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Alan Kirman

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ANTS, RATIONALITY, AND RECRUITMENT*

ALAN KIRMAN

This paper offers an explanation of behavior that puzzled entomologists and economists. Ants, faced with two identical food sources, were observed to concentrate more on one of these, but after a period they would turn their attention to the other. The same phenomenon has been observed in humans choosing between restaurants. After discussing the nature of foraging and recruitment behavior in ants, a simple model of stochastic recruitment is suggested. This explains the "herding" and "epidemics" described in the literature on financial markets as corresponding to the equilibrium distribution of a stochastic process rather than to switching between multiple equilibria.

In a series of experiments entomologists [Deneubourg et al., 1987a; Pasteels et al., 1987a] observed that ants in an apparently symmetric situation behaved, collectively, in an asymmetric way. When faced with two identical food sources, the ants exploited one more intensively than the other. Furthermore, from time to time they switched their attention to the source that they had previously neglected. The entomologists in question try to explain the unequal exploitation and suggest that here is a case in which asymmetric aggregate behavior arises from the interaction between identical individuals, each of whom acts in a simple way.¹ Thus, the behavior of the group as a whole cannot be inferred from analyzing one of the identical individuals in isolation. Without taking explicit account of the interaction between individuals, the group behavior observed during the experiments cannot be explained.

This observation is of interest to economists, since similar phenomena have been observed in markets. Indeed, the sort of

*At the insistence of Olivier Blanchard, this paper devotes more time to an examination of the behavior of ants than did earlier versions. I am grateful to him for his interest and encouragement. I am also grateful to Professors Deneubourg and Pasteels, who first introduced me to this particular problem and to an extensive literature on the subject of communication and interaction in ant societies. Finally, I am indebted to Hans Föllmer, whose help in developing the stochastic model was invaluable and with whom I am pursuing joint work on this problem, and to Luigi Brighi, Vincent Brousseau, Marcello Esposito, Paul Krugman, James Mirrlees, Lucrezia Reichlin, Robert Shiller, Hal Varian, Michael Woodford, and the members of the Economic Theory seminars at M.I.T. and Oxford University for help, comments, and suggestions. The usual disclaimer applies.

1. A more elaborate approach, which still depends on interaction and would still be consistent with the basic argument here, is to think of a society (of ants) as a collection of genetically preprogrammed individuals whose number and activity are regulated by feedbacks and mass communication [Oster and Wilson, 1978; Wilson and Hölldobler, 1988].

herding behavior involved in these experiments corresponds precisely to human behavior reported by Becker [1991]. When faced with two apparently very similar restaurants on either side of a street, a large majority chose one rather than the other, even though this involved waiting in line. There appeared to be no discernible difference in the quality of the food offered by the two restaurants, and the prices charged were almost the same. Becker suggests that the popularity of books may be thought of as reflecting similar phenomena. In addition, herding behavior has recently been suggested as a source of endogenous fluctuations in the price level in asset markets (see, e.g., Scharfstein and Stein [1990], Day and Huang [1989], and Shiller and Pound [1986]). This explanation is particularly appealing when, as in the papers cited, it does not rely on exogenous shocks to the system.

I present a simple model to explain the behavior of the ants, which can also be interpreted in terms of market behavior, and which explains not only asymmetric outcomes but also switches between these. Moreover, this model, although derived from experimental evidence of asymmetric behavior in ants, seems to be more relevant for markets than for social insect colonies.

EXPERIMENTAL EVIDENCE: THE PUZZLE

In recent articles Deneuboug et al. [1987a] and Pasteels et al. [1987a] describe the following experiment. Two identical food sources were placed equidistant from an ants' nest and were kept *constantly replenished* so that they always remained identical. After a period the ants always found and exploited both sources, and the question then is, how were the ants distributed, in "the long run," between the two. Intuitively, it might seem that, after a while, the ants would be split evenly between them.

In fact, the ants stabilized, for a while, in a very unbalanced situation, with some 80 percent at one source and 20 percent at the other. Furthermore, Pasteels et al. repeated their experiments and found similar results with three different species of ants, including both trail recruiting and group/trail recruiting species. To make sure that no subtle changes in the food sources were causing the preference of one over the other, they also tried the same experiment but with *one* food source and two symmetric bridges leading to it. The same phenomenon of asymmetric use, in this case of the bridges rather than of the food sources, was observed. These repeated findings suggest that one should look for a simple model

of the recruitment process which systematically gives rise to the asymmetric exploitation of symmetric sources. Indeed, De-neubourg et al. [1987b] do just that. They explain their observations by building a stochastic recruitment model, which they then approximate by a differential equation system. This has two steady state solutions corresponding to the asymmetric situations just described.

