The Origin of Predictable Behavior

Ronald A. Heiner

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By RONALD A. HEINER*

Despite vigorous counterargument by its proponents, optimization theory has been persistently attacked as an acceptable explanation of behavior. In one form or another, these attacks repeat the oldest critique of economics; namely, the ability of agents to maximize successfully. Over the years, this critique has taken various forms which include information processing limitations in computing optima from known preference or utility information, unreliable probability information about complex environmental contingencies, and the absence of a well-defined set of alternatives or consequences, especially in an evolving world that may produce situations that never before existed.

These complaints are not new to economics. Indeed, they have been present during the very intellectual sifting process that produced neoclassical optimization and general equilibrium theory. Thus, if we are to further elaborate this critique of conventional theory, the basic issue is whether there is anything new that is worthy of attention by someone well versed in standard tools and concepts. Are we simply advancing more refined or cleverly argued versions of older critiques, or extensions of them to areas not previously emphasized?

Such arguments would still represent an attack on the basic rationality postulate of economics (that agents are able to maximize), but without providing a clear alternative to traditional optimization theory. However plausible these arguments might be, ultimately they must be set aside by someone desiring a theoretical understanding of behavior, unless they lead to another modeling structure whose analytical ability can be explored and compared with existing optimization theory.

Another argument focuses on the desire to understand the "real" dynamic processes that actually generate observed behavior. In contrast, optimization is thought of as a surrogate theory based on false assumptions about agents' capacity to maximize. Thus, it can be defended only in terms of empirical testability, without really illuminating the underlying processes determining behavior.

Nevertheless, even if this view was fully accepted, it is unlikely by itself to cause a major shift away from conventional thinking. The reason is that evolutionary processes have long ago been interpreted as one of the key mechanisms tending to produce optimizing behavior; or conversely, optimizing models will predict the behavior patterns that will survive in an evolutionary process tending to select relatively superior performance.[1] The latter interpretation is in fact one of the dominant justifications for standard models against the criticism of unrealistic assumptions (i.e., the surviving agents of a selection process will behave "as if" they are able to maximize).[2]

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*Department of Economics, Brigham Young University, Provo, UT 84602. I am indebted to Axel Leijonhufvud for constant encouragement about applications to economics, and for numerous stylistic suggestions. Harold Miller helped familiarize me with a broad range of issues across the sociobiological, psychological, and behavioral science literatures. James Buchanan provided stimulating discussion about conceptual issues. I have also benefited from the advice and criticism of Armen Alchian, Ron Batchelder, Bruce Brown, Robert Clower, Daniel Friedman, Jack Hirshleifer, Kai Jeanski, Randy Johnson, Edward Leamer, Stephen Littlechild, John McCall, James McDonald, Richard Nelson, Gerald O'Driscoll, Dennis Packard, Clayne Pope, Lionello Punzo, Ezio Tarantelli, and Sidney Winter. Needless to say, these colleagues are not responsible for inadequacy in the conceptual framework or scope of ideas presented.

[1] See in particular Armen Alchian's well-known 1950 paper, and also Sidney Winter, 1964, 1971; Jack Hirshleifer, 1977; Richard Nelson and Winter, 1974.

[2] A still used reference on the "as if" point of view is Milton Friedman's 1953 paper. Some recent journal illustrations are Benjamin Klein and Keith Leffler, 1981, p. 634; Richard Posner, 1980, p. 5; Hirshleifer, 1977, p. 50; Nelson, 1981, p. 1059. The ultimate extension of this view is to claim not that agents are able to maximize (select most preferred actions), but rather that any ob-

In spite of the above conclusions, I believe there is a viable alternative to standard models—one that directly comes to grips with the persistent critiques of economic theory and which broadens our analytical horizon to encompass a much wider range of phenomena.

In particular, I believe that observed regularities of behavior can be fruitfully understood as "behavioral rules" that arise because of uncertainty in distinguishing preferred from less-preferred behavior. Such uncertainty requires behavior to be governed by mechanisms that restrict the flexibility to choose potential actions, or which produce a selective alertness to information that might prompt particular actions to be chosen. These mechanisms simplify behavior to less-complex patterns, which are easier for an observer to recognize and predict. In the special case of no uncertainty, the behavior of perfectly informed, fully optimizing agents responding with complete flexibility to every perturbation in their environment would not produce easily recognizable patterns, but rather would be extremely difficult to predict. Thus, it is in the limits to maximizing that we will find the origin of predictable behavior.

If the view taken here is correct, it means that predictable features of behavior do not arise from optimizing with no uncertainty in choosing most preferred behavior; and furthermore, evolutionary selection processes will in general not produce approximations to optimizing behavior. Rather, predictable behavior will evolve only to the extent that uncertainty prevents agents from successfully maximizing.

In the following, I sketch the line of thought and the observations which have led me to this conclusion, and briefly outline the elements of a modeling structure that can be applied to a wide range of topics. A number of applications are presented to illustrate the range of issues unified by the analysis, which is far broader than the reader is likely to anticipate without explicit examples.

I. Problems with the Methodological Arguments for Optimization

Optimizing with full ability to select most preferred behavior is rarely justified as an empirically realistic assumption. Rather, it is usually defended on methodological grounds as the appropriate theoretical framework for analyzing behavior. The chief defense is empirical fruitfulness in generating unfalsified predictions.

We might criticize this testability criteria with modern philosophy of science arguments.[3] Nevertheless, a long list of confirmed predictions would be persuasive evidence in favor of a theory. Yet, it is just here that we have a problem. Suppose we really asked to see the list of clearly implied, unambiguous predictions that have been derived from our basic optimization models.

The answer to this query, one that would be admitted by many practitioners in the field, is that at best we have developed a very short list. All sorts of behavior is consistent with or plausibly suggested by optimization models, yet still not predicted by them. For example, optimization models have never been able to imply the Law of Demand (buying less of a commodity when its price rises), which is probably the oldest and simplest behavioral regularity in economics. Of course, we can use the theory to argue it is unlikely that a negative income effect will outweigh the pure substitution effect, especially for goods that absorb a small fraction of a person's income.[4] The acceptance of this view is heavily influenced by our belief in the

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served behavior is consistent with the maximization of some function. This latter formulation is probably incapable of either theoretical or empirical disproof (see Lawrence Boland, 1981).

[3] See for example, B. Caldwell, 1982; also Karl Popper, 1969; Imer Lakatos and Alice Musgrave, 1970.

[4] I was told in a graduate price-theory class by Armen Alchian that the only clear implication of consumer theory is that with more income, a consumer will buy more of at least something. Harold Demsetz, when informed of this story, responded by saying, "well then just define holding cash balances as saving, and we have no testable implications, just one mass of tautologies." See also the opening remarks of Kenneth Arrow, 1982, p. 1; and the closing remarks of Vernon Smith, 1982, p. 952.

empirical validity of the Law of Demand. Yet, regardless of how cleverly we interpret a Slutsky equation, no clear prediction is implied.

