to be on the equilibrium path
(i.e., there are no events of zero prior probability possible).

APPENDIX 2

Lemma 8: Suppose $s_1 = J$ and s_2 differs from J. Then

$$L_1(J, s_2) = \text{Max}\{E(Z,J), \delta F_1(J, s_2)\} \qquad \text{and}$$

$$F_2(J, s_2) = E(S,J)/\delta \quad \text{if } E(Z,J) > \delta F_1(J, s_2)$$

$$\delta L_2(J, s_2) \quad \text{if } E(Z,J) < \delta F_1(J, s_2)$$

Proof: Under the conditions of the lemma, if firm 1 is the leader, then if firm 1 initiates entry in Period 3 it earns $E(Z,J)$, by definition. If firm 1 were to refrain from initiating entry, then firm 2 would have the opportunity to enter first in Period 4; in effect, firm 1 would be in the same position as if it had been designated the follower and the whole game started a period later. This is so because firm 2 draws no inference from firm 1's refusal to enter, and so behaves just as if it were a leader after such a refusal. Now firm 1's payoff to followership is $F_1(J, s_2)$, by definition. Hence, if firm 1 fails to initiate entry in Period 3, it earns $\delta F_1(J, s_2)$. It follows, therefore, that if $E(Z,J) > \delta F_1(J, s_2)$, then firm 1 will find it optimal to initiate entry; if the condition is reversed, then waiting is indicated. In the event of equality, firm 1 is indifferent across the actions.

Given this behavior by firm 1, $F_2(J, s_2)$ is just the payoff of an uninformed follower whenever firm 1 initiates entry in Period 3, i.e. whenever $E(Z,J) > \delta F_1(J, s_2)$, because information has no effect on payoff when the other firm initiates entry immediately. If firm 1 chooses to

wait instead, then firm 2 is in the position of being a leader, one period late.

Proposition 4: Given Al-A4, there exists a perfect Bayesian Nash equilibrium to the continuation game starting in Period 3 with the following properties on the equilibrium path. Furthermore, any perfect Bayesian Nash equilibrium shares this equilibrium path.

(1) $B_{it}(P^j, C^k) = 1$ iff $S(j,k) > 0$

(2) $A_{i3}(P^0, C^0, J) = 1$ if $E(Z,J) > E(S,J) > 0$

                    0   if $E(Z,J) < 0$

   $A_{it}(P^0, C^0, J) = 0$ if $E(Z,J) < 0$

                    Ó   if $E(S,J) > E(Z,J) > 0$

   Where Ó is the equilibrium strategy in a war of attrition.

(3) Assume that 1 denotes the leader and 2 the follower. Then W_{13} is just the leader's private information in Period 3, and A_{13} is given by (3.1)-(3.11).

   (3.1) $A_{13}(P^0, C^0, M) = 1$ if

       $E(Z,J) > \delta^2 x[yMax\{S(H,L),0\} + (1-y)Max\{S(H,H),0\}]$

              = 0   else

   (3.2) $A_{13}(P^0, C^0, E) = 1$ if

$$E(Z,J)>\delta^2 y[x\mathrm{Max}\{S(H,L),0\}+(1-x)\mathrm{Max}\{S(L,L),0\}]$$

$$=0 \quad \text{else}$$

(3.3) $A_{13}(P^0,C^0,I)=1$ if

$$E(Z,J)>\delta^2[xy\mathrm{Max}\{S(H,L),0\}+$$

$$x(1-y)\mathrm{Max}\{S(H,H),0\}+$$

$$(1-x)y\mathrm{Max}\{S(L,L),0'\}]$$

$$=0 \quad \text{else}$$

(3.4) $A_{13}(P^H,C^0,s_2)=1$ for any s_2

(3.5) $A_{13}(P^L,C^0,s_2)=0$ for any s_2

(3.6) $A_{13}(P^0,C^H,s_2)=0$ for any s_2

(3.7) $A_{13}(P^0,C^L,s_2)=1$ for any s_2

(3.8) $A_{13}(P^H,C^L,s_2)=1$ for any s_2

(3.9) $A_{13}(P^H,C^H,s_2)=1$ for any s_2

(3.10) $A_{13}(P^L,C^L,s_2)=1$ for any s_2

(3.11) $A_{13}(P^L,C^H,s_2)=0$ for any s_2

(4) Following the convention that firm 1 is the
designated leader, if firm 1 failed to initiate entry

in Period 3, then equilibrium-path strategies and beliefs for Period 4 are given by (4.1)-(4.24).

	P_1	C_1	s_1	P_2	C_2	s_2	W_{14}	W_{24}	A_{14}	A_{24}
(4.1)	P^0	C^0	J	P^H	C^0	M	P^0,C^0	P^H,C^0	0	1
(4.2)	P^0	C^0	J	P^L	C^0	M	P^0,C^0	P^L,C^0	0	0
(4.3)	P^0	C^0	J	P^0	C^H	E	P^0,C^0	P^0,C^H	0	0
(4.4)	P^0	C^0	J	P^0	C^L	E	P^0,C^0	P^0,C^L	0	1
(4.5)	P^0	C^0	J	P^H	C^L	I	P^0,C^0	P^H,C^L	0	1
(4.6)	P^0	C^0	J	P^H	C^H	I	P^0,C^0	P^H,C^H	0	1
(4.7)	P^0	C^0	J	P^L	C^L	I	P^0,C^0	P^L,C^L	0	1
(4.8)	P^L	C^0	J	P^L	C^H	I	P^0,C^0	P^L,C^H	0	0
(4.9)	P^L	C^0	M	P^0	C^0	J	P^L,C^0	P^L,C^0	0	0
(4.10)	P^L	C^0	M	P^L	C^0	M	P^L,C^0	P^L,C^0	0	0
(4.11)	P^L	C^0	M	P^0	C^H	E	P^L,C^0	P^L,C^H	0	0
(4.12)	P^L	C^0	M	P^0	C^L	E	P^L,C^0	P^L,C^L	0	1
(4.13)	P^L	C^0	M	P^L	C^L	I	P^L,C^0	P^L,C^L	0	1
(4.14)	P^L	C^0	M	P^L	C^H	I	P^L,C^0	P^L,C^H	0	0
(4.15)	P^0	C^H	E	P^0	C^0	J	P^0,C^H	P^0,C^H	0	0
(4.16)	P^0	C^H	E	P^H	C^0	M	P^0,C^H	P^H,C^H	0	1
(4.17)	P^0	C^H	E	P^L	C^0	M	P^0,C^H	P^L,C^H	0	0
(4.18)	P^0	C^H	E	P^0	C^H	E	P^0,C^H	P^0,C^H	0	0
(4.19)	P^0	C^H	E	P^H	C^H	I	P^0,C^H	P^H,C^H	0	1
(4.20)	P^0	C^H	E	P^L	C^H	I	P^0,C^H	P^L,C^H	0	0
(4.21)	P^L	C^H	I	P^0	C^0	J	P^L,C^H	P^L,C^H	0	0
(4.22)	P^L	C^H	I	P^L	C^0	M	P^L,C^H	P^L,C^H	0	0
(4.23)	P^L	C^H	I	P^0	C^H	E	P^L,C^H	P^L,C^H	0	0

$$(4.24)\quad \boxed{\,P^L\,}\,\boxed{\,C^H\,}\,\boxed{\,I\,}\,\boxed{\,P^L\,}\,\boxed{\,C^H\,}\,\boxed{\,I\,}\,\boxed{\,P^L,C^H\,}\,\boxed{\,P^L,C^H\,}\,\boxed{\,0\,}\,\boxed{\,0\,}$$

(5) After Period 4, entry is never initiated. Beliefs

are the same as W_{i4}. Of course, if entry was

initiated in Period 4, then the behavior described in

(1) occurs in Period 5, and the true values of P and

C are known.

Proof: To establish Proposition 4, I first show that the behavior
presented is a perfect Bayesian Nash equilibrium path, i.e. that given
that one firm adheres to (1)-(5), the other firm will also find it
optimal to do so. Since an equilibrium strategy must specify what a
firm will do in any subgame that can conceivably be reached, and not
just in those on the equilibrium path, I then show that any set of moves
off the equilibrium path can have no effect on (1)-(5). Thus, the
issues of multiple equilibria and the appropriate "refinements" of the
equilibrium concept do not arise in a meaningful way; no matter what
out-of-equilibrium beliefs are postulated, the equilibrium path is
unchanged.

(1) is a dominant strategy for all subgames in which the other
firm initiates entry, as established in Lemma 1. Therefore, it is also
part of a perfect Nash equilibrium.

(2) describes dominant strategies in the subgames where both firms
are uninformed for the cases $E(Z,J)>E(S,J)>0$ and for $E(Z,J)<0$, as shown

in Lemma 4. In the remaining possibility, when $E(S,J)>E(Z,J)>0$, a war of attrition with multiple equilibria is the result.

(3) lays out the behavior of a designated leader given equilibrium behavior by the follower. (3.4) and (3.7)-(3.10) are dominant strategies, given (1), by Lemma 2. (3.5), (3.6), and (3.11) are dominant strategies by Lemma 3. (3.1)-(3.3) give the strategies of an uninformed leader facing a follower who is informed in various ways. The informed follower's behavior is given by (4.1)-(4.8) for those subgames where the leader has not entered; these are dominant strategies, given (1), as will be shown below. Given (4.1)-(4.8), an uninformed leader can calculate the expected gains of waiting in Period 3. These values are the right-hand side of the inequalities in (3.1)-(3.3). Comparing them with the gains from immediately initiating entry, $E(Z,J)$, gives the leader's optimal decision rule for entry.

(4) gives the follower's beliefs W_{24} and entry behavior A_{24} given that the leader has failed to initiate entry in Period 3. The beliefs listed are a combination of the follower's private information and the inferences the follower draws according to Lemma 5. Since this is along the equilibrium path of a Bayesian equilibrium, the private information never contradicts the inferences (i.e. I temporarily ignore events of zero prior probability). In this context, the A_{24} values in (4.1), (4.4)-(4.7), (4.12), (4.13), (4.16), and (4.19) are shown to be optimal, given beliefs and the behavior in (1), by an argument identical to that used in proving Lemma 2: assumptions A2 and A4 jointly guarantee that knowing that $P=P^H$ or that $C=C^L$ makes immediate entry the expected-profit

maximizing strategy. Similarly, given the beliefs W_{24}, the actions described in (4.2), (4.3), (4.8)-(4.11), (4.14), (4.15), (4.17), (4.18), and (4.20)-(4.24), which show the follower staying out of the market, follow from an argument identical to that used in Lemma 3: assumption A3 says that if the only information the follower has is that $P=P^L$ or that $C=C^H$, then the expected value of entry is negative.

(5) simply asserts that if no one has entered by Period 4, then entry will never take place. This is a direct consequence of Lemma 7.

Now it is necessary to consider subgames that are off the equilibrium path, to make sure that the strategies described really are part of a perfect equilibrium. Deviations from the path can be classified into cases where A) a firm enters the market when it is not supposed to according to (1)-(5), or where B) a firm fails to enter when it is supposed to according to (1)-(5).

A) presents little difficulty, since any time a firm enters, the true values of P and C are revealed. Lemma 1 still describes the dominant strategy for the deviant's rival. Hence, a firm cannot gain anything by initiating entry under conditions other than those described in (1)-(5) of Proposition 4. Furthermore, since a leader, once it has initiated entry, has zero cost of remaining in the market, the follower would never have an incentive to violate Lemma 1 by entering when the profits are guaranteed to be negative.

B) is a bit more complicated. A number of subcases must be dealt with, corresponding to the different information sets a deviant's rival might hold.

B1) A firm initiates entry and the other firm fails to enter even though entry guarantees positive profits (i.e. Lemma 1 is violated): By Lemma 0, the firm which has entered will find it optimal to stay in the market, having already sunk the "entry fee". The deviant gains nothing (and in fact loses the S that is positive by assumption).

B2) An uninformed leader facing an uninformed follower fails to enter in Period 3 even though $E(Z,J)>E(S,J)>0$ (i.e. (2) is violated): The follower would find it optimal to initiate entry in Period 4 if it could be sure that the leader would not also try to initiate entry at that time, since its beliefs are based on public information that is common knowledge. Because the expected value of entry to an uninformed firm, given that two firms enter simultaneously, is less than $E(Z,J)$, the follower must worry about the leader changing its mind and plunging in a period late. Whether the follower chooses to initiate entry in Period 4, to never enter, or to play a mixed strategy in every succeeding period, the deviant leader gains nothing in expected value terms by failing to enter in Period 3. Hence the equilibrium path is not disturbed by this subgame.