However, an important extra piece of information not mentioned explicitly by Pasteels et al. in their original article, is that sometimes a “flip” occurred, and this resulted in the opposite concentrations at the two heaps, i.e., a change from 80 percent at source A to 80 percent at source B.² This would not arise in their theoretical model, but they attribute it to a temporary weakening of the chemical trail leading to the more frequented source. Thus, their model explains the asymmetry of the distribution of the ants, but does not predict any movement from one state to the other. It would obviously be better to be able to explain both the asymmetric feeding and the periodic switches since these are both somewhat unexpected, given the symmetry of the underlying situation. Indeed, the model constructed in the third section of this paper, unlike that of the entomologists, predicts that both of these features *must* occur.

Before proceeding to give the details of the formal model, I shall first give a description of the basic mechanics of foraging and recruitment behavior in ants, from which its structure is derived. This is of interest here since it provides a basis for comparing the underlying behavior of the ants and the suggestions for its rationalization, with that of human behavior in markets giving rise to similar phenomena.

FORAGING AND RECRUITMENT

As mentioned, the particular experimental observations that prompted this paper concern the recruitment of ants to food sources. There are some 12,000 different species of ants living in colonies that vary in number from ten individuals to twenty million individuals, and they exhibit a large variety of foraging and recruitment strategies.³ However, there are certain features of

2. Personal communication from J. Pasteels.

3. For a full account of these phenomena, the reader is referred to the recent monumental work by Hölldobler and Wilson [1990] or to the more concise account in Sudd and Franks [1987]. Much of the specific literature cited here is, unfortunately, too recent to be dealt with in these works.

these strategies that are common not only to ants but to other insects.⁴ When ants find food, they typically "recruit" other ants to that food. The rationality of this from the collective point of view is obvious, provided that food sources are sufficiently large not to be exhausted by a single ant. Indeed, those ants that do not recruit and that hunt singly are those, for example, which operate in arid environments where food is sparse and occurs in small quantities [Schmid-Hempel, 1984]. An explanation for the evolution of different types and intensities of recruiting behavior could be the trade-off between the expected gain to the colony from letting an ant search and that obtained by the redirection of that ant, by a successful forager, to a known food source. This trade-off varies with the different environments in which various species operate (see Pasteels et al. [1987b]).

Where ants do recruit, their behavior can be briefly summarized as follows. An ant that finds food returns to the nest and physically stimulates, either by contact or by chemical secretion, another ant to follow it to the food source (tandem recruiting) or recruits a group, or lays a chemical trail (by leaving pheromones) which attracts other ants. These forms of recruiting are listed in the order which is held by entomologists to correspond to increasing evolutionary levels, provided that, as just mentioned, the environment warrants the intensive joint exploitation of food sources. Some ants have evolved more sophisticated mechanisms and actually recruit with more or less intensity, depending on the amount of food found. Hangartner [1969], for example, showed that the amount of pheromone laid by one species was related to the richness of the food source.

An interesting problem is that of evaluating the efficiency of different recruiting and foraging strategies. One approach to such an analysis is to think of the ant colony as maximizing some objective function such as its total energy input. Since any food source in nature is always exhausted after a while, the problem is not only to maximize the total flow over time, but also to ensure that the flow does not drop below some minimum level during any period. Thus, to ensure survival, it is always useful to have some ants searching, even when there is a currently productive source (see Pasteels et al. [1987]). Optimal exploitation would involve transfer of ants from one source to another until the expected

4. For example: termites, Rickli and Leuthold [1987]; honeybees, Seeley [1985]; and gregarious caterpillars, Fitzgerald and Peterson [1988].

marginal return were equalized and would also involve a percentage of ants searching, sacrificing short-term gains for longer run survival. The number of ants recruited and the accuracy of that recruitment, i.e., the proportion that actually arrive at the source, should be positively related to the richness and frequency of arrival of food. The observed behavior of ants does, in fact, reflect some of these features. It is true that ants do transfer to new, richer sources, that the intensity and accuracy of recruitment is related to the richness of food sources, and that there are always some scattered searchers in most of the species whose recruitment is described by Hölldobler and Wilson [1990]. However, whether they have, in fact, fully adapted to solve this problem optimally is a question that is beyond the scope of this paper and is one that is not considered as resolved in the entomological literature.