We could pursue a number of other examples, all of which suggest that conventional models have never really been fruitful in generating testable implications.[5] For this reason, I believe allegiance to these models is not grounded in the claim of empirical fruitfulness, despite the usual rhetoric that this is the case. Rather, it is based on a deeper methodological issue about the effect of dropping the basic rationality assumption.[6]

Think of this issue in the following terms. Standard choice theory tries to explain behavior by matching the "competence" of an agent with the "difficulty" in selecting most preferred alternatives. It assumes for the purpose of theoretical explanation that there is no gap between an agent's competence and the difficulty of the decision problem to be solved (hereafter called a "*C-D* gap").[7] On the other hand, the presence of a *C-D* gap will introduce uncertainty in selecting most preferred alternatives, which will tend to produce errors and surprises. Such mistakes are by their nature unpredictable and erratic. Yet, it is only the systematic elements of behavior that we can hope to scientifically explain and predict. Thus, in order to theoretically isolate the systematic tendencies in behavior, we must exclude a *C-D* gap, no matter how implausible or unrealistic this might be.[8]

This perspective has been a dominant factor in loyalty to traditional optimizing concepts. Nevertheless, I believe it is mistaken, and that essentially the opposite view is true. To see why, think of the above argument as an empirical hypothesis about the effect of "irrationality"; namely, that the additional uncertainty from a larger *C-D* gap will generate more errors and surprises, thus producing more irregularity and noise in behavior. There are numerous complicating factors about how to test this hypothesis, especially how to measure a person's *C-D* gap. We can avoid these problems by broadening our horizon to consider an interspecie comparison between humans and other animals. Here it is clear without detailed argument that the average *C-D* gap of other animals is larger than that of humans.[9] Yet when we observe nonhuman species, the overwhelming qualitative impression is not one of greater irregularity, but instead of greater rigidity and inflexibility of behavior. Pattern is not more

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[5] Some other examples are: second Law of Demand, short- and long-run supply dynamics, risk aversion, time preference, self-interest, liquidity preference, expectation lag and adjustment structures, price-taking behavior, oligopoly strategic patterns, relative price vs. quantity elasticities, relative income-consumption elasticities, etc. The so-called "laws of supply and demand" have probably been the most empirically useful tools in economics (both in formulating simple hypotheses about market responses to parameter changes, and in providing the basic structural equation system used in modern econometric model building). Yet, these simple laws are not derivable from basic optimization concepts, and thus empirical analysis derived from them does not confirm these concepts.

[6] Without going into any details, I would also like to mention a large literature in behavioral psychology about the *matching law* (Richard Herrnstein, 1961, 1964, 1970), which has cast doubt on the validity of traditional maximization theory to explain behavior under certain reinforcement schedules. See P. de Villiers, 1977, for a summary of earlier experimental results, and for more recent experiments with human subjects, see C. M. Bradshaw, E. Szabadi, and R. Bevan, 1976; William Buskist and Harold Miller, 1981. For recent articles about the validity of maximization, see Herrnstein and Gene Heyman, 1979; Heyman and R. Duncan Luce, 1979; Howard Rachlin, John Kagel and R. C. Battalio, 1980; D. Prelec, 1982; and for recent experiments in which matching has dominated maximizing behavior, see Herrnstein and William Vaughan, 1980; Vaughan, 1981; John Mazur, 1981.

[7] Posing the problem in terms of a gap in an agent's decision competence relative to the difficulty of a decision problem was suggested to me by Axel Leijonhufvud.

[8] For a recent example of this view, see Jack Hirshleifer's 1980 price theory text, p. 9. A similar argument is used to justify "rational expectations" equilibria. See, for example, Robert Lucas, 1981, pp. 125, 223–24; and Robert Cooter, 1982b, p. 232.

[9] For analysis of cognative differences between humans and animals, and the evolution of intelligence, see M. Konner 1982, David Premack, 1983; P. Rozin, 1976; Carl Sagan, 1977; Harry Jerison, 1973; R. Masterton, William Hodos, and Jerison, 1976.

difficult but rather easier to notice in animals than in humans.

This qualitative difference between humans and other animals is obviously not new to us; it having long ago been given the capsulized description of "instinct." Still, I do not believe that we have recognized the significance of this general pattern for evaluating and constructing theoretical models of behavior. This pattern is telling us that it is not the absence of a *C-D* gap, but rather its presence which conditions regularity in behavior.

Why should this be the case? Think of an omiscient agent with literally no uncertainty in identifying the most preferred action under any conceivable condition, regardless of the complexity of the environment which he encounters. Intuitively, such an agent would benefit from maximum flexibility to use all potential information or to adjust to all environmental conditions, no matter how rare or subtle those conditions might be. But what if there is uncertainty because agents are unable to decipher all of the complexity of the environment (i.e., there is uncertainty due to a *C-D* gap)? Will allowing complete flexibility still benefit the agents? For example, if we could somehow "loosen up" the behavior of an organism without affecting its perceptual abilities, would it compete more effectively for food or mating partners than before?

I believe the general answer to this question is negative: that when genuine uncertainty exists, allowing greater flexibility to react to more information or administer a more complex repertoire of actions will not necessarily enhance an agent's performance. Even if we confine our attention to human behavior, we can find evidence for this proposition, especially in highly competitive situations with noticable elements of complexity relative to human information processing and other perceptual abilities.

For example, in sequential replication games of the basic prisoner's dilemma (see Robert Axelrod, 1980a), round robin competition identified the simplest strategy (the tit for tat strategy) as dominant over all of the others (submitted by persons in economics, mathematics, psychology, political science, and sociology).[10] Moreover, the worst performance came from the strategy that specified the most "sophisticated" learning and probability adjustment process to guide its behavior.[11] Another example is the publishing history on strategies to win at blackjack. Earlier books emphasized sophisticated card-counting, bet-variation methods (see especially Edward Thorpe's book, *Beat the Dealer*). However, while no one has challenged the mathematical validity of these earlier more complex methods, their actual use resulted in worse performance by most persons attempting to use them (which generated sizable unexpected profits to the casinos).[12] As a result, later books have steadily evolved toward more rigidly structured methods (for example, two recent books are *No Need to Count* and *Winning Casino Blackjack for the Non-Counter*).[13]

Consider also Rubic's cube. There are over 43 trillion possible initial positions from which to unscramble the cube. Minimizing the number of moves to solve the cube would

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[10] For a description of the tournament and its results, see Axelrod, 1980a. The top strategies were all variants of the simple tit for tat strategy, but none were able to beat the basic strategy (in particular, see pp. 8 and 18). When a second round of the tournament was run, tit for tat still won even though numerous more complex strategies were submitted (see Axelrod, 1980b). For recent analytical analysis on this issue, see David Kreps et al., 1982.

[11] Axelrod describes the worst of the submitted strategies in the first round:

> This rule has a probability of cooperating, *P*, which is initially 30% and is updated every 10 moves. *P* is adjusted if the other player seems random, very cooperative, or very uncooperative. *P* is also adjusted after move 130 if the rule has a lower score than the other player. Unfortunately, the complex process of adjustment frequently left the probability of cooperation in the 30% to 70% range, and therefore the rule appeared random to many other players. [1980a, p. 24]

[12] For example, see Richard Canfield, 1979, pp. 19, 37–38, 144–47, 150.

[13] Some of the major books in order of publication are: Thorpe, 1962; Lawrence Revere, 1969; John Archer, 1973; Ian Anderson, 1975; Virginia Graham and C. I. Tulcea, 1978; Canfield, 1979; Leon Dubey, 1980; Avery Cardoza, 1981. See Canfield's book, especially pp. 11–12, 16–19, 37–38, 60–61, 62–65. See also Dubey, pp. 11–12, 17–19, 64, 165–66, 168, 172.

require an extremely complex pattern of adjustment from one particular scrambled position to another. Yet, if mistakes are made in trying to select a short cut, the cube will remain unscrambled indefinitely. Consequently, cube experts have developed rigidly structured solving procedures that employ a small repertoire of solving patterns to unscramble the cube. These procedures follow a predetermined hierarchical sequence that is largely independent of the initial scrambled position.[14] However, they almost always require a much longer sequence of moves than the minimum number needed to unscramble the cube. Thus, they are not an approximation to the enormously complex behavior that would be exhibited by an omniscient agent who could immediately select the shortest sequence for each scrambled position. Note also that the information needed to behave in this fashion (present in the initially scrambled patterns on the face of the cube) is costless to observe and instantly available; one need only look at the cube while unscrambling it.