B3) An uninformed leader facing an informed follower fails to enter in Period 3 even though the inequalities described in (3.1), (3.2), or (3.3) show that such entry is a dominant strategy for the leader: Since the leader is uninformed, the follower has no reason to doubt his private information. If that information conveys bad news about the project as defined in the hypothesis of Lemma 3, then the follower knows that non-entry is a dominant strategy. If the follower has good news, then it faces a problem similar to that in B2) above. No matter what beliefs and actions the follower adopts, the leader's payoff

from deviating is strictly less in expected value terms than the payoff from conforming to (3.1)-(3.3); if the expected value of entry in Period 3 exceeds the expected value of waiting when the follower will reveal its information in Period 4, then initiating entry is surely superior to any waiting strategy that entails revelation later than Period 4. Therefore, this type of deviation cannot induce a breakdown in the equilibrium of the proposition.

B4) A partly or fully informed leader, facing a follower whose private information is a superset of the leader's, fails to enter in Period 3, even though it knows that $P=P^H$ or that $C=C^L$ (i.e. the leader violates Lemma 2 in a situation where the follower is aware of the violation): Whatever beliefs the follower has as a result of the leader's failure to choose an apparently (iterated) dominant strategy, and whatever actions it takes as a result of those beliefs, the leader's profits from deviating are guaranteed to be strictly less than they would be from following Lemma 2. Hence, such a deviation can never upset the equilibrium behavior described in (1)-(5) of the proposition.

Note that it is not necessary to deal with the case of a partly or fully informed firm failing to enter, despite good news, when its rival's private information is disjoint from its own. In that case, the rival will simply infer that the first firm observed bad news, since such a situation can occur on the equilibrium path. An implication of this point is that in a heterogeneous-learning equilibrium of the restricted game, all behavior appears to be on the equilibrium path (i.e., there are no events of zero prior probability possible).

APPENDIX 3

The following is a list of all the expressions $L_i(*,*)$ and $F_i(*,*)$ for the various subgames. Since the game is symmetric across players, so that $L_1(k,n)=L_2(n,k)$, where n and k are choices of information, I give only the L_1 and F_1 versions.

$F_1(J,J) = \delta xy\text{Max}[S(H,L),0] + \delta x(1-y)\text{Max}[S(H,H),0]$

$\qquad + \delta(1-x)y\text{Max}[S(L,L),0]$

$\qquad\quad$ if this expression (which is also

$\qquad\quad E(S,J)/\delta=F_1(J,I))$

$\qquad\quad$ is less than

$\qquad\quad E(Z,J)/\delta=[xyZ(H,L) + x(1-y)Z(H,H)$

$\qquad\qquad + (1-x)yZ(L,L)]/\delta,$

$\quad$ 0

$\qquad\quad$ if $E(Z,J)$ is non-positive

$\qquad\quad$ q such that $E(S,J)/\delta_> q_> E(Z,J)/\delta$

$\qquad\quad$ if $E(S,J)>E(Z,J)>0$

$L_1(J,J) = E(Z,J)$

$\qquad\quad$ if $E(Z,J)>E(S,J)$

$\quad$ 0

if E(Z,J) is non-positive

q such that $E(S,J){>}q{>}E(Z,J)$

if $E(S,J){>}E(Z,J){>}0$

$F_1(J,M) = \delta xy Max[S(H,L),0] + \delta x(1-y) Max[S(H,H),0]$

$L_1(J,M) = E(Z,J)$

if $E(Z,J){>}\delta F_1(J,M)$

$\delta F_1(J,M)$

otherwise

$F_1(J,E) = \delta xy Max[S(H,L),0] + \delta(1-x)y Max[S(L,L),0]$

$L_1(J,E) = E(Z,J)$

if $E(Z,J){>}\delta F_1(J,E)$

$\delta F_1(J,E)$

otherwise

$F_1(J,I) = \delta xy Max[S(H,L),0] + \delta x(1-y) Max[S(H,H),0]$

$+ \delta(1-x)y Max[S(L,L),0]$

$L_1(J,I) = E(Z,J)$

$$\text{if } E(Z,J) > \delta F_1(J,I)$$

$$\delta F_1(J,I)$$

$$\text{otherwise}$$

$$F_1(M,J) = F_1(J,I)$$

$$\text{if } E(Z,J) > \delta F_1(J,M)$$

$$\delta xyZ(H,L) + \delta x(1-y)Z(H,H)$$

$$\text{otherwise}$$

$$L_1(M,J) = xyZ(H,L) + x(1-y)Z(H,H)$$

$$F_1(M,M) = F_1(J,M)$$

$$L_1(M,M) = L_1(M,J)$$

$$F_1(M,E) = \delta xy\text{Max}[S(H,L),0] + \delta x(1-y)Z(H,H)$$
$$+ \delta(1-x)y\text{Max}[S(L,L),0]$$

$$L_1(M,E) = xyZ(H,L) + x(1-y)Z(H,H)$$
$$+ \delta^2(1-x)y\text{Max}[S(L,L),0]$$

$$F_1(M,I) = F_1(J,I)$$

$$L_1(M,I) = L_1(M,E)$$

$F_1(E,J) = F_1(J,I)$

$\qquad$ if $E(Z,J) > \delta F_1(J,E)$

$\qquad\quad \delta xyZ(H,L) + \delta(1-x)yZ(L,L)$

$\qquad\quad$ otherwise

$L_1(E,J) = xyZ(H,L) + (1-x)yZ(L,L)$

$F_1(E,M) = \delta xy\text{Max}[S(H,L),0] + \delta x(1-y)\text{Max}[S(H,H),0]$

$\qquad\quad + \delta(1-x)yZ(L,L)$

$L_1(E,M) = xyZ(H,L) + \delta^2 x(1-y)\text{Max}[S(H,H),0]$

$\qquad\quad + (1-x)yZ(L,L)$

$F_1(E,E) = F_1(J,E)$

$L_1(E,E) = L_1(E,J)$

$F_1(E,I) = F_1(J,I)$

$L_1(E,I) = L_1(E,M)$

$F_1(I,J) = F_1(J,I)$

$\qquad$ if $E(Z,J) > \delta F_1(J,I)$

$\qquad\quad \delta xyZ(H,L) + \delta x(1-y)Z(H,H) + \delta(1-x)yZ(L,L)$

$\qquad\quad$ otherwise

$$L_1(I,J) = xyZ(H,L) + x(1-y)Z(H,H) + (1-x)yZ(L,L)$$

$$F_1(I,M) = F_1(E,M)$$

$$L_1(I,M) = L_1(I,J)$$

$$F_1(I,E) = F_1(M,E)$$

$$L_1(I,E) = L_1(I,J)$$

$$F_1(I,I) = F_1(J,I) \,.$$

$$L_1(I,I) = L_1(I,J)$$

APPENDIX 4

The restricted model with N firms in Section IIC uses the same fundamental structure as the two-firm model. Let n be the number of profitable "slots" left in the industry, q the number of firms in the entry queue eligible to pursue them, and r the firm's own position in the queue. The following assumptions about the payoffs are needed:

A1') $Z(j,k,r) > S(j,k,n,q)$ for any j,k,r,n,q

A2') $Z(H,H,r) > Z(L,H,r)$, $Z(L,L,r) > Z(L,H,r)$ for any r

 $S(H,L,n,q) > S(H,H,n,q)$, $S(H,L,n,q) > S(L,L,n,q)$,
 $S(H,H,n,q) > S(L,H,n,q)$, $S(L,L,n,q) > S(L,H,n,q)$ for
 any n and q

A3') $Z(H,H,r) > 0$, $Z(L,L,r) > 0$, $Z(H,L,r) > 0$ for any r

A4') $yZ(L,L,r) + (1-y)Z(L,H,r) < 0$
 $xZ(H,H,r) + (1-x)Z(L,H,r) < 0$ for any r

These assumptions are completely analagous to the ones used in the two firm model. The formal proof of Proposition 3, based on A1'-A4', is now given.

Proposition 3: Given A1'-A4', $V(M,m)$ is strictly decreasing in m and $V(E,m)$ is strictly increasing in m.

Proof: The possible outcomes for firm i can be partitioned into five events: 1) Firm i is first in the queue and initiates entry. 2) Firm i is first in the queue and another firm initiates entry. 3) Firm i is rth in the queue, r>1, but first to enter. 4) Firm i is rth in the queue, r>1, and another firm initiates entry. 5) No firm enters. These are the only possibilities, given the entry behavior described above. Now suppose $s_i = M$.

The payoffs conditional on 1) and 3) are independent of m, since those are determined solely by the Z and S functions. The payoffs conditional on 2) and 4) are weakly decreasing in m; if the initial entrant is earlier than rth in the queue, then the payoff is independent, but if the initial entrant is after firm i, then more type Ms implies that entry is postponed on average.

The probability of being first in the queue is exogenous and independent of m, and the probability of initiating entry from that position is x, which is independent of m. The same basic argument applies to event 2).

Event 3) is less trivial, although the queue position probability is still independent of m. The probability of initiating entry given the rth position in the queue is equal to the product of x(1-y), the probability that $P=P^H$ and $C=C^H$, and (N-1-m)!(N-1-r)!/(N-1)!(N-1-m-r)!, the probability that the first r-1 queue positions are filled by type Es. Since this latter probability is strictly decreasing in m, the probability of event 3) is decreasing in m. Event 4)'s likelihood is the mirror image of event 3), if $P=P^H$ and $C=C^H$; the more type-M firms in the population, the higher the probability that one will enter before

firm i does, so that the probability of event 4) is increasing in m. If $P=P^L$ and $C=C^L$, then the probability of 4) is independent of m; another firm initiates entry if and only if there is some type-E firm in the population, so increasing the number of type Ms has no effect on the probability until m=N-1.

Finally, the probability that no firm enters given that s_i=M is (1-x)(1-y) if m<N-1 and is 1-x if m=N-1, so that the probability of event 5) is increasing in m.

It follows that the effect of increasing m is to shift probability mass from event 3) to events 4) and 5), and to shrink expected payoffs conditional on 2) and 4). But we know from A1', A2', and A3' that the payoff given event (3) is higher than the payoff given events (4) or (5). Therefore, V(M,m) is strictly decreasing in m. If s_i=E, then the same logic shows that increasing m has the effect of moving probability mass from events (4) and (5) to event (3), so that V(E,m) is strictly increasing in m. This completes the proof.

Corollary 3a: Suppose there exists m>0 such that V(M,m)$\geq$V(E,m). Denote the maximum such m by m_0. Then a pure-strategy Nash equilibrium in signal choices exists and, if m_0<N, has m_0+1 firms choose M and N-m_0-1 choose E. All firms choose M if $m_0$$\geq$N. If there does not exist m>0 such that V(M,m)$\geq$V(E,m), then all firms choose E.

Proof: First, m_0>0 exists if there exists m>0 such that V(M,m)$\geq$V(E,m), since the left-hand side of the inequality is strictly decreasing in m and the right-hand side strictly increasing. Suppose m_0<N. If m_0+1 firms choose M, the rest E, then the type M firms earn V(M,m_0) each and the type E firms V(E,m_0+1) each. A type M deviating to

E would earn $V(E,m_0)$; but $V(E,m_0)\leq V(M,m_0)$ by definition of m_0. A type E deviating to M would earn $V(M,m_0+1)$; but $V(M,m_0+1)<V(E,m_0+1)$ by definition of m_0. Since deviations are unprofitable, this configuration is indeed a Nash equilibrium.

To establish that no other type of signal-choice equilibrium is possible, suppose that $m'+1$ firms choose M, $m'<m_0$. Then a type E earns $V(E,m'+1)$; if it deviates to M, it earns $V(M,m'+1)$. But $V(M,m'+1)\geq V(E,m'+1)$ by definiton of m_0, so the deviation is profitable and destroys the proposed equilibrium. Now suppose that $m''+1$ firms choose M, $m''>m_0$. Then a type M earns $V(M,m'')$; if it deviates to E, it earns $V(E,m'')$. But $V(E,m'')\geq V(M,m'')$, so the deviation is profitable and again destroys the proposed equilibrium. Hence, exactly m_0+1 firms must choose $s_i=M$ to form a Nash equilibrium.