Indeed, there is an ongoing, animated debate among biologists over the idea that existing patterns of behavior have evolved so as to achieve optimality under the constraints of environment and morphology.⁵ The argument for the optimal foraging approach is made by Stephens and Krebs [1986]. They give an account of the debate and the criticisms of their viewpoint. The best known critique of the optimality and adaptive approach is given in Gould and Lewontin's [1979] paper on spandrels. They criticize the tendency to try to find criteria according to which some observed feature, structure, or behavior is optimal.

It seems to me, as an economist, that there are three particularly important issues, each of which finds an echo in a debate on behavior in the economic literature. First, the morphological constraints under which species operate are themselves changing (albeit slowly) over time as indeed is their environment. Second, survival does not imply optimality. Some plants survive as a result of having developed a sophisticated system for turning their leaves and flowers to follow the sun. But as Gould has remarked, they might have done much better to develop feet that would enable them to walk into the sunlight. Last, certain behavior and structural configuration may be locally optimal, in the sense that no small change will bring about an improvement and this may be sufficient to block, at least for some time, further evolution. However, the current situation may be far from globally optimal. These three points are clearly related.

5. One could also think of morphology itself as adapting but over a larger time scale.

All of the above discussion is related to the long discussion in economics as to the desirability of "rationalizing" observed behavior by finding some utility function that it maximizes. As Samuelson [1947] noted:

... it is possible to formulate our conditions of equilibrium as those of an extremum problem, even though it is admittedly not a case of an individual's behaving in a maximizing manner, just as it is often possible in classical dynamics to express the path of a particle as one which maximizes (minimizes) some quantity despite the fact that the particle is obviously not acting consciously or purposely.

This problem is central to what follows. While the economist is prepared to accept that insects may follow some mechanical rule of behavior which may have evolved so as to be close to optimal, or may be locally optimal in the space of possible strategies, if the same model is applied to economic agents, he usually requires that the behavior should be fully and consciously optimizing.⁶

A SIMPLE MODEL

I now develop a model that provides a simple formal structure for analyzing the recruiting problem. It is best thought of as applying to the tandem type of recruitment.⁷ The process suggested will explain the apparently curious behavior of the ants, and I shall then relate this to some economic examples.

Consider a situation in which there are a "black" source and a "white" source of food.⁸ In particular, each of the N ants is feeding at one or the other of them. The *state of the system* is defined as the number k of ants feeding at the black source; i.e.,

$$k \in (0, 1, \dots, N).$$

The system evolves as follows. Two ants meet at random (one could think of drawing two balls from an urn containing black and white balls). The first is converted to the second's color with probability $(1 - \delta)$. Which is the "first" and which is the "second" is, of course, of no importance since, with the same probability, they could have been drawn in the other order. There is also a small

6. Interestingly enough, this point was raised in an article on the demand behavior of pigeons, where the same issue arises [Battalio et al., 1981].

7. This does not detract from the significance of the model since, as might be expected from the structure developed here, empirical evidence shows that species using group/trail recruitment as opposed to tandem recruitment exhibit the same asymmetrical behavior (see Beckers et al. [1990]).

8. This simplifies matters, but one could consider any finite number of sources.

probability ϵ that the first will change his own color independently before meeting anyone. The probability ϵ is technically necessary to prevent the process getting “stuck” at $k = 0$ or $k = N$. It is always considered as small and in particular, when N the number of ants becomes large, ϵ goes to zero.⁹ When I interpret the model in terms of traders holding views, for example, this self-conversion may be thought of either as due to the arrival of exogenous “news” or the replacement of an existing trader by a new one who does not necessarily share the same view.

The dynamic evolution of the process is then given by

$$\begin{aligned}
 (1) \quad & \begin{array}{l} \nearrow k+1 \text{ with probability } p_1 = P(k, k+1) \\ k \\ \searrow k-1 \text{ with probability } p_2 = P(k, k-1) \end{array} \\
 & = \left(1 - \frac{k}{N}\right) \left(\epsilon + (1 - \delta) \frac{k}{N-1}\right) \\
 & = \frac{k}{N} \left(\epsilon + (1 - \delta) \frac{N-k}{N-1}\right).
 \end{aligned}$$

All that is necessary for our purpose is that $p_1 + p_2 \leq 1$, and this is guaranteed if N is greater than two and ϵ is small enough. Of course, k will stay unchanged with probability $p_3 = 1 - p_1 - p_2$.

This simple *Markov chain* is related to several standard urn models, in particular to Polya’s urn model. There are two special cases.