Finally, consider the research of Herbert Simon over a number of years,[15] which has shown that decision makers in a variety of contexts (including both individual and organizational behavior) systematically restrict the use and acquisition of information compared to that potentially available. For example, Simon's idea of "satisficing" represents a feedback mechanism between an internal target variable (called the "aspiration level") and the scope of information evaluated to implement that target. Over time, the feedback process will both guide and discipline the use of information and the resulting behavioral complexity that will evolve within a person or organization. Other learning, cognitive processes, and decision algorithms can be similarly interpreted.

The above examples suggest that allowing flexibility to react to information or to select actions will not necessarily improve performance if there is uncertainty about how to use that information or about when to select particular actions. Thus, an agent's overall performance may actually be improved by restricting flexibility to use information or to choose particular actions.

II. How Uncertainty Generates Flexibility Constrained Behavior

The argument to this point has suggested that uncertainty due to a *C-D* gap may generate flexibility constrained behavior. The next step is to characterize more precisely how such uncertainty might produce this result. To do so, a simple "reliability condition" is developed that specifies when to allow or prohibit flexibility to select potential actions or to use information that might prompt particular actions to be chosen.

Two major classes of variables determine the uncertainty resulting from a *C-D* gap. The first are environmental variables (denoted by $\mathbf{e}$) which determine the complexity of the decision problem to be solved by an agent (including the complexity of environmental situations potentially encountered; the relative likelihood of these situations; and the stability of the relationships that determine possible situations and their relative likelihood). The second are perceptual variables (denoted by $\mathbf{p}$) which characterize an agent's competence in deciphering relationships between its behavior and the environment.[16] Thus, the $\mathbf{p}$ and $\mathbf{e}$ variables determine the "gap" between competence and difficulty (the *C-D* gap) which produces

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[14] In following a typical set of instructions, one selects a side of the cube and begins by placing either its corner or its edge pieces in their proper positions; next, one places in sequence the pieces in the middle section; finally, one repositions the pieces on the remaining, opposite side of the cube (see Czes Kosniowski, 1981). Other similar procedures include D. Taylor, 1980; James Nourse, 1980; Patrick Bussert, 1981; B. W. Barlow, 1981.

[15] For example, Simon, 1955, 1959, 1969, 1976, 1978, 1979a; A. Newell and Simon, 1972.

[16] In economics, the $\mathbf{p}$ variables might describe mistaken perceptions about what is more preferred, information processing errors, unreliable probability information, etc.; while the $\mathbf{e}$ variables describe the complexity and volatility of both present and future exchange, legal, and political conditions. In biology, $\mathbf{p}$ might refer to the sensory and cognitive mechanisms of an organism, and $\mathbf{e}$ to the structure and stability of ecological relationships involving competition for food or mating partners.

uncertainty about how to use information in selecting potential actions. In general, there is greater uncertainty as either an agent's perceptual abilities become less reliable or the environment becomes more complex.

These relationships are formally represented as a vector-valued function, $\mathbf{U} = u(\overset{-}{\mathbf{p}}, \overset{+}{\mathbf{e}})$, which describes the structure of uncertainty from a *C-D* gap characterized by $\mathbf{p}$ and $\mathbf{e}$. The signs above $\mathbf{p}$ and $\mathbf{e}$ signify that uncertainty is negatively related to an agent's perceptual abilities, and positively related to the complexity and instability of the environment.

Now consider a conceptual experiment about an agent initially limited to a fixed repertoire of actions, and ask whether allowing flexibility to select an additional action will improve the agent's performance. Under certain conditions, the new action will be more preferred than the other actions in the agent's repertoire (the "right" time to select the action), but otherwise it will be less preferred than one of those actions (the "wrong" time to select the action). Depending on the likelihood of different situations produced by the environment, the probabilities of the right or wrong time to select the action are written as $\pi(\mathbf{e})$ and $1 - \pi(\mathbf{e})$, respectively.

Because of uncertainty, the agent will not necessarily select the new action when it is the right time to do so. The conditional probability of selecting the action when it is actually the right time is written $r(\mathbf{U})$, where the likelihood of so doing depends on the structure of uncertainty, $\mathbf{U} = u(\mathbf{p}, \mathbf{e})$. When this happens, the resulting gain in performance (compared to staying within the initial repertoire) is written $g(\mathbf{e})$, which depends on how the environment affects the consequences from different actions. Similarly, the conditional probability of selecting the new action when it is actually the wrong time is written $w(\mathbf{U})$, with consequent loss in performance of $l(\mathbf{e})$.

In the special case of no uncertainty, the new action would always be selected at the right time and never at the wrong time, so that $r = 1$ and $w = 0$. In general, however, the presence of uncertainty will imply $r < 1$ and $w > 0$.

We can intuitively measure the *reliability* of selecting a new action by the ratio r/w, which represents the chance of "correctly" selecting the action at the right time relative to the chance of "mistakenly" selecting it at the wrong time.[17] Greater uncertainty will both reduce the chance of correct selections and increase the chance of mistaken selections, thus causing the ratio r/w to drop (i.e., greater uncertainty reduces the reliability of selecting the new action).

Note also that $r(\mathbf{U})$ and $w(\mathbf{U})$ are not assumed to be known to an agent. The reason is that uncertainty produces mistakes about distinguishing the right from the wrong conditions to select an action, which distinction is necessary to determine the conditional probabilities of choosing an action under these two sets of conditions. For the same reason, the probability of the right situation to select an action, $\pi(\mathbf{e})$, may also be unknown to an agent. Thus, it is not assumed that an agent can tell whether a mistake has been made; nor are we necessarily dealing with situations where an agent consciously decides when to select an action. Rather, the more general issue is whether some process —conscious or not—will cause (or prevent) an "alertness" or "sensitivity" to information that might prompt selection of an action. For example, when will a person develop an alertness to potential information about whether to choose a particular action, or whether to modify a previous behavior pattern; or when will instinctive mechanisms in an organism precondition a sensitivity to certain environmental stimuli, while simultaneously blocking alertness to other potential stimuli.

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[17] The probabilities r and w can also be interpreted using Type 1 and Type 2 errors used in statistical hypothesis testing. Let the null hypothesis represent the right situation to select an action (when it is more preferred); while the alternate hypothesis represents the wrong situation for selecting it. Thus, intuitively, Type 1 errors represent *excluded benefits* from failing to respond under the right conditions, while Type 2 errors refer to *included mistakes* from still responding under the wrong conditions. If we let t_1 and t_2 denote the respective probabilities of these errors, they characterize r and w by $r = 1 - t_1$, and $w = t_2$. Thus, r equals one minus the chance excluded benefits, and w equals the change in included mistakes.