Now suppose that $m_0\geq N$. If all firms are type M, then each earns $V(M,N-1)$. A firm deviating to E earns $V(E,N-1)$, which is lower than the equilibrium payoff by definition of m_0. Finally, if no positive m exists such that $V(M,m)\geq V(E,m+1)$, then all firms choosing E is clearly the only Nash equilibrium.

Corollary 3b: For any given set of Z and S payoff functions satisfying A1'-A4', and also the conditions $(1-\delta)(1-x)yZ(L,L,r) < x(1-y)Z(H,H,1) < (1-x)yZ(L,L,r)/(1-\delta)$, there exists finite K such that in a K-firm game, each signal is observed by at least one firm in equilibrium.

Proof: Suppose all firms in an N-firm game are type M in equilibrium (i.e. $m0>N$). Using the partition of events in the proof of Proposition 3, the expected payoff for a type M, $V(M,N-1)$, is

$(x/N)[yZ(H,L,1)+(1-y)Z(H,H,1)]$ +

$(x/N)[dyS(H,L,n,2)+...+dN-1yS(H,L,n,N)$

$+d(1-y)S(H,H,n,2)+...+dN-1S(H,H,n,N)]$

The first term gives the expected payoff from being first in the queue and learning that price is high, while the second term gives the expected payoff of being later in the queue when price is high. If the firm were instead a type E, $V(E,N-1)$ would be

$(y/N)[xZ(H,L,1)+(1-x)Z(L,L,1)]$ +

$(x(1-y)/N)S(H,H,n,2)$ +

$((1-x)y/N)[dZ(L,L,2)+...+dN-1Z(L,L,N)]$ +

$(x/N)[dyS(H,L,n,2)+...+dN-1yS(H,L,n,N)$

$+d(1-y)S(H,H,n,2)+...+dN-1S(H,H,n,N)]$

The first term gives the payoff to being first in the queue and learning that cost is low, the second term is the payoff to being first in the queue when cost is high and price is high, the third term gives the payoff to being later in the queue when price and cost are low, and the final term is the payoff to being later in the queue when price is high. These expressions yield $V(M,N-1)-V(E,N-1)$:

$(1/N)[x(1-y)Z(H,H,1) - (1-x)y(Z(L,L,1)+dZ(L,L,2)$

$+...+dN-1Z(L,L,N))]$

$-(1/N)x(1-y)S(H,H,n,2)$

The limit as N goes to infinity of the square-bracketed difference in the first term is negative, because it was assumed that $x(1-y)Z(H,H,1)<(1-x)yZ(L,L,r)/(1-d)$ for all r. Therefore, there exists finite K such that $V(M,N-1)<V(E,N-1)$ for N>K. Starting with an equilibrium in which all firms are type E, the analagous argument goes through, showing that an expansion of industry size eventually makes it optimal for one firm to deviate to type M. This establishes the corollary.

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Chapter 3.

COMPETING NETWORKS AND PROPRIETARY STANDARDS:
THE CASE OF QUADRIPHONIC SOUND

INTRODUCTION

In the early 1970s, many observers felt that the predominance of stereo sound[1] was about to end. Recording engineers, musicians, critics, and audio hardware firms were touting a new system-- quadriphonic sound--as the next logical development in the recording and transmission of music.

The story of the subsequent attempt to replace stereo with quadriphonic sound, and of the ultimate failure of these efforts by 1976, is especially interesting in light of the burgeoning theoretical and empirical concern with compatibility and standardization issues in industrial organization. It demonstrates the difficulty of establishing a new technology whose benefits depend on wide adoption, and shows how the problems are magnified by large installed bases of old technology. In addition, because different firms sponsored incompatible systems of quadriphonic sound, the effects of competition on the possibility of replacing old technology are highlighted. Finally, the quad experience reaffirms the claim of Besen and Johnson (1986) that the vertical structure of an industry must be taken into account in assessing the prospects for technological change when compatibility is a serious concern.

Organization of this essay is as follows: Section I gives an overview of quadriphonic technology. Section II describes the market history of quad from 1970 to 1976. Section III analyzes the incentives and constraints facing the important actors, while Section

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[1]Introduced in the late 1950s, stereo splits musical recordings into two audio "channels," which, when played back through the dual speakers of a stereo receiver system, give a richer, more realistic sound than does single-channel monoaural recording.

IV contains my conclusions about the probable causes of the market outcome.

I. QUADRIPHONIC SOUND

Quadriphonic sound--also called four-channel, quadrasonic, surround sound, and quad, among other names--is a system for the reproduction of music that records four "channels" of information in the studio or concert hall, encodes that information on a vinyl disc or magnetic tape, and decodes the signal at the playback stage so that each of four loudspeakers carries a separate channel of music. By placing the four speakers in the corners of a room, the four separate tracks can be used to create the illusion that sound is coming from the front, sides, or rear, as well as from any of the four corners. A stereo system, be contrast, has only two channels and two speakers; it can create a localization effect along the line between the left and right speakers but obviously has no front to rear separation of sound.

Four-channel sound was advocated on a number of overlapping and contradictory grounds. The initial impetus came from psycho-acoustic studies, which claimed that up to 80% of the sound perceived by listeners at live concerts is reflected from the walls and ceiling, with the remaining 20% traveling directly from the orchestra to the listener's ears. Since many audiophiles seek to recreate at home the concert-hall experience, the addition of rear speakers with separate tracks could be used to generate realistic ambient and reverberated sound effects.

Other advocates sought to make the living room sound like a recording studio, where master tapes are frequently made with sixteen or more separate tracks that are then "mixed down" to two for stereo records and tapes. Four-channel would allow more of the original music to be expressed. Also, it was asserted that completely new musical effects could be created by producers who exploited the spatial localization properties of quadriphonic systems. Finally, some argued that a "surround-sound" field would sound richer and better than stereo regardless of the original recording site or the intentions of the producer, just as stereo is generally superior to monoaural sound.

Technology. Two distinct general approaches to the production of quadriphonic sound were developed. Matrix systems operated by encoding the four tracks of information into two channels on the vinyl disc. Just as in stereo, one side of the record groove conveyed left-side information and the other right-side music. Front-to-back separation of signals was expressed by undulations in the contours of the grooves. Upon playback, a decoder would use the cues conveyed by the corkscrewing motion of the stylus to synthesize the two recorded channels into a four-channel program. Different matrix systems, such as CBS's SQ and Sansui's QS, varied primarily in the coding algorithms used to go from four channels to two and back to four again.

Discrete systems (referred to as "real quad" by their advocates) were conceptually simpler, though technically more demanding. Four tracks of information were separately laid down on

the recording medium; for a disc, each side of the groove contained two tracks, with front-to-back information carried by "ribs" inscribed in the groove wall. A demodulator built into the receiver used the four recorded channels of information to produce a complete quadriphonic program.

The great advantage of matrix quad was that it put all the technical complexity into the "black box" decoder. Cutting a matrix record was physically no more demanding than cutting for stereo; the stylus, cartridge, and tone-arm tracking pressure on turntables were identical to those for stereo, and FM stations that broadcast in stereo could play matrix records without FCC approval. All the stereo listener needed to add to his system was a decoder, extra amplifiers, and two new speakers to enjoy matrix discs and broadcasts.

By contrast, discrete disc cutting heads were fairly complicated and expensive; a special stylus and cartridge were needed, and tracking pressure was higher; and discrete FM broadcasting used up more spectrum space than broadcasters were allocated, so that FCC approval would be needed for such broadcasts to become a reality. Furthermore, discrete discs had to be made with a special vinyl compound to ensure durability, as was discovered when early releases had their quad information erased after six to ten plays. Finally, discrete records, especially early ones, were more subject to noise and distortion and had less dynamic range than did the better matrix or stereo discs.

Where discrete technology surpassed matrix was in channel separation. Since only two channels of information were cut into a

matrix disc, the decoder was essentially trying to solve two equations in four unknowns. As a result, matrix was subject to a great deal of "cross-talk" from front to back, e.g. sound that was intended to come from the left-rear speaker would leak into the left-front speaker. Since front-to-back separation was the raison d'etre of quad, this was a serious handicap. Discrete, by its very nature, gave excellent front-to-back separation; it was widely considered the "ultimate" four-channel system. These advantages and disadvantages are summarized in Table 1.

Quadriphonic decoders started out as bread-board collections of transistors, but before long they were put onto integrated circuits (ICs) that reduced size and cost. For matrix systems, ICs provided an economically feasible way of attacking the channel separation problem, a problem that had previously been brushed off (erroneously) by matrix advocates as not detectable by the listener. The fixes used to improve perceived separation were referred to generically as "logic."

The earliest and simplest versions of logic exploited the fact that humans tend to focus on the loudest source of sound around them. A built-in IC would simply cut the volume of a speaker if it was interfering with the desired perception of directionality. To strengthen the impression of a soloist in the center-rear, for example, the front speakers would be muted during the soloist's passages. Unfortunately, this approach tended to break down into acoustic chaos if multiple directions were desired, and the constant damping and turning up of speakers led to a "pumping" effect that many listeners found irritating. Later versions of logic used more

Table 1: Comparison of Audio Systems

	Stereo	Matrix	Discrete
Systems	--	SQ, QS	CD-4
Output with stereo discs	stereo	stereo (possibly "enhanced")	stereo
Output with matrix discs	stereo	quadriphonic	stereo
Output with discrete discs	stereo	stereo	quadriphonic
Advantages	--	-low cost hardware -high fidelity -broadcast in stereo	-good 4-channel separation
Disadvantages	--	-poor 4-channel separation	-lower fidelity -greater cost -extra spectrum needed for broadcast

sophisticated techniques of creating an impression of localization, taking into account phase shifts, wave profiles, and so on. Sansui's Vario-Matrix logic actually altered the parameters of the decoding algorithm to enhance the illusion.

Compatibility. Both matrix and discrete four-channel were compatible with stereo software and hardware. The results of playing each type of disc on each type of software are displayed in Table 1. Stereo discs played on quad systems came out in stereo; in fact, matrix proponents asserted that up to 80% of stereo records had "hidden" quad information (mostly ambience) encoded in their grooves, and that this extra information would create an "enhanced stereo" sound when played back through a matrix decoder. Quadriphonic records played on a stereo system likewise produced stereo output.

To get four-channel output from records required a matrix disc and a matrix decoder or a discrete disc and a discrete demodulator. A demodulator would do nothing for a matrix disc, and a decoder ignored discrete discs. The result of such mixing and matching would be stereo sound, albeit with the left and right information each projected from two speakers instead of one.

Compatibility across matrix systems was a more subtle issue. Playing an SQ-encoded disc through a QS decoder resulted in a quadriphonic effect, with front-to-back separation and even spatial localization, but it was not the sound image intended by the artists and recording engineers. Engineers and critics disagreed about the value of such matrix miscegenation, with some feeling that the effect was superior to stereo and others criticizing it as "not true quad."

Quad provided a form of "upward compatibility" with stereo, protecting two-channel disc libraries and hardware installations. In fact, since it was possible to upgrade stereo systems to four-channel by adding equipment, existing investments were not rendered obsolete even in the event that a stereo listener wished to switch to quad.

II. HISTORY OF FOUR-CHANNEL SOUND

Quadriphonic sound had a short, but eventful, sojourn in the marketplace, from 1971 to 1976, although technical developments began before this period. After describing the events leading up to the introduction of competing four-channel systems, I discuss technical advances, sales of quad hardware, the software picture, and developments in radio.

Early Development

The first important quadriphonic medium was tape. By 1969, quad open-reel tapes were being sold, and in 1970, the first quad eight-track cartridge players were announced by RCA and Motorola. The cartridge format for quad became known as Q-8.[2]

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[2]Although the vinyl disc was the primary medium for the transmission of recorded music, cassette and eight-track tapes were an important factor also. Quad technology did not become available on cassette; by contrast, four-channel eight-tracks were produced and sold in substantial numbers. Eight-track tape was especially important in the automotive sound market, and the spread of quadriphonic systems in cars depended on tape technology.

At first, two competing systems for eight-track quad, both discrete, coexisted in the marketplace, but fairly quickly CBS abandoned its own system and standardized on the approach of RCA. Matrix systems were never developed for tape, which suggests that even at Columbia, engineers believed that discrete four-channel separation was the goal of quad.

Because eight-track tape in general, not just the quadriphonic variety, was in a struggle (eventually lost) against cassettes for market dominance, the four-channel experience in tape vis-a-vis stereo is hard to analyze. It is clear that the opinion of most manufacturers, retailers, and industry observers was that the fate of quad hung on success in the disc market; vinyl records accounted for about 70% of software revenues in 1972 [Business Week, 11/11/72, p.72], and victory in this larger arena was both a necessary and sufficient condition for victory in tape.