In the first, $\epsilon = 1/2$ and $\delta = 1$, there is no interaction, and the first person chooses his group randomly with equal probability. This is the *Ehrenfest urn model* with an equilibrium distribution that is binomial, $\mu(k) = [n/k]2^{-n}$ ($k = 0, \dots, n$).

Second, $\epsilon = \delta = 0$ (in this case, the first person always moves with certainty to the second’s group). In this case the process is a *martingale* with final absorption in $k = 0$ or $k = N$, with prob [absorption in $k = N$ | initial state $= k_0$] $= k_0/N$. For an interesting class of general cases, see Arthur, Ermoliev, and Kamovskii [1985]. What is of interest here is the *equilibrium distribution* $\mu(k), k = (0, 1, \dots, N)$ of the Markov chain defined in (1). That is, we wish to know what proportion of the time will the system spend in each

9. Consider the following scheme: an ant converts with probability ϵ . If no conversion takes place, then a second ant is drawn, and the first converts to the second’s group with probability γ . Then δ in our expression is given by $\delta = (1 - \gamma + \gamma\epsilon)$.

state. This is given by

$$(2) \quad \mu(k) = \sum_{l=0}^N \mu(l)P(l, k).$$

Using the fact that our symmetric process is reversible, we have

$$(3) \quad \mu(k)P(k, l) = \mu(l)P(l, k).$$

We can thus write

$$(4) \quad \mu(k) = \frac{(\mu(1)/\mu(0)) \dots (\mu(k)/\mu(k-1))}{1 + \sum_{l=1}^N (\mu(1)/\mu(0)) \dots (\mu(l)/\mu(l-1))},$$

where

$$(5) \quad \frac{\mu(k+1)}{\mu(k)} = \frac{P(k, k+1)}{P(k+1, k)} \\ = \frac{(1 - (k/N))(\epsilon + (1 - \delta)(k/(N-1)))}{((k+1)/N)(\epsilon + (1 - \delta))(1 - (k/(N-1)))}.$$

The precise form of $\mu(k)$ depends on the relative value of ϵ and δ . Since it is clear from the discussion that the interesting case is that in which the distribution is concentrated at the extremes, it is of interest to know for which values of the parameters ϵ and δ this will occur. In Figure I three cases are illustrated.

It is obviously case Ia which corresponds to the situation arising in the experiments. The uniform distribution (Figure Ib) occurs when $\mu(k+1)/\mu(k) = 1$ for all k ; that is, when $P(k, k+1) = P(k+1, k)$ for all k . But this is easily calculated and requires that $\epsilon = (1 - \delta)/(N - 1)$.

If then $\epsilon < (1 - \delta)/(N - 1)$, that is, if ϵ is small enough, the distribution has the form shown in Figure Ia. Two things are worth noting about the process. First, no specific assumption about the size of δ is necessary to obtain the distributional form of Figure Ia, except that it be strictly less than one. Thus, no assumption is needed about how "persuasive" individuals are. All that is needed is that the probability of self-conversion be relatively small. Second, although persuasiveness is independent of the number in each group, the probability, a priori, that a majority, once established, will decrease, diminishes with the size of that majority. This is important in what follows, since it implies that large majorities will tend to be stable, at least for a certain time.

Examples of the evolution of the process for different values of

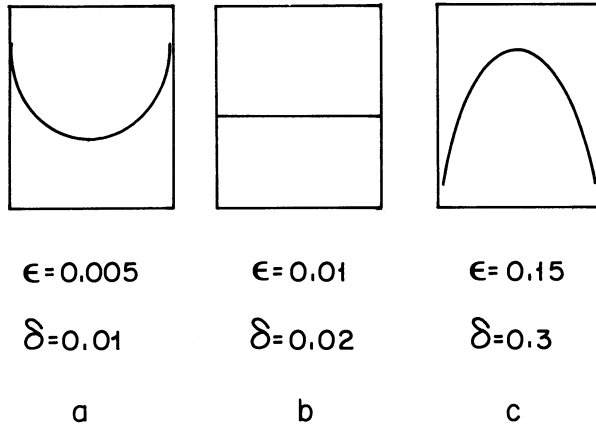


FIGURE I

Equilibrium Distributions for the Model with State Space $\{0, 1, \dots, N\}$ with Three Different Values of ϵ and δ and $N = 100$

ϵ and δ are shown in Figure II. When the probability ϵ of self-conversion is relatively high, and $1 - \delta$, the probability of being converted by another agent is relatively low, as in Figure IIa, the state k/N of the system fluctuates around one-half, (that is, 50 of the 100 individuals simulated are in each of the two groups). However, in Figure IIb, where the probability of self-conversion is very low and the probability of being converted by another agent is high, the system spends little time around the value of one-half and a great deal of time in the extremes (that is, with nearly 100 individuals in one of the groups). Although the average value of the system over the period is about one-half, this is not really important, since it spends so little time at that value.