Now, with the above components, we can formulate an answer to the question posed earlier: *when is the selection of a new action sufficiently reliable for an agent to benefit from allowing flexibility to select that action.*

To answer this question we must determine whether the gains $g(\mathbf{e})$ from selecting the action under the right conditions (when it is actually more preferred) will cumulate faster than the losses $l(\mathbf{e})$ from selecting it under the wrong conditions (when it is actually less preferred). Thus, combine the above elements in the following way. Right conditions occur with probability $\pi(\mathbf{e})$, which are correctly recognized with probability $r(\mathbf{U})$; so that the expected gain from allowing flexibility to select another action is $g(\mathbf{e})r(\mathbf{U})\pi(\mathbf{e})$. Similarly, the expected loss conditional on allowing the action to be selected is $l(\mathbf{e})w(\mathbf{U})(1-\pi(\mathbf{e}))$. Accordingly, gains will cumulate faster than losses if $g(\mathbf{e})r(\mathbf{U})\pi(\mathbf{e}) > l(\mathbf{e})w(\mathbf{U})(1-\pi(\mathbf{e}))$. Hence, simple rearrangement yields the following *Reliability Condition*:

$$\frac{r(\mathbf{U})}{w(\mathbf{U})} > \frac{l(\mathbf{e})}{g(\mathbf{e})} \cdot \frac{1-\pi(\mathbf{e})}{\pi(\mathbf{e})}.$$

The left-hand side of the inequality is a *reliability ratio*, $r(\mathbf{U})/w(\mathbf{U})$, which measures the probability of "correctly" responding under the right circumstances relative to the probability of "mistakenly" responding under the wrong circumstances. The right-hand side of the inequality represents a minimum lower bound or *tolerance limit* (hereafter denoted simply by $T(\mathbf{e}) = l(\mathbf{e})/g(\mathbf{e}) \times (1-\pi(\mathbf{e}))/\pi(\mathbf{e}))$, which a reliability ratio must satisfy. That is, $T(\mathbf{e})$ determines how likely the chance of selecting an action under the right conditions must be compared to the chance of selecting it under the wrong conditions before allowing flexibility to select that action will improve performance.

We can intuitively interpret the ratio $r(\mathbf{U})/w(\mathbf{U})$ as the "actual" reliability of selecting an action, in comparison to the minimum "required" reliability specified by the tolerance limit, $T(\mathbf{e})$. The components of the Reliability Condition summarize a potentially complex set of relationships between an agent's repertoire and the structure of the environment.[18] Nevertheless, these relationships boil down to a conceptually simple answer about when to allow flexibility to select an additional action: *do so if the actual reliability in selecting the action exceeds the minimum required reliability necessary to improve performance*. Stated in its simplest notational form, this answer amounts to the condition, $r/w > T$.

The question which motivated this answer was phrased in terms of adding a new action to an agent's repertoire. However, once the Reliability Condition has been obtained we can also apply it to a range of further issues about when to allow or ignore particular actions. For example, it can be applied to dropping actions from a repertoire; namely, retain only those actions which satisfy $r/w > T$ compared to ignoring them.

We can also think of the Reliability Condition as solving a "decision" problem in which an agent determines what information he will allow to influence his behavior; or alternatively, as a "design" problem in engineering the appropriate information sensitivity of an agent. For each possible action, the Reliability Condition must be satisfied before allowing potential information to

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[18] Both the agent's repertoire and the environment may contain a large number of possibilities, and the consequences from selecting an action may vary with different environmental situations. This will also complicate how to measure an agent's performance. Regardless of how performance is measured (for example, it may involve some kind of average over actions and/or environmental conditions), $g(\mathbf{e})$ and $l(\mathbf{e})$ still represent the gain or loss in performance from correct or mistaken selections, respectively; and $r(\mathbf{U})$, $w(\mathbf{U})$ still represent the conditional probabilities of these correct or mistaken selections. The probabilities $r(\mathbf{U})$ and $w(\mathbf{U})$ also result from a complex set of relationships that determine the source and likelihood of particular errors that interact to generate these probabilities. In addition, $l(e)$ and $g(e)$ may depend on an agent's internal components, such as the morphological attributes of an animal.

The objective of this paper is to develop only the bare essential modeling elements needed for a simple analytical solution, whose structure is invariant to the above-mentioned complications. In particular, the basic form of the Reliability Condition will remain the same. Much greater detail about the analytical structure, including extensive applications to economics and other fields, is now in progress.

prompt its selection. Those actions that can be guided with sufficient reliability are permitted; those that cannot are eliminated. In this way, an agent's outward behavior is determined by his response pattern to potential information.[19]

III. Four General Implications

Now that we have the Reliability Condition, its implications in four basic areas are briefly discussed.

A. *Uncertainty Generates Rules Which are Adapted Only to Likely or Recurrent Situations*

Note a simple but important feature of the tolerance limit. For any given l/g ratio, the likelihood of wrong to right conditions, $(1-\pi)/\pi$, increases for smaller π; so that T also rises as the probability of right circumstances π decreases (see Figure 1). Thus, *an agent must be more reliable in selecting an action if the right situations for exhibiting it are less likely. Moreover, the required reliability quickly accelerates to infinity as the likelihood of right situations drops to zero.* Thus, for a given structure of uncertainty, $\mathbf{U}=u(\mathbf{p},\mathbf{e})$, which determines the reliability of selecting a particular action (i.e., which determines the ratio $r(\mathbf{U})/w(\mathbf{U})$), the Reliability Condition will be violated for sufficiently small but positive, $\pi(\mathbf{e})>0$.

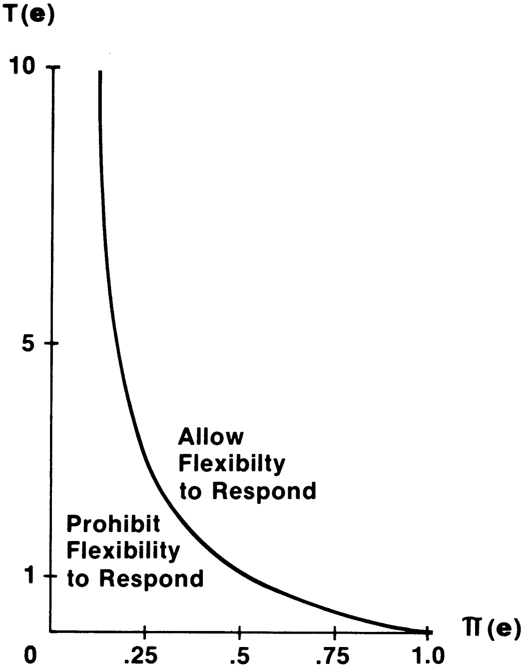

FIGURE 1

The curve shows how the tolerance limit $T(e)$ changes for a constant $l(e)/g(e)$ ratio (in this case $l/g=1$) as the probability of right conditions π varies. Note how quickly T begins to rise as π drops below .25. The curve represents a boundary of minimum reliability that must be satisfied (i.e., $r/w>T$) before responding to information will enhance an agent's performance.

This intuitively means that to satisfy the Reliability Condition, an agent must ignore actions which are appropriate for only "rare" or "unusual" situations. Conversely, an agent's repertoire must be limited to actions which are adapted only to relatively likely or "recurrent" situations. Thus, a general characteristic of such a repertoire is that it excludes actions which will in fact enhance performance under certain conditions, even though those conditions occur with positive probability, $\pi(\mathbf{e})>0$. We thus have a formal characterization of the pervasive association of both human and animal behavior with various connotations of "rule-governed" behavior, such as instinct, habits, routines, rules of thumb, administrative procedures, customs, norms, and so forth. All of these phrases refer to some type of rigidity or inflexibility in adjusting to different situations as a universal qualitative feature of behavior.

Therefore, since behavior patterns which satisfy the Reliability Condition must have this property, we will call them *behavioral rules* or simply *rules*. Note that we have been

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[19] The relationship between information sensitivity and output complexity is also recognized in cybernetics; see Norbert Weiner, 1948, and W. Ashby, 1956. A reference in organizational behavior that refers to this is Barry Staw, Lana Sanderlands and Jane Dutton: "...a fundamental principle of cybernetics..., the number of output discriminations of a system (i.e., its behavioral repertoire) is limited by the variety of information inherent in its input" (1981, p. 517).

able to derive the basic rigidity feature which justifies attributing to such behavior patterns the idea of rules. This contrasts sharply with the typical procedure of using the language of rules (often with the intent of suggesting certain connotations to the reader), yet without really justifying from a more basic theoretical structure why such terminology is appropriate.