By the end of 1970, various approaches to quadriphonic sound from discs were introduced. The simplest methods were called "reverb" or "enhanced stereo" systems, and the leading example was the proposal by Dynaco to extract inadvertently encoded out-of-phase and other ambient information from stereo discs. This approach used an ordinary two-channel amplifier and a simple add-on decoder, with an extra speaker or two and some wire to bridge the amplifier's output terminals. The extra speaker was to be placed in the rear of the room, where it would project a simulation of ambient sound.

More sophisticated were proposals for matrix discs, which would use stereo cutting but would be deliberately encoded with four-channel information. Quad playback would require an extra stereo amplifier, two extra speakers, and a decoder. At the March 1970 meeting of the Audio Engineering Society, Peter Scheiber, a musician and inventor, demonstrated his approach to matrixing, based on psychoacoustic principles. The Scheiber system, later patented, failed to impress listeners at the AES, with one observer referring to it as "two and a half channels of stereo" and "definitely not true quad" [Radio-Electronics, 10/70, p.87]. It did, however, become the foundation for many later matrix developments.

By March 1971, Electro-Voice had announced and demonstrated its own matrix system, Stereo-4, as had Sansui with its QS-I, which was also packaged as a stereo enhancer. Other manufacturers introduced "delay-line" reverberation units that put an out-of-phase "echo" in the rear speakers, using stereo records. Finally, Japan Victor Company (JVC), 51% owned by Matsushita, bucked the trend toward "synthetic" quad by launching their discrete disc system, CD-4, which they planned to market in Japan and the United States.

Three record labels--Enoch Light's Phase III, Ovation Records,
and Gold Crest Records--quickly announced plans to release discs
encoded for the Electro-Voice matrix system. By September 1971,
Columbia Records had come out with its own SQ matrix system, the
first decoders to be built by Sony. Columbia's entry into quad was
seen as particularly important, since it was the largest producer of
records (about one and a half times the sales of its nearest rival).
Like the Electro-Voice equipment, the CBS/Sony decoder retailed for
about $55, although the first SQ black box with logic was to be sold
for $165. Columbia Records announced that its quad discs would cost
one dollar more than did stereo discs.

By November of 1971, the quadriphonic arena was full of
incompatible or partly-compatible systems, and no clear winner seemed
poised to emerge. One observer said, "The plain fact is that [four-
channel] appears to be headed toward disaster, toward strangulation
by confusion....The buyer is easily turned off by such minor
discomforts as having to choose between a number of wildly different
techniques for producing a service which he's not certain he wants in
the first place." [Radio-Electronics, 10/71].

Nevertheless, momentum was building among manufacturers, as
evidenced by quad receivers from Marantz, Scott, Fisher, Pioneer,
Sanyo, Panasonic, Sony, and Toshiba at the Consumer Electronics Show
in 1971. Talk abounded of quad as the logical "next step" in high
fidelity; the transition from mono to stereo was seen as the model
for a switch from stereo to quad. Early sales of decoders in 1971
encouraged such beliefs [Radio-Electronics, 10/71, pp.34-5]. And
unlike the advent of stereo, which was pushed along mostly by smaller

component and record manufacturers, giant firms were behind four-channel.

Aside from the incompatibility problems across quad systems, the biggest potential obstacle to a four-channel revolution appeared to be the difficulty of demonstrating the new technology satisfactorily. The need to be surrounded by four speakers in a relatively quiet background environment about the size of a living room meant that retailers would need to make a special effort, and possibly to modify their facilities, in order to persuade customers of the virtues of quadriphonic sound. Retailers would have to be convinced, at least as much as consumers, that four-channel was the medium of the future.

One potential persuader would have been the radio broadcasting of quad. FM broadcasts of quadriphonic material were possible with any matrixing system, since the same two-channel signal was propagated over the air. Discrete broadcasts were a different matter; to carry the extra pair of front-to-back modulation channels, discrete systems tended to encroach on the "guard band" between frequencies and the subsidiary communications authorization (SCA) band, which is sold to firms like Muzak and to services such as reading for the blind. Thus, discrete broadcasting required FCC approval, which everyone anticipated would come only after a lengthy process. Station KIOI in San Francisco received permission to experiment with the Dorren system of discrete quadcasting, and General Electric likewise was granted approval to test out its own system on its station WGFM in Schenectady, N.Y. [Radio-Electronics, 1/72, p.4]

Progress toward untangling the matrix rivalries began at the end of 1971. First, the Scheiber and Electro-Voice systems were jointly declared to be compatible. Second, Electro-Voice announced a new, "universal" decoder that would accommodate Stereo-4, SQ, and possibly QS, to be released at the beginning of 1972. This latter development was significant because a standard SQ decoder made hash out of Stereo-4 and vice versa, and because even though Columbia Records would soon have many SQ discs on the market, Stereo-4 already had 100 records available on eight labels, about 75,000 decoders sold, and 69 FM stations using encoders to enhance stereo discs and live performances.

The Quad Wars

Hopes of a simple, compatible matrix future for quad were dashed when RCA, the other major record company, announced in January, 1972 that it was backing an improved version of JVC's CD-4 discrete system. (JVC was already RCA Records's licensee in Japan.) RCA was supported by Matsushita, through its Panasonic and Victor subsidiaries. It hoped to solve durability problems with CD-4 (playing a discrete record on a stereo system erased the front-to-back information on the disc) and release records by the end of the year. This event marked the beginning of the well-publicized and protracted "quad wars."

Initial reaction to RCA's decision was surprisingly hostile. Many who felt that total compatibility was the only way to dispel consumer confusion and hesitancy about quad believed that RCA was

acting as a "spoiler" to prevent CBS from establishing SQ as a standard. CD-4 was alleged to be in a "premature" stage; RCA's announcement would only serve to inhibit sales of matrix, and even stereo. The argument is quite close to that of Farrell and Saloner (1986) on installed base and product preannouncements, in which announcements can influence which equilibrium is realized. Supporting the impression of CD-4 prematurity was the fact that by November, 1972, RCA had released only five discs to CBS's seventy in four-channel [Business Week, 11/11/72, p.76]. Furthermore, the first receivers with discrete demodulators were not expected to appear on the market until mid-1973, whereas fifty-one hardware manufacturers, accounting for 70% of unit sales, were claimed by CBS to be already installing SQ decoders in their equipment.

RCA, for its part, responded that matrix was "a Mickey Mouse approach that only simulates four-channel" [Business Week, 11/11/72, p.76]. Implicit in this criticism was that matrix wasn't much better than stereo to the listener, and that matrix would therefore sink the entire four-channel concept if it were not vigorously challenged. CBS insisted that SQ was a big improvement over stereo and psycho-acoustically equivalent to discrete quad, but its case was undercut by the introduction of a stream of logic devices designed to enhance the separation of matrix quad, each improvement touted as the ultimate solution.

The battle between matrix and discrete quickly evolved into a struggle to present one's own system as the eventual, inevitable winner. All firms were obviously aware that expectations could determine outcomes, and they sought in their promotional efforts to

portray their systems' trajectories as triumphal parades to mass acceptance. Eventually, quad proponents would divert part of their efforts to promoting quad in general, but in the early going, the emphasis was on internecine warfare between matrix and discrete proponents.

In the lull before RCA brought out discrete records, CBS formally merged its system with the Electro-Voice/Scheiber team's, recognizing Scheiber's patent and agreeing to produce decoders optimized for Stereo-4 as well as SQ. That left Sansui, with its QS matrix, as the only matrix holdout from the Columbia world; Sansui cited technical reasons for believing its system superior, such as better directionality of sound image and no sound cancellation losses from out-of-phase information. With no record company affiliation, Sansui was not seen as a significant threat to SQ dominance, but this perception turned out to be inaccurate. More and more hardware firms, especially in Japan, installed both types of decoder in their receivers.

Early in 1972, EMI Ltd., a British recording company with several labels worldwide, including Capitol in the U.S., signed up with SQ for its quad products. On the other side, the Phillips group, including labels Mercury Records and Deustche Grammaphon, elected CD-4. By June of 1972, RCA's first Quadradisc (its trade name for CD-4 records) was released, amid claims that it could be played repeatedly on a stereo system without damage [Radio-Electronics, 6/72,p.4]. RCA announced that its four-channel offerings would be priced the same as two-channel discs, and it said that it hoped to go all quad and phase out stereo LPs entirely, since CD-4 was stereo compatible.

Technological Developments 1972-76

Discrete quad had to overcome a number of immediate problems. First, the durability of CD-4 discs required improvement, since early versions were partly erased after only a few plays. By 1974, new vinyl compounds that solved the problem had been introduced. Second, the stylus and cartridge needed to play discrete records were originally too expensive for general use. More affordable pickup cartridges were quickly developed, and it was discovered that a special stylus, known as a Shibata stylus, practically eliminated the erosion problem on discrete records at a reasonable cost. Third, the cutting heads used to produce CD-4 albums were expensive, finicky, low-speed devices that restricted the fidelity and playing time possible. An improved, lower-cost CD-4 cutting head was introduced by JVC at the International Music Industry Conference in May of 1974, alleviating these difficulties. Finally, early discrete receivers were bulky and expensive; new discrete demodulators using ICs reduced their cost and size [Billboard, 5/18/74].

For SQ, the issue was always whether or not it amounted to more than just stereo with two extra speakers. Columbia kept insisting that its brainchild was already as good as having four separate channels, but by May, 1973, the SQ decoder had gone through five separate generations to reach its "full-logic" form [Radio-Electronics, 5/73], and this still was not the end of the process. CBS announced in 1974 that new technology from Tate Audio, a British firm, would (again) solve the separation problem. This new decoder

logic vastly increased separation and could handle QS as well.
Unfortunately, Tate was still negotiating with integrated circuit
manufacturers to reduce its complex device to an affordable chip when
it announced the product [Merchandising Week, 6/17/74, p.6], and quad
disappeared from the market before it could be produced on a large
scale.

At the Consumer Electronics Show in June 1974, Sansui touted
its new Vario-Matrix logic system for QS, which not only gave greater
front-to-back separation, but also upgraded the playback of SQ and
stereo material; 60 firms were expected to incorporate Vario-Matrix
over the next year. Unlike CBS, Sansui stood pat with this
technology for the duration.

The following year, a second and final round of improvements
occurred. New cutting technologies that drastically reduced the cost
of CD-4 production facilities, and improvements in pressing
technology lowered the incremental cost of discrete over stereo to 13
cents per disc, about 10% of average cost [Billboard, 5/24/75, p.
12].

The CBS Technology Center introduced new stereo-enhancement
circuitry for SQ, which could be added (at the manufacturing stage)
to any full-logic decoder for under $25. The new circuitry bent the
linear stereo sound field into a horseshoe shape, keeping center-
front information in the same location. CBS said that while previous
SQ stereo enhancement was "nominal," the new system was "dramatic"
[Billboard, 5/24/75, p. 12]; there was no explanation as to why SQ
had been pushed as a stereo enhancer for the previous year. Also, a
new high-end SQ full-logic decoder, the Audionics Shadow-Vector, made
its debut at a staggering $1,250 [Billboard, 6/21/75, p. 5].

Technological developments that entered the pipeline in 1975 came out after events in the market had passed them by. For example, a new CD-4 demodulator on an IC was announced at a price of only $50 [Billboard, 11/29/75, p. 40], and Ford announced a Motorola-built Q-8 autosound system as an option for the Lincoln Continental [Billboard, 12/13/75, p. 38]. But with the collapse of quad sales, further work was halted.

Market Penetration 1973-76

Throughout 1973, hardware manufacturers vigorously pushed quadriphonic sound; almost every major firm had four-channel offerings at the top end of its product line, and most had a number of entries for the middle range. While SQ was by far the most widespread system, many receivers included add-on slots for CD-4 demodulators even if they didn't build in such circuitry.

Press and consumer excitement about quad seemed to portend a transition from stereo that would be quicker than the one from mono to stereo. Articles touting quad as the wave of the future abounded in general-interest and hobbyist magazines, usually including a discussion of the matrix-discrete split and its possible impact on consumers. Company spokesmen were frequently quoted making bullish statements about the superiority and inevitability of four-channel.

However, consumers were easily confused by the multiplicity of quad systems, and dealers reported that customers were fearful of being stranded with the wrong system. Dealers generally were not terribly enthusiastic about four-channel, believing that it ought not

to have been released without a single standard, an extensive software library, and better recording quality. Many were unhappy that customers were deferring purchases until the dust settled in the quad wars, noting that sales of stereo equipment were also adversely affected.