To see exactly how the process evolves when the number of agents becomes large, consider the asymptotic form of μ when N becomes large and ϵ becomes small. In particular, choose ϵ for each N such that $\epsilon N < (1 - \delta)$. In this case μ can be approximated by a continuous distribution $f(x)$ on the unit interval; i.e., where $x = k/N \in [0, 1]$.

Thus, let $N \rightarrow \infty$ and $\epsilon = \alpha/N$ and $\delta = 2\alpha/N$. Redefine μ as $f(k/N)$, and consider the continuous limit distribution f as $N \rightarrow \infty$. Then we have the following.¹⁰

10. This result was proved by Hans Föllmer.

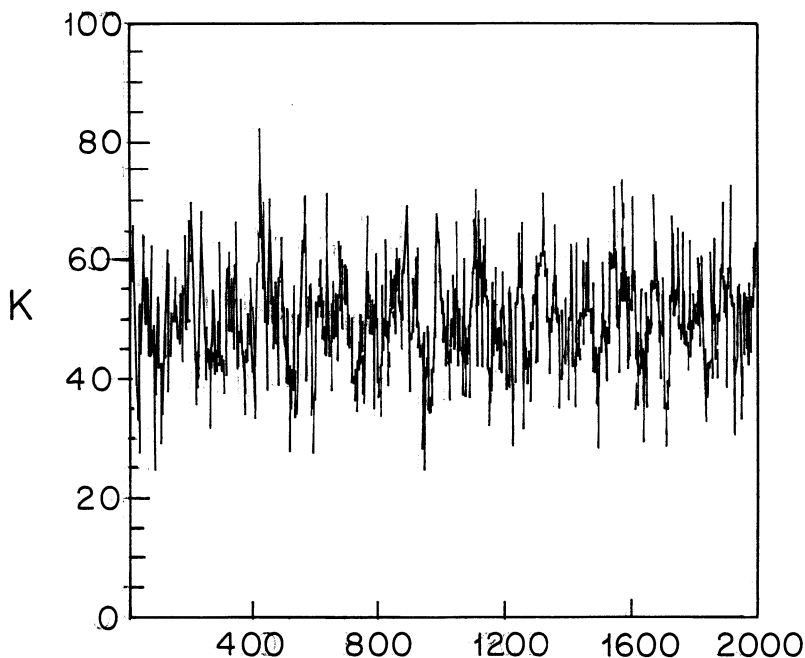


FIGURE IIa

100,000 meetings, every fiftieth plotted, $\epsilon = 0.15$, $\delta = 0.3$.

PROPOSITION. f is the density of a symmetric Beta distribution; i.e.,
 $f(x) = \text{const } x^{\alpha-1}(1-x)^{\alpha-1}$.

Proof. For N large we have

$$\frac{\mu(k+1) - \mu(k)}{\mu(k)} \approx \frac{f(k/N + 1/N) - f(1/N)}{f(k/N)}$$

and hence

$$N \frac{\mu(k+1) - \mu(k)}{\mu(k)} \approx \frac{f(k/N + 1/N) - f(k/N)}{1/N f(k/N)}.$$

However, as $N \rightarrow \infty$, this right-hand term is just $f'(x)/f(x)$. Furthermore, since by assumption $\epsilon = \alpha/N$ and $\delta = 2\alpha/N$, substituting from (2), keeping k/N constant, and letting $N \rightarrow \infty$, we have that the

$$\lim_{N \rightarrow \infty} N \frac{\mu(k+1) - \mu(k)}{\mu(k)} = \frac{f'(x)}{f(x)} = \frac{(\alpha-1)(1-2x)}{x(1-x)},$$

and this completes the proof.