If we use the jargon of standard economics, rule-governed behavior means that an agent must ignore actions which are actually preferred under certain conditions. Thus, as intuitively suggested above, the resulting behavior patterns are *not* an approximation to maximizing so as to always choose most preferred alternatives (i.e., behaving "as if" an agent could successfully maximize with no *C-D* gap).

In general, rules restrict behavior to only a limited repertoire of actions. Such restrictions do not assume an awareness of all the potential actions or information which are thereby implicitly ignored. Thus, no explicit decision about what potential actions to ignore is necessarily involved.

An agent need only be capable of determining when to select particular actions from a limited range of allowable alternatives. To do so does not require an ability to understand why the resulting behavior patterns evolved. This is obviously the case for animals, where we do not expect them to have an "intellectual awareness" of why they are programmed to exhibit certain behavior patterns. Yet even for humans, the general characteristic will be an inability to articulate a full understanding of why particular behavior patterns have arisen. This is implied even though human behavior is much more flexible than that of other species, and even though conscious mental processes are involved in most human behavior patterns.[20]

As a simple example involving human behavior, consider the solving methods for Rubic's cube mentioned above in Section I. The environment represents all of the different scrambled positions or "situations" which might eventuate on the face of the cube, of which there are over 43 trillion. If each situation is produced by a simple random draw from the set of possible situations, the probability π of the right situation (the appropriate scrambled position) arising for any particular solving sequence is extremely low. Assuming the l/g ratio (resulting from unscrambling the cube in greater or lesser time, or number of moves) is not close to zero, the required reliability for selecting each of these sequences will also be very high. Without this ability, the repertoire of solving patterns must be severely restricted in order to satisfy the Reliability Condition, and structured so that their use is largely independent of particular scrambled positions (i.e., they are adapted only to the recurrent features of the environment).

B. *Selection Processes do not Simulate Optimizing Behavior*

Up to this point we have thought of performance simply in terms of an agent's "preferences" about the consequences of particular actions. Now generalize its meaning to represent any factor that determines whether behavior will continue or persist in the environment encountered by an agent. This might involve a preference evaluation, competition for profits or investment capital, or possibly biological determinants of physical survival or reproductive probability. Whatever the interpretation, we can apply the Reliability Condition to determine when allowing flexibility to use potential information or to select actions will improve rather than worsen performance.

Now suppose the actual process generating behavior is an evolutionary process that tends to select relatively superior performance at any point of time. From what has already been derived, this implies that such selection processes will tend to produce rule-governed behavior that is not an approximation to always selecting actions that maximize performance. Thus, in general, evolutionary processes will *not* generate simulations to optimizing behavior. Rather,

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[20] For related comments about the legitimacy of standard psychotherapy practices, see Donald Campbell's 1975 presidential address to the American Psychological Association.

they will tend to produce rules that systematically restrict the flexibility of behavior compared to that which would be exhibited by a full optimizer in the absence of uncertainty.

As mentioned earlier, this implication directly contradicts one of the dominant justifications for assuming agents are able to optimize. Predictable behavior is not an "as if" simulation to optimizing, but rather will evolve only to the extent that agent's are unable to maximize because of uncertainty.

Generalizing the meaning of performance also implies that we are not necessarily dealing with traditional economic agents, such as consumer, firm, worker, investor, etc. Rather, we can think of an agent as any system of interacting components. For example, a system might refer to biological entities such as individual organisms, species, ecological systems, or possibly to subsystems within organisms studied in physiology or molecular biology. Still other examples might be computers or other artificial cybernetic mechanisms.

Whatever the interpretation, the Reliability Condition characterizes when to allow flexibility to use information or select actions applicable to that interpretation. For example, we might apply it to the following situations: when is it the right time to unscramble Rubic's cube by starting from a middle section rather than from one of its outer sections; when is it the right time to purchase more of a particular commodity rather than other commodities; when is it the right time to search for additional price or quality information about potential future purchasing decisions; when is it the right time for an animal to deviate from its usual foraging strategies for food; when is it the right time to cooperate by helping other individuals (i.e., when is it the right time to be "altruistic" rather than "selfish");[21] when is it the right time to modify genetic information to perpetuate traits acquired in the lifetime of a particular organism (i.e., when is it the right time to use "Lamarkian" genetic transmission);[22] or more generally, when is it the right time to use feedback from the environment to modify behavior (i.e., when is it the right time to "learn")?

C. *Weak Selection Processes May Allow Dysfunctional Behavior to Persist*

The preceding discussion implicitly assumed that selection processes would quickly eliminate relatively inferior performers. If this is actually the case, the Reliability Condition implies the evolution of behavioral rules that appropriately structure and limit the flexibility of behavior. The empirical examples that helped motivate the formal analysis also involved behavior produced in highly competitive conditions (i.e., biological competition for survival between nonhuman agents; strategies to win at blackjack, or in prisoner's dilemma games, or in Rubic's cube contests; organizations competing in exchange environments for profits or investment capital, etc.).

On the other hand, what if there is something about the environment that only sluggishly weeds out worse performers, or which only infrequently produces situations that severely punish vulnerable behavior. This possibility is fundamentally important when genuine uncertainty exists, because there is no magical element (empirically or in theory) to guarantee that only appropriately structured behavior will evolve. Indeed, the core assumption is literally the absence of ability to decifer all of the complexity of the environment; especially one whose very structure itself evolves over time.

Thus, consider an evolving world produced through a mixture of selective processes. These processes will have varying degrees of severity in reacting to differential performance between competing agents. Such a world will be a continual mixture of appropriately and inappropriately structured behavior. In some cases, weak selection processes may allow relatively dysfunctional

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[21] Hirshleifer uses "recognition coefficients" (which represent particular examples of the $r(\mathrm{U})$ and $w(\mathrm{U})$ probabilities) to determine the reliability of helping strategies in identifying other agents with altruistic traits (1982, pp. 26–29). See also W. D. Hamilton, 1964; John Maynard Smith, 1964; Robert Trivers, 1971.

[22] On the "irreversibility" of genetic translation, see Jacques Monod, 1972, pp. 104–17.

behavior to persist: possibly with worse average performance than other agents; or with slowly dwindling performance over time; or with vulnerable performance that awaits only the next infrequent but severe test to challenge its further persistence in the environment.

This is clearly a different view from trying to comprehend the world as continually tending toward optimizing behavior. Indeed, we may be able to explain major features about the structure, occurrence, and error patterns of dysfunctional behavior. Only one class of possibilities is mentioned here, and briefly reconsidered at the conclusion of this paper. In particular, we can analyze the pattern of vulnerable behavior arising from political institutions, especially in the form of dysfunctional complexity in trying to manipulate the outcomes resulting from exchange competition. Specific instances of this issue have had a long history in economics about the scope of government regulation, and the debate over discretionary vs. rigid monetary policy.[23]

D. *Greater Uncertainty will Cause Rule-Governed Behavior to be More Predictable*

What is the effect of *greater* uncertainty on rule-governed behavior? In general, greater uncertainty (from either less reliable perceptual abilities or a more unpredictable environment) will both reduce the chance of recognizing the right situation to select an action, and increase the chance of not recognizing the wrong situation for selecting it. That is, greater uncertainty will both reduce $r(\mathrm{U})$ and increase $w(\mathrm{U})$, so that the reliability ratios, $r(\mathrm{U})/w(\mathrm{U})$, of particular actions will drop.