By the beginning of 1974, a full year after its commercial introduction, quad was either "here to stay" or a disappointment, depending on who was asked. Hardware manufacturers were installing multiple four-channel decoders on more and more of their products, and major quad proponents CBS, Sansui, RCA, and JVC continued to make bullish statements and to launch promotions. Quad hardware accounted for 25-30% of dollar sales, and optimists saw 70% by year's end [Merchandising Week, 2/25/74].

Adding to manufacturer optimism was a Chase Econometrics Associates study commissioned by SQ proponents that said, "Quadriphonic sound will eventually replace stereo much as stereo has displaced monophonic sound in the audio market. By the end of the 1980s, this takeover should be almost complete" [Merchandising Week, 6/17/74, p.6]. Furthermore, some stores were doing a big business in quad, especially those whose personnel believed in the medium and had invested in demonstration facilities. The Sam Goody chain in New York, which pushed quadriphonic sales, had 15% of its revenue from four-channel; Lafayette Electronics, a national chain that was an early quad booster reported this ratio as 50% [Billboard, 8/10/74, p.37].

These results were exceptional, however. Sales of all models were very poor in the South and Midwest, while low-end quad receivers

had failed to sell in any region, and were being dumped by manufacturers at very low prices. Many retailers complained that certain CD-4 records were not durable, while software availability problems and lack of matrix/discrete compatibility aroused universal hostility. Consumers feared buying equipment that might soon be obsolete, especially considering quad's greater expense. Those retailers that tried hard to sell four-channel equipment complained that customers were confused by bad-mouthing of quad in other stores. Disillusionment was setting in by the end of 1974.[3]

Manufacturers were not yet ready to give up. JVC, RCA, and W/E/A were still pushing discrete quad, both with public statements and promotional efforts. Similarly, CBS and Sansui maintained pressure for their systems, and other manufacturers continued to include decoders in much of their product lines. In fact, quad offerings, though less widespread than at the June 1974 Consumer Electronics Show, were still fairly plentiful at the January 1975 show. A Billboard survey [1/11/75, p.CES-4] of 15 top receiver firms found 43 models that were quad or quad-capable. Twenty had built-in CD-4 circuitry and another 11 had slots for add-on demodulators. Thirty-six carried SQ decoders, though only 15 of these included full logic. QS was represented on 24 receivers. A strong trend toward "universal systems" that incorporated more than one mode of

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[3]According to Merchandising Week [9/9/74, p.1], "After years of haggling over which type of 4-channel to promote for Christmas, audio dealers have finally agreed to back a single system--stereo....Many dealers feel that heavy pre-Christmas promotion last year lost much of its impact by catering to the almost non-existent market for 4-channel sound (generally, well under 15% of a dealer's business)." One store spokesman in Atlanta said, "[quad is] a dead duck as far as I'm concerned and as far as this company is concerned."

quadriphonic reproduction could be seen; 29 discrete and discrete-adaptable units included at least basic SQ decoding, and 15 had full-logic. Twelve receivers were truly universal, with built-in CD-4, full-logic SQ, and QS (but not necessarily Vario-Matrix); six of them sold for over $800, but three JVC models were under $600, and Pioneer offered units in a similar price range.

The manufacturers were giving quad one more chance to prove itself in the marketplace. Thus, 1975 would see the final thrust, after two years of disappointing sales, with large promotional expenses gambled on turning around quad's performance. Pioneer launched a half-million dollar promotion in April, featuring a discount on a complete four-channel sound system, nationwide advertising, free records, and a tie-in to the Macy's department store chain [Billboard, 4/12/75, p.37]. Half of all dealers carrying Pioneer signed up for the program.

JVC established 30 "Quadracenters" at major audio retailers across the U.S., using special sales training for dealers and educational seminars for consumers to advance the quad concept [Billboard, 5/3/75, p.1]. Because of the universal decoding capability of many receivers, JVC planned not to stress the advantages of CD-4, but rather the superiority of quadriphonic sound in all its forms.[4] Elaborate incentives and advertising (including

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[4]As a result of four-channel's precarious situation, a peculiar "detente" emerged in the quad wars. The CD-4 camp agreed to stop claiming that their format enhanced stereo, and they conceded in their literature that matrix systems did this well. This posture dovetailed with a new emphasis by the matrix sponsors on stereo enhancement. However, CD-4 proponents stressed to retailers that discrete gave much better separation in quad, and that less than 20% of matrix equipment had the full-logic circuitry needed to give anything close to acceptable quadriphonic performance [Billboard, 6/7/75, p. 52].

3-D ads to be viewed through punch-out goggles) were included in the program, as well as a toll-free phone number for locating Quadracenters. Free membership was extended in the RCA Quadraphonic Record and Tape Club for all JVC purchasers at such stores.

At the June 1975 CES, all this activity and promotion continued, but there were signs that the firms were whistling in the dark. Panasonic executives admitted they "went off the deep end on quad" but resolved not to give up, while Sansui was looking to the long term, when growing FM broadcasts in matrix quad would establish the market permanently [Billboard, 6/14/75, p.1]. The QS sponsor publicly discounted the importance of what it saw as a temporary downward fluctuation from a sales trend of 8% annual growth [Billboard, 8/9/75, p. 38].[5]

However, declining sales and retailer alienation, even among four-channel boosters [Billboard, 8/30/75, p. 32], began to drive manufacturers away from quad. Pioneer's president admitted that his firm's $475,000 promotion in April had failed to cut quad inventories, even though stocks of stereo equipment were exceptionally low [Billboard, 8/23/75, p.43]. Fisher, a hardware firm that had plunged optimistically into quad, was faced with so much unsold four-channel inventory that it nearly went out of business. Under new management, it entered into a deal with the R.J. Reynolds Tobacco Company to sell complete quad systems for half price with the submission of two empty Winston cigarette boxes. In addition to slashing its bloated quad inventory, Fisher hoped to

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[5]Perhaps in desperation, Sansui planted a bullish story in Billboard, under their own PR man's byline but without identifying his affiliation [Billboard, 9/20/75, p. 24].

reestablish its credibility with retailers by restoring its almost

nonexistent stereo product line [Billboard, 9/27/75, p. 49].

Sherwood, another hardware manufacturer, marked down its only

quad model by 40% and prepared to abandon the field. The trend

continued with Marantz reporting that quad was "dead" as a "demand

item" [Billboard, 10/25/75, p. 44], while at a trade show in

Philadelphia one observer noted that "as for quad--you should almost

forget it ever existed." JVC America, Onkyo, and Sansui each showed

only one four-channel model amid a vast array of stereo equipment

[Billboard, 11/22/75, p. 51].

From this point on, quad was dead, although the firms

responsible for pushing it delayed the funeral as long as possible.

Cuts of 40-50% on Pioneer, Sansui, Harmon-Kardon, Technics, JVC, and

Kenwood quad were instituted, along with discounts on turntables,

speakers, cartridges and headphones [Billboard, 1/10/76, p.38].

Nevertheless, unit sales continued to fade. Pacific Stereo, a retail

chain with 45 stores in California and another 20 in the Midwest, cut

back on the display space allocated to quad [Billboard, 1/10/76, p.

39]; in Portland, Oregon, the consensus was that "Quad is a

merchandising negative," and Stereo Unlimited reported that four-

channel software represented 12% of stock, but only 5% of sales; in

Milwaukee, high-end stereo boomed while quad died; and in Seattle,

all dealers surveyed "agreed that quad has proved to be the biggest

dud of 1975."

At trade shows throughout 1976, a few die-hard quadriphiles

continued to talk about the eventual redemption of four-channel, but

new products were entirely stereo. The excitement that had attached

to quad was transferred to videodiscs, which ironically had an even more abortive career. In 1987, the everyday term for an audio receiver was still "stereo."[6]

Software Development

Throughout 1973, SQ and QS software libraries, although still dwarfed by stereo, grew rapidly. Given the novelty of the technology, quad seemed to be doing rather well. Columbia reported that it sold $6 million worth of its 160 SQ albums in 1973 (about $13 million at retail, or about two million units), and expected to increase SQ product on by 35% for 1974 [Billboard, 3/23/74].

One distributor of CD-4 material, Warner/Electra/Atlantic (W/E/A), said that of 25 discrete albums released in mid-1973, 860,000 copies were sold by March 1974 [Billboard, 3/2/74, p.1]. Furthermore, the quad sales were in excess of stereo sales already made on these records, so that no cannibalization was involved. Discrete proponents took these results to be signals of future success.

The bullish predictions for sales of quad records in 1974 turned out to be exaggerated. CBS ended up selling about $6.6 million of quad records in 1974, significantly less than its anticipated sales of over $8 million [Billboard, 3/8/75, p.32]. RCA

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[6]It appears that quad may eventually return through the agency of the videocassette recorder (VCR). Where once the goal was to recreate the concert hall in one's living room, today the example of the movie theater beckons. The current terminology is "surround sound"; the technology appears to be a an updated version of delay-line stereo enhancement.

and W/E/A together sold approximately $6 million worth of CD-4
albums, a flat performance relative to the previous year.

Part of the problem was a simple lack of quad software, as by
March 1974 only about 500 quad LPs had been released [Merchandising
Week, 2/25/74]. The figures on software availability do appear to
show progress throughout 1974; by July, 130 CD-4 records were
available, along with about 300 SQ and 340 QS discs [Radio-
Electronics, 10/74, p.4]. By December, RCA and W/E/A alone accounted
for about 170 LP releases (all in CD-4). However, only 19 quad
offerings were on the July 20 Billboard list of the top-selling 200
LPs; of these, SQ dominated with 11 CD-4 had 7, and QS had only one.
The highest ranking quad release was twenty-third on the list
[Billboard, 7/20/74]. A large fraction of four-channel software was
classical music, while so-called "middle-of-the-road" (MOR) music was
also heavily represented. Rock artists seemed especially reluctant
to record in quad.

Adding to the software difficulties was the oil rationing
program instituted after the 1973 Arab oil embargo, which
precipitated vinyl shortages and price run-ups. With scarce raw
materials, record companies put a higher priority on releases for the
larger stereo market; CD-4, which required a purer vinyl compound,
was especially hard hit.

Of course, quad's vinyl problem would not have existed had
record firms pursued a "single-inventory" policy in which albums were
released only in quad. Given all the technological effort that went
into making quadriphonic discs stereo-compatible, this was the
logical approach. RCA started out with a single-inventory policy,

and even managed to sell two million copies of an Elvis Presley double-LP on Quadradisc, 95% for stereo use, thereby establishing the stereo compatibility of CD-4. However, retailers generally chose to segregate Quadradiscs in special quad bins separate from stereo--a policy that helped quad hardware owners looking for scarce four-channel product but kept stereo buyers in the dark about the records' existence [Billboard, 5/18/74, p.3]. RCA was quickly forced to join Columbia in a double-inventory format, releasing albums in both stereo and quad.

In response to the complaints of retailers and consumers, quad's sponsors took steps aimed at increasing the availability of software and improving the salability of what was released. Taking no chances on discs being stocked in stores, RCA started a Quadraphonic Record and Tape Club, with an initial mailing to 200,000 people; discrete manufacturers would include order forms in hardware packages. The Columbia House club's brochure began to include SQ material, as pop artists produced more music in the medium. Even JVC announced that it would sell discs by mail from Japan, including releases not available in the United States. Finally, a new catalog of quad software for dealers was issued by an independent publisher [Billboard, 3/8/75, p. 4].

Despite this apparent progress, retailers were less enthusiastic than they had been a year earlier, and top-selling artists still avoided quad. Only eight of the top 100 and 15 of the top 200 best-selling LPs were available in quad at the time. Some breakthrough was needed for four-channel sound to regain its momentum with the public. CBS sought to achieve this with its announcement

that the musical group Chicago would have five of its gold albums released in SQ. Along with a massive promotion organized around the theme "At Last...In Quadraphonic Sound", kicked off at the January 1975 Consumer Electronics Show, Columbia hoped that winning over this major group to quad, as well as other artists such as Poco and Billy Joel, would restore belief among retailers and consumers in the ultimate success of four-channel [Billboard, 12/21/74, p.1]. The company also hoped that manufacturers other than the primary system sponsors might be influenced to keep producing quad receivers [Billboard, 1/4/75, p.4].