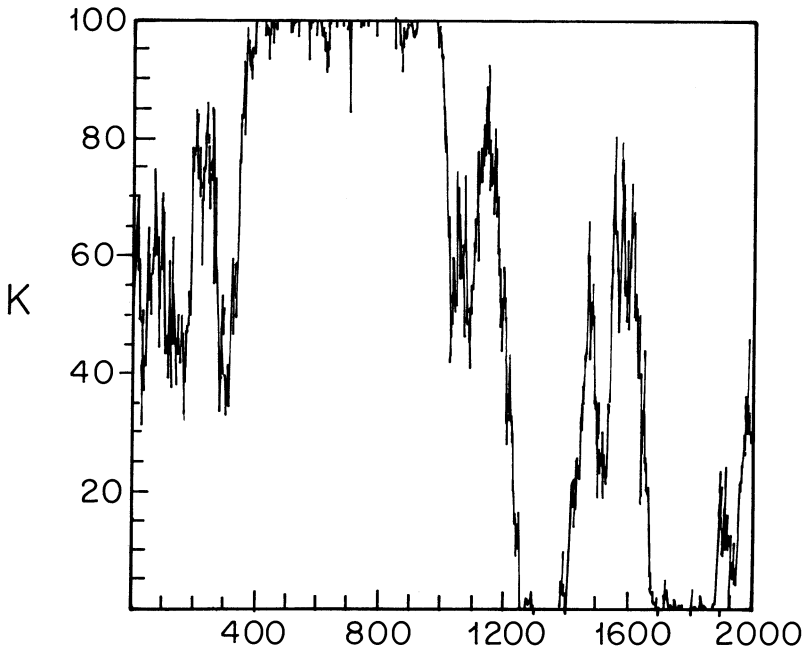


FIGURE IIb
100,000 meetings, every fiftieth plotted, $\epsilon = 0.002$, $\delta = 0.01$.

In concluding the presentation of the model, it is important to emphasize one thing. The stochastic process presented here gives the probability of moving from one state to another, where a state is defined by the proportion of ants exploiting each source. None of these states is, itself, an equilibrium. The only meaningful equilibrium is the *equilibrium distribution of the process*, that is, the proportion of time it spends in each state. This is not then a situation with multiple equilibria, in the normal sense, since *every* state is always revisited, and there is no convergence to any particular state.

OBSERVATIONS

An important observation is that the characteristics of the process just modeled might be thought of as being due to a very special feature of the first experiment conducted by Pasteels et al. The apparently innocent assertion that the two food sources are *identical* is not in fact really correct, although even to those

sophisticated ant species that lay a chemical trail in proportion to their observation of the richness of the source this would appear to be the case. However, a little reflection shows that the difference between stock and flow is crucial here. As more ants feed at a source, the experimenter has to supply more food to that source in order to maintain it at the same level. Thus, feeding here is self-reinforcing: the more ants, the greater the flow of food. This, for ants, is a highly artificial situation, although no doubt one that a colony would be happy to encounter. However, in the experiments with one food source and two symmetric bridges leading to it, this objection is removed. In any event, in either of these frameworks, an ant will always contribute the same to total welfare, whichever source he goes to. There is no tendency for returns to diminish as exploitation increases, and this explains, in part, the source of the instability. While unlikely in the ant world, such a feedback situation is common in certain markets. Indeed, it may well happen that there is a positive feedback, in the sense that following the majority actually increases marginal benefit to the individual. This reinforces the characteristics of the original model.

In confining my attention to the particular structure of the entomologists' experiments, I have omitted many aspects of reality. Generalizing to a larger number of sources would not change the analysis, but if these sources arrive and then disappear, the model would become more complicated. Searching for new sources then becomes important, the problem becomes more complex, and its dynamic solution less clear. In this case, however, the role of the "lost ants" emphasized by Deneubourg et al. [1987b] becomes important.

MARKETS

Having looked in some detail at the source of ants' asymmetric behavior, let me now look at the idea of recruitment or contagion in the context of some economic examples. The simplest way to do this is to mention again the principal features of the ant process and see how these correspond to particular aspects of economic models.

The first feature of the ant model is that it involves agents making different choices. These choices may be made on the basis of different tastes, different expectations, or the awareness of some externality, for example. There are many examples in the literature

of agents being grouped in this way into different "types,"¹¹ and I shall discuss some of these.

The next feature is that agents "recruit" other agents to their particular choice. This "recruitment" may take three forms. First, an agent may persuade another of the superiority of his choice either because of better information or a better knowledge of the functioning of the market. Second, the very fact that the first agent makes a particular choice may lead, through externality, to the second agent concurring in that choice. Third, there may be a general externality of the Keynesian "beauty queen" type or resulting from technological spillovers for example.

Lastly, the process is intrinsically dynamic. It stays in one "regime" for a considerable period before switching to another. In terms of standard economic models this might, loosely speaking, be thought of as moving from one equilibrium to another, though formally this is not really correct.