As these ratios drop, some of them may no longer exceed their respective tolerance limits, resulting in violations of the Reliability Condition. More violations will occur as uncertainty becomes more pervasive. Thus, greater uncertainty will cause behavioral rules to be more restrictive in eliminating particular actions or response patterns to potential information. This will further constrain behavior to simpler, less sophisticated patterns which are easier for an observer to recognize and predict. Therefore, *greater uncertainty will cause rule-governed behavior to exhibit increasingly predictable regularities*, *so that uncertainty becomes the basic source of predictable behavior*.

This is the most important implication of my analysis, one that has far-reaching implications across a diverse range of fields. It also has important implications for how we have been trying to model behavior. It implies that genuine uncertainty, far from being unanalyzable or irrelevant to understanding behavior, is the very source of the empirical regularities that we have sought to explain by excluding such uncertainty.[24] This means that the conceptual basis for most of our existing models is seriously flawed.

A major symptom of this has been the dominant tendency to model more complex decision problems by implicitly upgrading the competence of the agent to handle that complexity (so that traditional optimizing concepts can be used). For example, the number of decision alternatives or competing agents is increased, or complex probabilistic contingencies are introduced, or repercussions from future events are permitted, etc. Over the years this has resulted in the characterization of increasingly sophisticated,

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[23] Another area involves differences in productivity between U.S. and Japanese industrial firms, because of differential ability either to manage a complex internal use of inputs, or to adjust to volatile external marketing conditions ("just in time" rather than "just in case" inventory management; greater employee discretion in production line monitoring; longer promotion, investment, and *R&D* planning horizons; etc.) See William Abernathy, Kim Clark, and A. Kantrow, 1981; Y. Mondon, 1981; Y. Sugimori, K. Kusunoki, and S. Cho, 1977; R. Clark, 1979; Anthony Athos and Richard Pascale, 1981; William Ouchi, 1981.

[24] The various authors that have emphasized the importance of uncertainty (for example, Frank Knight, 1921; the Australian view typified by F. A. Hayek, 1967, and Israel Kirzner, 1973; the subjectivist views of G. L. S. Shackle, 1969, 1972; etc.) have given the impression that genuine uncertainty and its effects cannot be represented with formal modeling tools. The approach suggested here is quite different: to harness the determinants of uncertainty in a modeling structure that characterizes regularity in behavior. Closely related ideas have also been recently analyzed by Richard Bookstaber and Joseph Langsam, 1983.

"optimal" behavior strategies, with little fruit in understanding observed behavior.

This trend is typified by recent Bayesian models of optimal risk behavior, which are synonymous with sophisticated continually updated response to new information. Some examples are optimal "search" models that specify various sequential strategies for job search, price or quality information, etc.[25] Yet, they bypass the issue that overides everything else: when to permit any search given the uncertainty in detecting whether the positive gains from efficient search strategies will outweigh the required search costs; especially when a diverse range of search opportunities might eventuate, and the timing of these future opportunities is also unknown.

IV. Explaining Predictable Behavior: Framework and Illustration

The reliability theory briefly outlined above can be applied to the full spectrum of cases produced by different structures of uncertainty. It thus represents a general framework for analyzing behavior under all of these possibilities. On the other hand, standard choice theory analyzes the special case where there is no uncertainty due to a *C-D* gap.[26]

The narrowness of standard optimizing concepts is evidenced in the dominant tendency (even after years of extensive experience with conventional models) to steer away from incorporating genuine uncertainty into the analysis of behavior.[27] In contrast, the Reliability Condition directly harnesses the determinants of uncertainty to characterize regularity in behavior. This amounts to a reversal of the explanation assumed in standard economics, which places these determinants in the residual "error term" between observed behavior and the more systematic patterns claimed to result from optimization.

Thus, the idea of uncertainty as the source of predictable behavior is both a generalization and a major shift away from the explanatory framework of existing models, one that may be of importance to a number of fields. The following statements briefly summarize the major differences between the new framework (the economics of genuine uncertainty) and that of traditional optimization theory:

1) The basic theoretical objective is to understand the behavioral implications of genuine uncertainty, rather than the implications of maximizing for a given set of preferences or expectations. Genuine uncertainty results from a gap in an agent's decision competence relative to the difficulty in selecting more preferred alternatives, so that error and surprise cannot be avoided.

2) A wide range of factors contribute to uncertainty. In economics, these include cognitive limitations in processing given information or in interpreting potential information from the environment; vulnerable perceptions about preferences or expectations taken as given in traditional choice models; unreliable probability or expected utility information taken as given in standard risk-behavior theory. In addition, uncertainty may involve the ability to infer from past experience what was misunderstood that led to previous error; or the abil-

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[25] See, for example, David Blackwell and M. A. Girshick, 1979; Thomas Ferguson, 1967; Peter Diamond and Michael Rothschild, 1978; Stephen Lippman and John McCall, 1979; Hirshleifer and John Riley, 1979.

[26] This conclusion also applies to the more recent models of behavior under uncertainty, which assume agents can infer reliable probabilities of future situations; and also recognize all possible events that might eventuate, or possible actions that might be useful to select. Such ability to comprehend the future is much more difficult than avoiding computational mistakes in a static world of known utility information over a fixed set of options. Consequently, these models are not moving closer but rather further away from dealing with genuine uncertainty due to a *C-D* gap. The reason is that in order to apply traditional optimizing concepts, the competence of the agent has been implicitly upgraded to handle the extra complexity resulting from an unpredictable future. On this issue, see the closing remarks of John Hey, 1979, pp. 232–34.

[27] For example, a recent statement by Lucas flatly concludes: "In situations of risk, the hypothesis of rational behavior on the part of agents will have usable content, so that behavior may be explainable in terms of economic theory.... In cases of uncertainty, economic reasoning will be of little value" (1981, p. 224; see also p. 223).

ity to identify potential actions which might be selected, or contingencies that might affect the consequences of future behavior.[28]

3) Optimizing with no uncertainty in choosing more preferred alternatives does not tend to produce systematic and stable regularity in behavior. Rather, it tends to destroy such regularity as successively more information can be reliably interpreted in guiding more complex behavior. This does not mean that formal optimization tools cannot be used, but rather that understanding how uncertainty affects behavior will systematically redirect the formulation of models and the questions to which they would be applied.

4) Predictable regularities of behavior are the manifestation of behavioral rules that represent patterns of behavior for which deviations exist that are preferred under certain conditions, but which are nevertheless ignored because of uncertainty in reliably interpreting potential information about when to deviate.

5) Intrinsic to behavioral rules is the ignoring or lack of alertness to potential information, the reaction to which would direct behavior into more complex deviations from such rules; even though such information may be costless to observe. Conversely, it is the alertness or sensitivity to information that determines the patterns and complexity of rules manifested in behavior. The Reliability Condition is a simple but general characterization of when greater flexibility to administer more complex behavior or to use more information will improve rather than worsen performance.

6) Behavioral rules not only involve outward symptoms of information sensitivity, but also internal mechanisms that generate such sensitivity. Thus, research in fields such as psychology, biology, and engineering has direct bearing on the structure of such rules. In contrast, traditional economic models have largely ignored research in these and other fields.

To help see the range of issues unified by the above analytical framework, a few illustrations are briefly presented.