These efforts were partly successful. By August, 21 of the top 105 and 38 of the top 200 LPs (23 CD-4, 13 SQ, and 2 QS) were available on quad discs [Billboard, 8/9/75, p. 1]. Chart performance plummeted in November, but by the end of the year, the top-selling LP was available on quad disc, 23 of the top 105 and 32 of the top 200 records [Billboard, 12/20/75, p. 62]. This was quad's high-water mark on the charts. Labels were putting a higher priority on getting out best-selling albums in quad, frequently using their own mixers to produce a four-channel version of the artists' work. Unfortunately, this practice delayed release of the quadriphonic version of a record by about a month or two after the stereo release, frustrating dealers and listeners.[7]

As far as the intersystem battle was concerned, discrete was winning over label after label. Arista Records announced for CD-4

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[7]Simultaneous release was more common with classical music, where the quad audience was a larger fraction of the total. For example, a release of "Also Sprach Zarathustra" sold over 35,000 units in quad and 31,000 in stereo; "Swan Lake" sold 24,000 units in quad, to 22,000 in stereo; and "Boulez Conducts Stravinsky" sold 12,000 in quad and 13,000 in stereo.

(the decision was made by a former CBS employee). A&M Records switched to CD-4 for all its quadriphonic output [Billboard, 4/5/75, p. 1], and Fantasy also entered the discrete camp [Billboard, 6/28/75, p. 14]. Discrete was clearly on the road to having a dominant share of the quad software released, but the big question for JVC and RCA was whether such a victory would be meaningful.

In 1976, the bottom dropped out of quad sales on both the hardware and software sides. Record guides cut back or eliminated separate listings of four-channel software [Billboard, 3/27/76, p. 69, and 8/7/76, p. 27], thus making it much harder for quad owners (and the stores they patronized) to locate what product there was. Labels released less and less of their best-selling material in quad, with the exception of classical product. Chart penetration declined to the levels of 1974: 7 or 8 discs in the top 106, 12 to 15 out of the top 200 [Billboard, August through December, 1976]. Record stores moved to get rid of all quad recorded products [Billboard, 10/23/76, p. 1].

Radio

Broadcasting of four-channel music on FM stations continued to grow, as SQ and QS encoders for stereo enhancement were sold to more outlets and even more played matrix records over the air. Discrete broadcasting took another small step forward with the formation in 1973 of the National Quadriphonic Radio Committee (NQRC) by the Electronics Industry Association. The NQRC was recognized by the FCC and commissioned to make a technical evaluation of eleven proposed

standards for quadriphonic broadcasting. Nine of these were discrete
systems, including the Dorren and GE systems being tested in San
Francisco and Schenectady.

While the studies went on, matrix proponents were actively
recruiting radio stations. Sansui sold its QS encoders to over 70
radio stations. CBS had over 55 SQ encoders installed nationwide,
with five in New York City alone, and over 400 stations received SQ
recordings from the company [Billboard, 8/9/75, p. 42]. While the
novelty of advertising a radio station as "all quad" at first seemed
to boost ratings, there was little evidence that the matrix
technology was having a large effect on listener preferences in the
long run--certainly no impact comparable to the introduction of FM
stereo.

At the end of 1975, the NQRC reported its findings to the FCC,
just in time for quad's slide to oblivion in the audio marketplace.
These findings were generally favorable to the discrete systems
tested. The FCC, sensing a lack of urgency to the matter, waited
until July 1977 to issue its formal Notice of Inquiry into FM
quadcasting, inviting comment from interested parties on whether or
not the Commission ought to adopt standards in this area. Over a
thousand letters were received [Radio-Electronics, 1/79, p.51].

Simultaneous with the Notice of Inquiry, the FCC decided that
the tests performed by the NQRC were out of date, because matrix
systems incorporating new logic devices had been introduced since the
tests began. As a result, the Commission ordered the FCC Labs to
perform listening tests of the "best implementation" (as determined
by listeners) of QS, SQ, a British system called Matrix H, and

discrete methods. The discrete methods of quadcasting fell into two categories: 4-4-4 and 4-3-4, the latter also known as semi-discrete. The middle digit denotes the number of channels actually transmitted over the air. Thus, matrix systems were called 4-2-4.

The results of the tests were equivocal; 4-4-4 was preferred by 52% of the listening panel, SQ by 48%. SQ was a clear winner among the matrix systems, with 77% preferring it to QS. Panelists seemed most interested in concert-hall ambience rather than surround-sound effects [Radio-Electronincs, 1/78, p.4]. CBS used the results to argue not only that discrete broadcasting should not be approved, but that SQ should be made the exclusive standard for matrix broadcasting. This proposal met fierce resistance.

The FCC voted to extend its inquiry in 1979, but combined the issue of discrete quad with the possibility of reducing FM channel spacing in order to permit more stations on the air. Vehement objections from SCA users such as Muzak were answered in 1980, when the FCC issued a finding that 4-3-4 or 4-4-4 systems would not interfere with adjacent channels and would not affect channel spacing [Broadcasting, 7/21/80, p.34]. Since the Commission had earlier noted that 4-2-4 had been around since 1972 but had not achieved "overwhelming public acceptance," it was inclined to allow a market solution to choosing a discrete quad system. Once again, comment was invited, this time on the merits of a market versus a regulatory solution.

Given the total dormancy of four-channel sound among artists and consumers, the FCC's repeated disinterrings of the quad corpse smacked of necrophilia. The real source of these proceedings,

however, was the constraint of administrative law that a matter once

sent out for comment had to be pursued to a conclusion. As one

observer noted, the FCC was "just going through the motions" [Radio-

Electronics, 11/77, p.4].

III. ANALYSIS OF THE QUADRIPHONIC EXPERIENCE

Explanations for quadriphonic sound's failure to establish itself permanently are not hard to invent. Participants in the audio industry advanced theories even before the outcome became clear. The difficulty lies in evaluating the importance of the various possible causes, and in tracing their complex interactions. Candidate explanations include weak demand for quad, competitive disadvantage relative to the stereo installed base, retailer resistance, chicken-egg development problems with software and hardware, and fragmentation of the market by incompatible proprietary standards.

Quad's failure can best be understood in the context of Farrell and Saloner's (1986) model of installed bases with network externalities. This framework, rather than the bandwagon approach of Chapter 1, is appropriate because the timing of payoffs was crucial to users' decisions about adopting quad. Lack of software, i.e. a low level of current benefits, was the most frequently cited objection to quad by retailers and consumers. Uncertainty about the preferences of other consumers did not appear to be a significant factor.

In the installed base model, a flow of users enters the market at an exogenous rate, each user deciding which of two networks to join, an old technology that has been in existence for some time, or a new technology that appears at a later date. The benefit a user derives from joining a particular network, net of any fees he might

pay, is determined both by the size of the network and by the intrinsic quality of the technology employed. Users all have the same, commonly known, tastes.

Equilibrium network sizes are determined by three factors in this model: the relationship between the benefit functions of the two technologies, the size of the old network when the new technology is introduced. and, possibly, consumer expectations about which network is destined to succeed. Farrell and Saloner show that the parameter space can be divided into a region where the unique perfect Nash equilibrium is that all users adopt the new technology after its introduction, a region where the unique equilibrium is no adoption of the new, and a third set of values for which there are multiple equilibria.

In the case of quad, the primary source of positive network externalities was the fact that a larger base of users implied a greater variety of quad software available. Pure communication effects, such as the ability to play others' records on one's own equipment, seem to have been relatively unimportant. It is plausible to assume that all network benefits had been exhausted for stereo equipment; given the large size of the stereo user base by 1971, further increases in network size had a negligible effect on stereo software availability.

Since both matrix and discrete audio equipment were perfectly capable of playing two-channel recordings, consumers in the market for a new sound system had only to weigh the potential benefits of quadriphonic sound against the additional costs of quad. Assessment of quad's benefits required the consideration of two issues. First,

assuming that software was available, how much better was four-channel sound compared to its cheaper rival, stereo? Second, was enough interesting music available in quad, and how quickly would software be released? I analyze each of these questions in turn.

Weak Network-Independent Demand

If quadriphonic sound simply failed to provide extra utility to buyers compared to stereo, holding constant the availability of software, then it is easy to understand why the concept did not take hold. This explanation was advanced by a number of observers, many of whom seemed to feel that quad was simply a gimmick designed to attract the uninformed consumer. Determining the consumer benefits of quad after the fact is obviously problematic, although contemporary reviews in various publications give strong indications. The effort is worthwhile, because making a pass at this issue helps the analysis of other explanations as well.

The value of quadriphonic sound to a listener depended on the quality and availability of software, as well as the chain of hardware from stylus through speaker, with special emphasis on the decoder or demodulator. Some of the considerations in evaluating four-channel sound were the same as for stereo, or even mono: low amounts of noise and distortion, wide dynamic range, and flat response across frequencies. In addition to these traditional criteria of high fidelity, quad introduced new issues: Was concert-hall ambiance effectively simulated? Were the spatial relationships between instruments definite and stable? Was the sound richer and

more enveloping than stereo? And was the quad effect overly sensitive to the listener's position at the exact center of the speakers?

The relative merits of SQ, QS, and CD-4 according to these criteria are hard to discern with complete confidence, but independent tests performed by consumer and hobbyist publications, as well as analysis of claims made by manufacturers, allow fairly firm conclusions to be drawn. From the beginning, matrix systems were superior to discrete by the traditional standards of high fidelity, primarily because of the technical difficulty of cutting a discrete disc, but also because the extra localization information contained in CD-4 tended to "crowd out" some of the dynamic range available [Radio-Electronics letters section, 6/72, 9/72, 10/72, 11/72; Consumer Reports, 6/75, p. 384].

On the distinctively quadriphonic aspects of performance, there was remarkable agreement among independent observers. Matrix systems unaugmented by logic were simply inadequate. According to Consumer Reports, "SQ generally did a good job of reproducing ambiance, and ambience effects gave an agreeable openness to the sound. But listening positions turned out to be critical; changing them by as little as a foot or so could significantly change the effect. With music intended to convey unconventional spatial effects, the four-channel [sound] image was usually hard to pin down, lacking in solidity, and disconcertingly changeable from moment to moment." The logic systems of a few SQ receivers helped quite a bit, but even with this equipment "Two out of every three SQ discs auditioned in these tests did not seem to benefit much from decoding. They offered little improvement over their performance when played simply as

stereo" [Consumer Reports, 6/75, p. 383]. This signified little

improvement over two years before, when one reviewer noted that "some

of the Columbia SQ library...cannot always justify the added expense

of four-channel" [Radio-Electronics, 5/73, p. 54]. Billboard's

critic consistently complained that there was insufficient separation

on SQ discs; in one case, he said, "loss of rear speakers only

dampens the album by about 10%, 15% at the most. Still, the album is

probably one of the best to date in the SQ system" [Billboard,

8/23/75, p. 62].

QS without Vario-Matrix logic suffered from "the same vague

four-channel image and directionality as the SQ decoders without

logic" [Consumer Reports, 6/75, p. 383]. With Vario-Matrix, QS had

better directionality and solidity than SQ, but less ambience.

Consumer Reports felt that, on balance, QS and SQ were equally

effective [Consumer Reports, 6/75, p. 383].

All outside observers agreed that discrete provided the best

quad effect, with disagreements centering on the artistic purposes to

which this technical capability was put. If concert-hall mimesis was

the goal, CD-4 "contributed subtle but realistic ambience effects,

solid directionality, and a fine feeling of openness" [Consumer

Reports, 6/75, p. 384]. If "surround-sound" spatial effects were

wanted, that also worked well. In either case, listening position

was not nearly so critical to the effect as it was with matrix, and

the recording engineers' intentions were transparent to the listener

[Consumer Reports, p. 384]. The bottom line: "More than half the

discrete discs in CU's library sounded much better in quad than when

played in stereo. In conventional stereo they lacked relief--sounded

'flat'--when compared to the quad version." Furthermore, most of the good records were purchased after mid-1974, signifying important progress in recording techniques [Consumer Reports, p. 384].

Objections to CD-4 seemed to come mostly from people unsympathetic to the use of quad for new musical effects. As one retailer put it, "Giving absolute separation on all four channels, as done often in quad, seems fakery to me....The manufacturers are trying to make quad exciting, but they're killing it. JVC is the biggest offender here because all the demo records they've sent here have that separation." [Billboard, 8/30/75, p. 32]. On the other hand, a critic reviewing a CD-4 recording of a symphony rhapsodized, "This LP portends the future of classical music...[There is] a diagram on the jacket showing that the chorus is dead rear and, for example, the violas about 45 degrees to right front. And that's where they are!" [Billboard, 2/15/75, p. 58].