I shall first mention three economic examples that have a very close family relationship to the ants process and shall then consider other examples that can be modeled in the same way.

Becker's [1991] restaurant example, mentioned previously, corresponds most closely to the results for the ants experiments, and the ants model can be applied directly. It is enough for an individual who is going to dine at one restaurant to suggest to another that he do the same. This corresponds to tandem recruiting in ants. If both derive pleasure from each other's company and furthermore continue to dine at the same restaurant until one of them meets someone who dines at the other, then this corresponds to the ants process and will lead to polarization. Becker himself explains the concentration of diners at one restaurant by an externality arising from the greater pleasure experienced by eating at the more popular of the dining places. He uses this externality to derive an asymmetric equilibrium but does not explain how it is attained. The ant model, particularly with trail recruitment, could be applied to this example, and such a general externality, while not necessary, could be incorporated by having the probability, $1 - \delta$, of conversion to the majority increase with the size of the majority. This would make the process more extreme.

Another example from the study of evolutionary games by Foster and Young [1990] involves a similar mechanism. In their

11. A "type" may be defined by some characteristic that leads to a particular choice or by the choice itself.

case, individuals are randomly matched and play a Prisoner's Dilemma game against each other for a random length of time. Each individual plays a pure strategy, and the proportion of those playing a particular strategy varies with the success of that strategy; i.e., there is recruitment to successful behavior. The introduction of a small random element, the arrival of new individuals who replace some old ones, "self-conversion," leads to precisely the sort of random fluctuations yielded by the ant process, as opposed to the simple convergence to cooperation which, it has been claimed, occurs without perturbation.

Recently, a series of economic models using, as a basis, a stochastic urn type process (see, e.g., Arthur [1989] and David [1985]) similar to the ant process have been used to explain technological progress. These involve the idea that there is an externality from adopting a technology used by a majority of firms. New firms are explicitly "recruited" to one technology or the other. However, the arrival of new firms in these models leads to rather different outcomes than those described here. In particular, the models developed by Arthur et al. [1985] exhibit convergence to a particular state. This sort of process involving a constantly growing population and the equilibria associated with it may well be more appropriate for the study of innovation in which one technology eventually dominates an industry after a period of fluctuations as the number of firms grows.

Yet, in the case of other markets, it seems more reasonable to consider the switching of behavior within a given population. It is not a new idea to develop models in which there are agents of different types or with different views and to introduce processes that involve "contagion," "mimicking," or "herding," and that can be thought of as corresponding to recruitment in the ants model. A recent example is the paper on "Bulls, Bears and Market Sheep" by Day and Huang [1989]. The epidemic view is emphasized by Eichengreen and Portes [1987] who say: "Indeed epidemiological metaphors like fever and contagion feature prominently in the literature on financial crises." This sort of diffusion of opinion is discussed at length by Shiller and Pound [1986]. They explicitly discuss classical epidemic models such as those of Kermack and McKendrick [1927] or Bailey [1975]. They make the point that direct "interpersonal communication among peers seems to produce the kind of attention and reassurance that leads to changes in behaviour." Orléan [1990] considers bubbles in financial markets arising from what he calls "mimetic contagion" and Topol [1990]

develops a model in which agents obtain information held by other agents, and this also produces an epidemic type of effect. In all of these models the notion of "recruitment" or "contagion" plays an explicit role.

There are many other models in which differences of opinion play an important role (see Varian [1987]), to which the notion of "recruitment" could be applied. Sentana and Wadhvani [1992] have a model with "smart" traders and "feedback" traders using Black's [1988] term. The number of traders following each strategy could be made to follow the ants process with the probability of conversion depending on the relative success of each group. Frankel and Froot [1986] consider an example in which there are two types of traders: "chartists" and "fundamentalists." In their model, although the proportion of "chartists" and "fundamentalists" does not change, the weight assigned to their views by portfolio managers does. It would seem more natural, however, to use something like the ants process to model people's opinions themselves as changing. De Long et al. [1991] have a model where there are rational sophisticated traders and "noise traders" and the proportion of noise traders rises when they are making higher returns than sophisticated traders. This could be thought of as "recruitment" to a more successful strategy. Scharfstein and Stein [1990] have "smart" and "dumb" managers, and the proportion of these could be made to vary as a result of interaction and relative success. In the last two cases there is a difficulty. How could "smart" managers be persuaded to become "dumb?" In De Long et al. how could rational sophisticated traders be turned into mistaken "noise" traders even if the latter earn more?¹²