A. *The Consistency of Rule-Governed Behavior*

Traditional choice theory has tended to equate normative rationality with logical consistency of behavior, as described by various transitivity, intertemporal consistency, probability assessment, and other assumed conditions. For example, Jacques Drèze provides the following evaluation of the risk behavior axioms of standard expected utility theory:

> ... a consistent decision-maker is assumed always to be able to compare (transitively) the attractiveness of acts, or hypothetical acts and of consequences as well as the likelihood of events. These requirements are minimal, in the sense that no consistency of behaviour may be expected if any one of them is violated; *but they are very strong, in the sense that all kinds of comparisons are assumed possible, many of which may be quite remote from the range of experience of the decision-maker*. This is also the reason why the axioms have more normative appeal than descriptive realism; few people would insist on maintaining, consciously, choices that violate them, but their spontaneous behaviour may frequently fail to display such rigorous consistency.
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> [1974, p. 11, emphasis added]

Drèze is quick to acknowledge and discount the descriptive validity of the expected utility axioms, but like many others he still feels secure in their normative validity in characterizing truly rational behavior under uncertainty.[29] Nevertheless, one might ask what

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[28] The latter determinants have recently been described as particular types of uncertainty, such as parametric versus structural knowledge by Richard Langlois (1983) and "extended" uncertainty by Bookstaber and Langsam. They are extensions of the "unlistability problem" introduced by Shackle (1972). Whatever terminology or type of uncertainty is involved, we can characterize regularity in behavior depending on how each type of uncertainty affects the reliability of using information or selecting potential actions.

[29] See, for example, John von Neumann and Oskar Morgenstern, 1944, pp. 17–30; L. J. Savage, 1954, pp. 6–7, 19–21, 56–68, 82–84; Friedman and Savage, 1948.

would be the implication of a logically correct set of axioms (or a decision algorithm for search and learning behavior) *if obeying those axioms (or using the algorithm) would require the use and sensitive response to unreliable information* (for example, information remote from the range of experience of a decision maker)? To the extent this is the case, rule-governed behavior will ignore such axioms (or a decision algorithm) regardless of the logical properties violated in disobeying them.[30] Similar issues apply to traditional microeconomic theory. For example, what if preferences are less reliable for commodity bundles remote to a consumer's normal purchasing experience? Must we avoid this likely possibility in assuming fully connected preferences? Or is the violation of this assumption itself a major source of price-response regularities of consumers?

B. *Social Institutions Evolve Because of Uncertainty*

Neoclassical decision and general equilibrium models are typically without any explicit institutional structure, and have thus tended to direct attention away from questions about the evolution of particular forms of market organization and other social institutions.[31] In contrast, the Reliability Condition naturally suggests the systematic importance of such institutions to determine the scope and complexity of exchange relationships, and other social interactions involving cultural norms, customs, and aggressive behavior.

In this regard, it is noteworthy that Schotter's recent book on the theory of institutions defines them in a manner immediately implied by the Reliability Condition: "A social institution is a regularity in social behavior that...specifies behavior in specific recurrent situations, and is either self-policed or policed by some external authority" (p. 11).

Thus, evolved institutions are social rule-mechanisms for dealing with recurrent situations faced by agents in different societies. That is, institutions are regularities in the interaction between agents that arise because of uncertainty in deciphering the complex interdependencies created by these interactions.[32] I will return to this topic in Section V below, which considers the evolution of legal and exchange institutions.

A persistent theme in human literature illustrates a closely related issue that has been largely ignored by traditional choice theory; namely, the attempt of individuals to constrain or bind the flexibility of their actions.[33] A famous example in *The Odyssey* describes Ulysses trying to prevent himself from responding to the allurement of certain sirens: "...but you must bind me hard and fast, so that I cannot stir from the spot where

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[30] See Paul Slovic and Amos Tversky, 1974, Slovic and Sarah Lichtenstein, 1983; Dirk Wendt, 1975; D. Conrath, 1973; Detlof Winterfeldt, 1980; and for systematic empirical evidence see Daniel Kahneman and Tversky, 1979, 1981, 1982; Ward Edwards, 1962; William Fellner, 1961; R. M. Hogarth, 1975. Some recent attempts to modify standard expected utility theory by dropping the "independence" or "substitution" axiom include Mark Machina, 1982 (equivalence relationships to global risk-aversion axioms); Graham Loomes and Robert Sugden, 1982, 1983 (regret theory); and S. H. Chew and K. R. MacCrimmon, 1979a, b; Peter Fishburn, 1981; R. Weber, 1982 (*alpha*-utility theory).

[31] See the following diverse range of analytical perspectives, including Alchian, 1950; James Buchanan, 1975, 1977; Buchanan and H. G. Brennan, 1981; Ronald Coase, 1937; Carl Dahlman, 1980; Demsetz, 1967; Hayek, 1967, 1973; Menger, 1871, 1883; Nelson and Sidney Winter, 1982; Andrew Schotter, 1981; Joseph Schumpeter, 1942; Oliver Williamson, 1975, 1979, 1981.

[32] Consider a person within a complex interdependent society, where uncertainty in deciphering these interdependencies quickly increases as they widen beyond his immediate experience. The Reliability Condition implies that his behavior will quickly become insensitive to nonlocal social contingencies. If among such contingencies are effects on other individuals, this implies a relatively sensitive or "self-interested" motivation toward a person's own self (and family), and away from alertness or "sympathy" toward other persons. This implication underlies the ideas Adam Smith developed in the *Theory of Moral Sentiments*, published prior to the *Wealth of Nations*. See Coase (1976) for a number of passages from the *Theory of Moral Sentiments*; for example, Smith, 1969, pp. 321–23, 347–48, 109–10.

[33] See John Elster, 1979; R. H. Strotz, 1955; and N. Howard, 1971. Another classic moral dilemma of great literature poses the protagonist in a situation with abnormally convincing information that "right circumstances" are at hand to engage in behavior precluded by social or religious norms.

you shall stand me...and if I beg you to release me, you must tighten and add to my bonds."

C. *Uncertainty and the Reliability of Expectations*

Both past and present economic models are crucially dependent on how they incorporate expectations in guiding behavior. Economists have been aware that beliefs about the future are often mistaken, and thus have been uneasy in both formulating and applying their models.[34] More recently, "rational expectations" models have attempted to resolve these problems by assuming that expectations correctly identify the mean and variance of stochastic variables that affect future environmental contingencies.[35] A key motivation for such models is to predict how "optimal" behavior will respond to changes in the structure of the environment, especially changes influenced by government policy. Yet, from a broader perspective, it is clear that most species that have evolved in nature exhibit relatively programmed behavior patterns that are highly insensitive to environmental changes, even if such rigidity results in their extinction. At best, such models could apply more broadly only by continually introducing specializing assumptions about the type of expectation "rationality" guiding the behavior of particular species.

Thus, in all of our existing models, either we are analyzing the maximizing response to possibly wrong expectations, or we avoid this issue by assuming expectations are reliable. In order to make progress in analyzing the role of expectations, we must understand how their use and formation are affected by genuine uncertainty in comprehending the future. For example, how reliable are agents' abilities to formulate beliefs about the future; and given the vulnerability of such beliefs, when will agents sensitively react to them, or when will they be alert to information that might prompt them to revise them?

D. *The Pattern of Behavioral Complexity Evidenced in Nature*

My departure from standard choice theory was suggested by the general pattern of animals having a larger *C-D* gap than humans, yet regularity in their behavior is much more noticeable than for humans. The Reliability Condition implies a simple formal characterization of this overall pattern. Suppose we start with a given combination of the $\mathbf{p}$ and $\mathbf{e}$ variables, and consider a conceptual experiment where the $\mathbf{e}$ variables are held fixed, but the perceptual abilities of an agent are successively reduced compared to their initial effectiveness. This will increase the uncertainty in administering the initial behavioral repertoire, thus reducing the reliability ratios of particular actions. As already discussed, greater uncertainty will in general require a more inflexible structure of rules; that is, some of the actions in the initial repertoire must be excluded because their selection no longer satisfies the Reliability Condition.