In light of this evidence, it seems reasonable to conclude that quadriphonic sound did provide benefits for many listeners, and would have produced benefits for many others who never made a purchase. Discrete quad was on a fairly steep improvement curve as new recording and pressing techniques reduced the degree of noise and distortion in the software, and its separation capability allowed truly significant new musical effects. Matrix quad seemed to reach technological maturity by 1976, providing high-fidelity but little excitement. Still, Sansui's surveys showed that 60% of their QS hardware sales were based on customers hearing quad in a friend's home [Billboard, 3/15/75, p. 75], suggesting that more than salesmanship was involved in matrix sales.

Competition From Stereo

The large pre-existing network of stereo hardware and software is an obvious cause of quad's difficulties, but the interpretation in Farrell and Saloner (1986) must be modified, because four-channel and two-channel systems were not totally incompatible. Additions to the quad network could not hurt two-channel owners, because quad software played back in stereo on their machines; similarly, quad owners could enjoy stereo records. Hence, the possibility of being completely "stranded" with an obsolete and useless product was foreclosed. (From a normative point of view, the "upward compatibility" of quad with stereo rendered impossible the phenomenon of socially inefficient adoption of quad --"excess momentum"--in the sense of Farrell and Saloner. "Excess inertia"-- a socially inefficient failure to adopt four-channel--was still possible.)

Superficially, it might appear that the partial compatibility between the two audio systems should have eliminated quad's handicap of a small initial installed base. The flaw in this reasoning is that quadriphonic equipment was generally an inefficient way of enjoying stereo. Until the late stages of four-channel's demise, two-channel receivers cost about 60% less than quad systems of equivalent sound quality [Consumer Reports, 6/75, p. 381], not even counting the cost of quad's two extra speakers. An investment in four-channel, therefore, could only be justified on the basis of anticipated use with fully compatible software. And the availability of that software, in turn, depended on the size of the quadriphonic user base.

Compatibility of quad with stereo, producing stereo sound, was considered absolutely essential by all major players. It meant that four-channel receivers could be sold without the existence of a large quad software library, and that a single inventory software policy was possible. The single inventory policy was basically abandoned, however, and the ability of quad receivers to play stereo records cut two ways. By failing to render existing consumer investments obsolete, stereo compatibility encouraged consumers to stick with two-channel hardware and software. Furthermore, software producers' incentives to turn out quad records were weakened because stereo records could be sold to the quad user base.[8]

The matrix-discrete split hindered the growth of quad to the extent that it divided the quad user base, thereby reducing the size of the market available to any artist or label that incurred the extra fixed cost needed to release a quad record. For such a division of the base to occur, consumers would have had to think of matrix and discrete as fairly close substitutes; otherwise, the two systems would have served different clienteles, and the elimination of one or the other would have done nothing to promote software availability.

On the hypothesis that the user base was indeed being harmfully split, and that consumers were being repelled by having to guess

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[8]It is interesting that the apparent success of the compact disc (CD) is occurring even though the CD player will not accept vinyl discs and the conventional turntable cannot play CDs. The demise of the vinyl LP is a distinct possibility, and that threat seems to be, if anything, encouraging conversion to CDs. The flaw in this analogy, of course, is that the demand for quad may well have been low simply because the technology did not work well enough, while compact discs perform acceptably.

which quad system would emerge victorious, manufacturers introduced "universal" receivers that contained one or both types of matrix decoder and a discrete demodulator. This measure failed to eliminate fears of being stranded with a losing system for two reasons. First, because of the expense of the circuitry, "universal" equipment tended to be especially costly and to include only one mode in top-quality fashion, with the others being less than state-of-the-art. In the listening judgements of the Consumer Union panelists, no receiver was above average on both SQ and CD-4 performance, with the best SQ systems seriously deficient on discrete playback [Consumer Reports, 6/75, p. 385]. Second, a large number of cheaper, non-universal models had already been sold when the newer equipment was introduced, and so constituted most of the installed base of quad systems; indeed, the non-universal receivers continued to sell up to the end.

Assuming that the new technology provides superior value at equal network sizes (which is at least plausible for quad, as I argued in the previous section) the installed base model of Farrell and Saloner (1986) predicts non-adoption of the new in two circumstances. One possibility is that the cost of waiting for the new network to grow exceeds the gain, even if every future user also joins the new network; in this case, the superior performance of the new technology in the future, when its network grows large, is shrunk by time discounting and so motivates no one to sign up. Non-adoption is the unique equilibrium here. The other possibility is that the new network's growth is worth waiting for if all future users join it, but that without such growth, the old network dominates. In this situation, expectations determine the equilibrium: if everyone

expects future growth of the new, then it does grow; if not, then the new technology will not get off the ground.

For the audio system buyer, the issue in these terms was whether the anticipated increment of listening pleasure due to quad was worth the additional expenditure, assuming that all future users decided to buy four-channel receivers. If the growth of the quad user base was not going to be quick enough, or did not provide enough additional benefit to offset the cost of waiting, then the user would not be willing to spend twice as much on the new technology. In this case, non-adoption would be the unique equilibrium. Alternatively, non-adoption could have resulted even if the upfront cost of four-channel were more than justified by future network benefits, if users were pessimistic about such future growth actually occurring.

From the advertising copy of quad system sponsors, it is clear that they believed the situation to be one in which customer (and retailer) expectations mattered. Each stressed that its system was the wave of the future, citing as evidence the growing number of records released in the format, past hardware sales, and new sign-ups of record labels. Much of this advertising was in the trade press, suggesting that sponsoring firms were extremely concerned that retailers believe in four-channel's future. The Appendix describes in more detail the retailer's relationship to quadriphonic sound.

The Sponsors' Role

Given the apparent drawbacks of having competing four-channel systems, how did the sponsoring firms manage to end up in such a

situation? The obvious place to look is the private motive of each firm to earn rents from a proprietary technology. Absent such a motive, quad would have been unlikely to be introduced at all, but the rivalry over who would appropriate these rents played a major role in undermining the new concept.

The game in the early part of the seventies among CBS, JVC, and RCA pivoted around who would introduce which system when. JVC jumped ahead with CD-4 in Japan in 1970, and seemed to be eying the U.S. market, also. CBS's introduction of SQ in 1971 may have been motivated by a desire to preempt CD-4 and prevent its establishment as the quad standard. The fact that matrix was technically simpler than discrete, though more limited, made SQ a good tool for preemption, but not necessarily the best choice for establishing quad as superior to stereo. [Forbes, 8/15/74, p. 49].

Interestingly, when RCA announced its decision to go with discrete in 1972, it was perceived by many industry observers as a "spoiler," entering with a premature technology in order to forestall SQ's acceptance as a standard. Yet early matrix systems, lacking even rudimentary logic, were also technologically premature. The four-channel experience teaches an important lesson about new technologies with positive consumption externalities: Incompatible systems offered by different firms will tend to reach the market at an earlier stage of development than would compatible systems, as each sponsor tries to get the jump on the others in building a network. This point has generally been overlooked in the literature on compatibility, because that work (except for Arthur (1975)) assumes that new products hit the market in a single, unchanging form, rather than being improved over time.

When a retailer or a manufacturer asserted that a quadriphonic system was "premature," it was implicitly suggesting that the product ought to have been held back longer in development, and that such a delay would have been beneficial to the complainant, the consumer, or both. But why should anyone other than the producer (and perhaps a few foolish purchasers) be concerned with the adequacy of the offered product? One reason is that if an inferior version of quad were to develop a network and become the standard, it might inhibit the growth of superior (and possibly more profitable) versions developed later. A second reason is that an inadequate four-channel product might disenchant purchasers and critics and thereby discredit the whole idea of quad, given the widespread ignorance and confusion about the new medium, and the difficulty the consumer faced in separating truth from exaggerated or spurious promotional claims.

This analysis suggests one possible explanation for quad's failure in the marketplace. The discrete system had many "bugs" in 1972: discs lacked durability, demodulators badly restricted dynamic range, recordings suffered from noise and distortion, etc. Progress on all these problems was taking place, but it was not until late 1974 that CD-4 was truly capable of fulfilling its potential; in fact, in 1975, Consumer Reports felt that more progress on fidelity was still needed [Consumer Reports, 6/75, p. 385]. However, discrete quad offered the prospect of significant audio progress, something better than stereo. The matrix systems, when introduced, failed to impress many listeners with their quad capability, although some improvement was generated later by adding logic.

It is possible that Columbia did not wait for improvements in logic before launching SQ because it was afraid that CD-4, a system

with more ultimate potential, would be able to solve its technical problems and take over as the standard. By an early introduction of SQ, CBS could act as the spoiler, preempting the market before CD-4 was ready. Once faced with SQ's presence, JVC and RCA were forced to push discrete hurriedly into the market to avoid being locked out permanently by matrix technology. According to this hypothesis, these early introductions then discredited the idea of quad with many retailers and consumers, since the products simply did not live up to their promotional claims. As a Sansui spokesman put it, "Quad seemed to have grown too fast, too far, too quickly. It was prematurely born, and prematurely died as we were all too bullish two years ago. A lot of really simple decoders with no ICs available turned off consumers."[Billboard, 3/8/75, p. 32].

In the battle of quad against stereo, the existence of competing technologies hindered four-channel's success in another way. It led to a diversion of manufacturers' promotional efforts into internecine battles (the "quad wars") instead of efforts to promote quad in general, since system-specific appeals were much less subject to free-riding inefficiencies. Promotion of one system over another, besides expending resources in mutually cancelling rivalry, contributed to the confusion and skepticism of prospective customers by creating an atmosphere of contradictory and unverifiable claims. Summit meetings between rival sponsors never succeeded in generating a useful collusive arrangement on promotion that would maximize joint industry profits.[9]

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[9]In any case, the promotional decisions facing quad's sponsors were made under conditions that diluted the firms' incentives to make quad succeed. The sponsors all had stakes in existing stereo technology, so that the marginal benefit to each promotional dollar was net of cannibalized stereo sales.

Labels and Artists

Perhaps the single factor most cited for damaging quadriphonic sound was the scarcity of four-channel software. In the context of the theoretical model of installed base followed in this analysis, this attribution of blame seems beside the point, since it is precisely the chicken-egg character of software/hardware relations that generates the network externality in the first place. However, looking at the conditions of record production sheds light on why the externality existed and suggests policies that quad's sponsors might have undertaken to overcome the barrier.

Artists had little financial incentive to record their work in quad under conventional recording contracts; although they would still be able to sell to the large stereo audience if they did, it was equally true that quad owners would buy stereo discs. An artist might be able to sell a quad album to listeners he would not ordinarily reach, because of their hunger for any software to use with their equipment, but this was not likely to make a significant difference. As a result, according to Columbia's director of quad recruitment activities, "Most of the artists, through a combination of apathy and lack of quad knowledge, did not consider it important to release quad product" [Billboard, 8/9/75, p. 39].

The costs of producing four-channel records instead of two-channel were substantial. Producers, mixers, and artists had to make decisions about where to locate performers and microphones in the studio, and how to mix down the many recorded tracks into four

channels to create the desired sound image. Artistic choices between ambience or surround sound, a "natural" spatial distribution of musical elements or unconventional effects, and stable or dynamic locations, had to be made. All this took a great deal of expensive studio time, especially when artists and producers were still learning about the medium.

Matrix recordings could be difficult to produce, because the encoding from four channels to two followed by decoding (modified by logic) into four again, caused unpredictable and non-intuitive divergences between the sound image in the studio and on playback [Billboard, 8/9/75, p.45]. Discrete cutting, at this stage, required expensive special equipment, and was subject to an unusual amount of noise and distortion. Artists committed to CD-4 also believed that exploiting the medium's possibilities required rethinking the whole process of arranging and recording music.

In addition, artists and producers feared that a poor quad product might hurt their reputations. Given the greater technical problems in physically transferring the musical information as imagined by producers onto a vinyl disc, even a flawless job in the studio might come out sounding bad. Matrix systems tended to move sound sources away from their intended location on playback, while discrete disc cutting, at least in the beginning, required finicky and expensive cutting heads that operated at extremely low speeds.

All of these fixed costs had to be spread over a relatively small base of quad listeners, because of the rejection of single-inventory policies by record retailers. Given the double-inventory policy maintained by most labels, an artist would have to make both a

stereo and a quad version to reach both markets. This obviously

entailed much extra work. As one producer put it, "Many have done

quadrasonic because the record companies have told them they must

have quad. They very painfully do a quadrasonic album and they sure

don't want to do one in stereo and then go back and do it in

quadrasonic." [Billboard, 8/10/74, p. 48].