This raises the question of rationality in recruitment models in general. Recruitment will make sense where there is an externality produced by behaving in the same way as the recruiter, as in the case of tandem recruitment, or where there is a general externality in which case the individuals may be thought of as sampling the majority view through their meetings. In the examples of financial markets, the rationality of behaving with everyone else may be questioned. In some models expectations are self-fulfilling when everyone is in agreement. This is by no means always the case. In the simplest version of the Frankel-Froot model (used by Kirman [1991]), for example, it is not true, even when the market contains

12. The problem here is that the *ex ante* utility of the rational agents is higher than that of the noise traders, so it is not clear why the number of the latter should expand.

only chartists, that expectations are rational.¹³ However, Black [1988] shows that in a model in which agents have a degree of risk aversion that declines with wealth, a positive feedback trading strategy may be wholly rational. It could be argued that in models in which the ants process is appropriate individuals are not in general fully optimizing. Since they know that at some point, another market view will predominate, they should hedge against this. Two arguments, one theoretical and one empirical, limit the force of this criticism when market behavior is thought of as being described by the ants model. First, since the process is Markov, the expected time to switch from one extreme state to the other is unmodified by the length of time spent in such an extreme state. Furthermore, the consequence of a change may be difficult to predict. In a model in which there are "fundamentalists" and "chartists" and the fundamentals follow a random walk, neither the direction nor the magnitude of the result of a change in the majority view will be predictable. Second, empirical evidence from the foreign exchange market, for example, suggests that most positions taken are very short; indeed, many are cleared daily. This may well mean that the agents involved are not solving the full intertemporal maximization problem, but does suggest that the sort of behavior involved in the ants model may be consistent with empirical observations.

Furthermore, while it is possible to build models of markets in which herding together on certain views or choices is fully rational, the transition phase from one extreme to another may, in some such models, violate rationality. However, in the ants process, the switches are so rapid that it would be difficult to adapt expectations, through learning, to reflect the intermediate situation.

A further point is in order. I have insisted on the equilibrium in the ants model as being the limit distribution of the stochastic process involved. However, if one tries instead of modeling the process of interaction, to solve for a static equilibrium, as Becker did in his restaurant example, then in some models the ants process will spend most of its time in one or another of these equilibria. Thus, the process can be reconciled with the more static notion of multiple equilibria and provide an explanation for switches from one to the other. Indeed, if one thinks of a noncooperative game in which the Nash equilibria consist of

13. Paul Krugman pointed this out to me.

everybody playing the same strategy, then the model would pass from one to another such equilibrium as the game was repeated over time.

Last, if the ant process is a reasonable model of behavior in some asset markets, it has consequences for empirical work. It leads to the sort of regime switches suggested by Hamilton [1989], though the characteristics of these regimes might be very different from those he specifies. In his model, regime switches are the result of exogenous shocks, while here they are endogenous. As Evans [1991] has pointed out, standard tests will fail to detect the presence of periodically collapsing bubbles in asset prices. The ants model will generate such bubbles. Furthermore, Diba and Grossman's [1988] argument that bubbles must be perpetually explosive does not hold since individuals in the ants model do not persist indefinitely in the views that would produce such an explosion.

CONCLUSION

The model presented in this paper explains the apparently strange behavior of ants in a number of experiments and provides a different way of looking at closely related phenomena in economic markets such as Becker's restaurant example. This simple type of recruiting model leads to the evolution of quite complicated dynamics as a result of rather simple individual behavior. Such "self-organizing" models have been used in other disciplines (see Nicolis and Prigogine [1977]) and in economics (see Lesourne [1992]).

It should be observed that the type of interaction in the ants model does not depend on specifying any proximity of agents, i.e., those who are more likely to meet with each other. The random encounters specified are thus similar to those envisioned in much of the searching and matching literature (see, for example, Diamond [1989]). This approach could be extended to model explicitly the communication network and to study the modification of opinion within this framework, using the Ising model, for example. This approach was first explored in a general market by Föllmer [1974] and more recently by Durlauf [1989], and it would be interesting to see what effects it would have on the phenomena studied here.

The most important feature of the process suggested in this paper is that there is perpetual change. Many models are developed

with the specific intention of finding a steady state to which an economy or market will finally converge or of defining a static equilibrium. Yet, for example, financial markets are often thought of as being characterized by periodic switches of the collective mood of investors. Such switches in the ant model are, unlike those in many models, not driven by exogenous shocks. In conclusion then it seems, paradoxically, that this model has perhaps more to teach us about the way in which economic agents act than about the normal behavior of ants.

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE, ITALY

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