Yet record companies did not seem to try very hard to get

artists and producers to record in quad. For example, there do not

appear to have been financial incentives given for four-channel

output [Billboard, 8/10/74, p. 48], and while system sponsors CBS and

RCA spoke frequently about trying to "win over" artists to quad, this

referred primarily to entreaties and appeals for "artistic growth."

The main reason why the labels did not pressure artists more directly

is that while a record company usually has a great deal of bargaining

power with new performers, the established, best-selling musicians

have many suitors desiring to reward them with lucrative contracts.

Under these circumstances, an arrangement whereby a top-flight artist

agreed to record quadriphonic albums might have cost more than the

additional revenues expected.

As a result of the record companies' inability to sell artists

on quad, they were forced to resort to a remixing program. The

performer recorded a stereo version only, and then the label used its

own producer and mixer to cut a quadriphonic disc from the multitrack

master tapes. This practice had two major drawbacks. First, it led

to extreme conservatism in the exploitation of four-channel

capabilities, because the artists had a veto over the remixers'

efforts. For example, at A&M Records, "since none of A&M's artists

or producers are expressly arranging music for the quad medium, Bornstein [A&M's quad remixing expert] does not try to change in any way the concept of their music by interjecting directional gimmicks or altering the balance of voice with instruments....The artist and his producer have final approval of the quad mix and Bornstein is cognizant of their potential for nixing his efforts, so he doesn't do anything radical" [Billboard, 8/9/75, p. 39]. This conservatism was not calculated to impress the listener with quad's possibilities.

The second problem with record company remixes was that four-channel releases frequently lagged behind the stereo product by long intervals, and because of the added time (about 30 hours per mix) and expense of remixing, only a few albums were worth the trouble. Columbia's SQ remixer believed that simultaneous release of stereo and quad would boost sales, but only star acts ever got this treatment, and even for them it was not a certainty; for a less prominent artist, 200,000 copies in stereo might be sold before the quad release actually reached the stores [Billboard, 8/9/75, p. 39]. Delays of one to two months were common, sapping the sales momentum generated by advertising and media coverage of new albums.

IV. CONCLUSION

The effort to establish quadriphonic sound in the home audio
market ultimately failed. Thousands of consumers were left owning
quad hardware for which little four-channel software was produced.
Large firms dumped tremendous quantities of inventory at a loss. And
the very idea of quadriphonic sound became one that evoked scorn and
hostility from most industry participants.

This outcome, in one sense, is puzzling. Quad technology was
backed by the most prominent hardware and software companies, touted
in many advertisements and articles, and enjoyed by many who had the
opportunity to use it. Yet it never completely overcame its original
status as a novelty, a curiosity, a gimmick. Unlike other audio
technologies that disappeared from the market, such as eight-track
tape, quad did not go through the common growth, saturation, and
substitution pattern of the product life cycle. Rather, it never
quite got off the ground, despite its impressive institutional
support.

The proximate causes of quad's failure are readily apparent. A
glacial pace of software development and technical deficiencies in
the systems led to sluggish demand. The lack of demand then
discouraged software development. Confusion among the public about
the nature, performance, and operating characteristics of quad, and
especially about the merits and demerits of matrix versus discrete
technology, prevented four-channel from becoming the perceived "next
step" after stereo. In the face of customer ambivalence, and hence

difficulty in developing a simple and convincing rationale for quad, audio retailers by and large made only weak efforts to sell the new medium, and were quick to abandon it when it was not instantly successful.

This list of observable phenomena, however, does not constitute an exhaustive explanation for quad's demise; instead, the items mentioned themselves require explanation. In the context of the installed base model, the following description seems most accurate:

First, the intrinsic value of quad, holding user bases (and hence software availability) constant, appeared to be greater than that of stereo for many listeners. This value improved over time as the technology developed.

Second, because the four-channel user base was so small relative to stereo, quad ownership had lower current benefits (when its greater cost was considered) than did stereo. The matrix-discrete split substantially worsened this disadvantage.

Third, had retailers and consumers been more optimistic about quad's future prospects, their optimism would have had a self-fulfilling quality in shifting the equilibrium to one where quad eventually succeeded. The matrix-discrete split also worked against the new technology in this area, by making the status quo a more focal equilibrium and by diverting promotional efforts to the quad wars at the expense of fighting stereo. The incentives facing the firms go a long way toward explaining why retailers felt that quad was underpromoted and why consumers seemed bewildered by conflicting advertising claims.

Fourth, quad might have been more successful, even to the extent of reaching a position in which adoption was the unique

equilibrium, had the new technology been released at a later date, when its quality had significantly improved. Because stereo had already exhausted all the network externalities possible, such a delay could only have helped quad. As it actually happened, the relatively poor quality of early four-channel products seriously hurt the medium's reputation with consumers, retailers, and artists. The premature introduction of quad seems to have been driven by the rivalry between matrix and discrete sponsors, each of which sought to avoid being preempted by the others' entry.

Using the installed base model to guide analysis demonstrates its usefulness in "seeing through" the welter of historical data. Without measurement of the consumer payoff for various network sizes, however, it cannot make clear-cut predictions about adoption of new technology. The model does rule out partial adoption, because it assumes homogeneous consumers and rational expectations; in the case of four-channel sound, those assumptions failed, and partial adoption occurred.

This study suggests some general lessons about the introduction of products with significant demand-side economies of scale. First, competition in such markets tends to be "winner-take-all", because the first firm to transfer a proprietary technology to a large base of users gains an enormous advantage. Firms therefore have an incentive to attempt preemption. In their haste to beat rivals to market, however, they may introduce "half-baked" products of poor quality, reducing the likelihood that any product will succeed.

The second lesson is that the preemption battle will likely feature rivalry through advertising. To the extent that this

advertising carries conflicting messages about the relative quality of the different contenders, consumers may believe negative claims about rivals, but disbelieve favorable statements about the sponsor. The entire product concept can be discredited in the crossfire.

Third, integration of hardware and software production within a single firm does not always overcome the liability of a small initial user base. Coordination and incentive problems cannot be bypassed simply by bringing activities within the same legal entity. Careful attention to lines of authority and to compensation policies remains essential in order to achieve adequate software availability.

Fourth, markets with demand-side economies of scale are susceptible to multiple expectational equilibria. While theoretical work has focused on consumers' expectations, in many cases retailers' beliefs are more important; their advice not to buy a certain product will tend to be credible with customers. Depending on the particular market, other opinion makers may also be important in forming consumer expectations.

APPENDIX

A Note on the Retailers' Role

Audio equipment reached consumers through retailers of many types--department stores, mass merchandise outlets, and audio specialty stores (both chains and independents). The specialty stores were particularly important in selling more expensive types of equipment, and hence were crucial for quad. Without a willingness by these outlets to stock four-channel hardware, the technology could not take hold.

More important than the mere physical availability of quadriphonic equipment, however, was the provision of information and persuasion about quad and its merits. Because of the confusion about the various four-channel systems, and the general tendency for customers to be affected by the advice of salesmen when making purchases of expensive hi-fi equipment, the attitudes and behavior of store personnel had a big effect on quad's degree of success. Hence, skepticism among retailers about the merits of four-channel sound played a large part in restricting its market penetration.

Something that is only indirectly addressed by economic theory, but which is critical for the sale of experience goods under conditions of uncertainty and bounded rationality, is the availability of a selling strategy, or pitch, that meets at least the following criteria: simplicity of message, so that it can easily be taught to large numbers of sales personnel and so that it can be readily understood by most consumers; plausibility, so that buyers

can believe in the touted benefits of the product being pitched; and
relevance to the customer's preferences, so that if the message is
understood and believed, then the buyer will decide that purchase is
optimal. Two basic selling strategies evolved for quad, with some
retailers stressing one approach, some the other, and the rest making
no coherent effort to sell the technology.

The most straightforward pitch can be labelled "quad first."
In this approach, after "qualifying" the customer (i.e. ascertaining
his relevant price range), the salesman sought to convince him that
quad was superior to stereo, that the quad software library was
sufficient for immediate enjoyment, and that four-channel was growing
and viable in the long run. (Note that this pitch is close to
asserting that adoption of the new technology is the unique
equilibrium in the installed base model.) The message was inherently
simple, but to achieve plausibility and relevance in the mind of the
customer it usually required a special listening room in which quad
software could be switched from four-channel playback to two-channel
at the push of a button. This comparison was the most effective
known method of convincing buyers that quad was superior; given the
uneven quality of quad software, demonstration selections had to be
chosen carefully.

The "quad first" strategy required salesmen to know a fair
amount about the various systems and models, since if the pitch
succeeded the buyer would immediately attempt to set up a complete
four-channel system. In addition, the retailer needed to help the
buyer gain access to quad software, even carrying it himself if
necessary. Most of the stores that were truly stellar four-channel

performers, with perhaps 40-60% of their total revenue derived from quad (as compared to the peak 5-8% industry average), pursued this strategy.

The second major selling strategy was "stereo now/quad later." Here, the salesman sought to convince the buyer that quad was the wave of the future, that owning a four-channel receiver provided option value for when the new medium took over, and that in the meantime it could be used as part of a stereo system with two speakers. (Here the argument is equivalent to the assertion that adoption of the new technology is the focal choice among multiple equilibria in the installed base model.) This message was not as simple as the "quad first" argument, since it raised the issue of whether buying a stereo receiver now and upgrading to quad later, when more software might be available, was not a better choice. However, plausibility and relevance were much cheaper to establish, because the focus was no longer on the buyer's listening judgement about four-channel versus stereo, but rather on the expected, future marketplace acceptance of quad. Salesmen, at least until the end of 1975, could point to the commitment of manufacturers to quad, and could also note that the major record labels (CBS, RCA, W/E/A) were primary boosters of it, strengthening claims about its "inevitability."

Implementing the "stereo now/quad later" strategy did not require the retailer to share in the costs of finding quad software, since the buyer planned on playing stereo discs until more four-channel product was available. Nor was a listening room absolutely essential. However, the retailer did need to carry a fairly broad

selection of models, and universal models in particular, since the future value of a quad receiver would be compromised if it lacked the format that turned out to dominate the market. This strategy, if implemented aggressively, could raise the percentage of quad revenue significantly, but rarely up to the 40% level.

A third strategy, "stereo enhancement," was pushed by matrix manufacturers but adopted by few retailers. The idea that matrix decoders and rear speakers could significantly improve the sound of stereo discs lacked plausibility, especially since many matrix discs themselves were not improved by decoding. As one retailer, put it, "The concept of quad as enhancement for stereo just sounds like something drummed up or propagated in the trades [publications]. It has no effect on sales." [Billboard, 8/9/75, p. 36].

The primary motivation for pushing quad was that retailers earned higher profits per sale, with four-channel equipment generally fetching higher prices and with two extra speakers adding to the payoff. Balanced against this incentive was the additional time, expense, and effort needed to sell quad. Listening rooms took up valuable display space, training of salesmen was expensive, and even with optimal techniques, more hours were needed to sell a four-channel unit than a stereo one. According to the president of the manufacturer Pioneer, about half of all pitches for stereo sales were successful, compared to one-fifth for quad [Billboard, 8/23/75, p. 42].

Also militating against retailer enthusiasm for quadriphonic sound was the potential loss of consumer goodwill from selling systems that turned out to be overpriced, underperforming, or

impossible to supply with software. The risks of steering a customer to stereo if it turned out _ex post_ that quad was the better choice were small; the stereo system would do what it was promised to do, and upgrading could be accomplished with an add-on decoder or demodulator. The risks of urging quad on a customer if stereo were the right move loomed larger; the possibility that the system might not work well, as with many matrix decoders or early discrete discs, or that it would become an expensive and useless white elephant if software were not forthcoming, exposed the retailer to customer antagonism and diminishment of reputation.

Finally, most audio dealers believed that the scarcity of quad software was a major drag on sales, as was the confusion engendered by the matrix versus discrete battle. While the former concern was as much a symptom as a cause of quad's problems, the latter complaint was consistent with the view that the competition between quad and stereo was a question of selecting from multiple equilibria. As Farrell and Saloner (1986) point out, when more than one new system is introduced against an existing installed base, the focal point is much more likely to be nonadoption of the new systems. At industry meetings and in surveys throughout 1974 and 1975, retailers emphasized these two points again and again, frequently resorting to angry rhetoric.

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