Now apply this result to us as human observers watching other species with less reliable cognitive equipment than ourselves. We should notice a systematic pattern of greater rigidity and inflexibility in nonhuman species compared to our own behavior. This implication is testable to the extent that the effectiveness of different species' cognitive abilities can be independently measured from simply watching outward behavior (for example, relative brain to body mass). In addition, if we compare across a number of species, there should emerge a general pattern that correlates greater rigidity in behavior with less effective cognitive equipment.[36]

These implications characterize a pervasive qualitative pattern, one that is systematically evidenced in the comparative study of different species. Yet, they were obtained in a very simple way from the Reliability Condition. This is a significant indication that we are on the right track in understanding be-

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[34] See John Hicks, 1935; Richard Muth, 1961; Axel Leijonhufvud, 1968, pp. 366–85, Rudiger Dornbusch and Stanley Fischer, 1978, pp. 270–75, 283–86.

[35] See for example, Thomas Sargent, 1979, and Lucas, 1981.

[36] For analysis of some of the more rigid, "forced" behavior movements of simple organisms, and other major instinctive patterns, see Roger Brown and Richard Herrnstein, 1975, pp. 23–31.

havior, especially in developing a modeling structure that naturally suggests the very consideration of such questions.

E. *Explaining Instinctive Behavior*

The currently accepted explanation of instinctive rigidities is that they accomplish some function which is useful or adaptive most of the time for the natural environments in which they are exhibited.[37] But as already discussed, this feature is itself implied by the Reliability Condition; namely, that rule-governed behavior will ignore adjustment to unlikely contingencies, thus limiting response patterns to only the more probable or recurrent features of the environment. A number of implications concerning ecological structure, niches, extinction, etc., can also be derived (rather than simply described or assumed) from the analysis.

Explanation of specific behavioral rigidities can be obtained by using the Reliability Condition, $r/w > T$, with explicit variables and assumptions about an organism's perceptual components ($\mathbf{p}$) in terms of the sensory ($\mathbf{s}$) and cognitive ($\mathbf{c}$) attributes of particular organisms. In addition, we can introduce morphological ($\mathbf{m}$) attributes of organisms, along with the environmental variables ($\mathbf{e}$) which determine the structure of the environment. By understanding how these variables (denoted $\mathbf{z} = (\mathbf{s}, \mathbf{c}, \mathbf{m}, \mathbf{e})$) affect the reliability and tolerance limit components of the model, particular rule structures can be derived and compared with observed behavior of different organisms (including humans).

F. *Brief Application to Imprinting*

Consider very briefly the phenomenon of *imprinting*.[38] Suppose that responding to a particular pattern in the environment is crucial to an organism's survival (for example, following its parents). Suppose also that without highly developed cognitive mechanisms, if the organism did not initially know the particular pattern, then it could not reliably distinguish that pattern from a number of similar patterns (i.e., a newly born organism could not reliably distinguish its parents from similar adults); but given a specific *reference pattern* to "lock onto," it can reliably distinguish it from other similar patterns. However, if the wrong pattern is locked onto, the organism's survival would be severely jeopardized.

In particular, the probability of right circumstances π to lock onto a pattern is often a function of time since an organism's birth (for example, $\pi(t)$ is the chance of seeing only an organism's parents at time t since birth). Recalling that the required reliability (i.e., the tolerance limit T) will quickly increase as π drops to zero, we can derive the following two-stage behavioral process: stage one is a pattern-locking mechanism that reacts to whatever pattern first appears after the mechanism is initiated; while stage two is a resistance mechanism that severely constrains stage one to only certain sensitive periods for which the required reliability is very low (i.e., $\pi(t)$ is close to 1.0).

It can further be shown that the implied sensitive periods will be highly predictable across particular organisms of a species. In addition, comparative regularities across species in relatively sensitive learning periods can be derived. For example, we can characterize less rigidly patterned sensitivity phases in the development of human children in acquiring language, and the display of other cognitive skills.[39]

G. *Punctuated Dynamics for Scientific Inquiry*

The work of Thomas Kuhn (1962) (see also Popper, 1969; Lakatos and Musgrave,

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[37] The classic reference on instinct is Nino Tinbergen, 1951 (for example, pp. 151–84, especially 156–57 and 152–53). Other references include John Alcock, 1979, pp. 57–76, 87–102; Brown and Herrnstein, 1975, pp. 31–59; William Keeton, 1980, pp. 490–512, especially 503, 494, 496, 498; Eric Pianka, 1978, pp. 82–86, 152–53.

[38] See Alcock, 1979, pp. 67–73; Keeton, 1980, pp. 498–500; Konrad Lorenz, 1981, pp. 259, 275–87; David McFarland, 1982, pp. 303–05; W. R. Hess, 1973.

[39] See for example, Alcock, 1979, pp. 73–79; E. Mavis Hetherington and Ross Park, 1979; R. Grinder, 1962; Lawrence Kohlberg, 1966, 1969; N. Chomsky, 1972; J. Piaget, 1947, 1952. For related material from ethology, see Lorenz, 1981.

1970) has emphasized a systematic pattern of resistance in the behavior of scientists to quick and sensitive reaction to new ideas and theories. Yet, when sufficient anomalies and awkwardly interpreted evidence about a previous theory build up, a major shift in ideas (a "scientific revolution") will relatively quickly occur. This is an illustration of dynamic properties discussed below in Section VI. The Reliability Condition also implies other features in the behavior of scientists, such as: (a) resistance to accepting or using several competing theories unless there also exist easy to decipher (and reliable) criteria of when to switch between them; (b) similar resistance to incorporating new concepts or variables into accepted theories unless reliable criteria on how to use them are available (consider an economist's reaction to incorporating sociological variables into economic models); (c) differences in accepting and rewarding (salary, promotion, etc.) theoretical vs. empirical research in different fields depending on the reliability of observable data studied in those fields (for example, see Leijonhufvud's 1973 parody about "Life Among the Econ").[40]

H. *Uncertainty and Consensus in Social Judgments*

Finally, in the area of ethics and social policy, consider the theory of justice advanced by John Rawls (1971). Underlying his whole analysis is the recognition that if individuals have reliable information about their own future circumstances (will they be smart or resourceful, or have special educational opportunities, or own highly valued property, etc.), they will respond to such information in the way they view social policies and institutions that would affect their particular situations.[41] This will produce a wide diversity of opinions about how to formulate and apply normative principles. Hence, in order to produce a highly uniform consensus or *regularity* in social judgments, Rawls introduced a pervasive uncertainty into the conceptual problem in the form of a "veil of ignorance." Such a procedure virtually eliminates reliable information (even in probabilistic form) about any particular individual's specific future circumstances that might eventuate depending on what principles are mutually agreed to by the whole group.[42] With a sufficient structure of uncertainty, individual judgments might be constrained to possibly a single, universally accepted principle of justice to guide social policy.

The important point is that the source of such a universal consensus, as well as the other behavior patterns discussed above, is uncertainty in using potential information about when to deviate from these regularities.

V. Application to Economic Modeling

In this section, the Reliability Condition is briefly applied to a few modeling issues in standard economics.

A. *Reluctance to Insure Against Rare Disasters*

Extensive empirical studies have shown that people are reluctant to insure themselves against large but rare disasters, in a manner that directly contradicts expected utility theory (see Howard Kunreuther et al., 1978). A recent statement by Kenneth Arrow summarizes the dilemma posed for standard "uncertainty" theory:

> A striking real life situation has given grounds for doubt about the validity of the expected utility hypothesis. Since 1969, the U.S. government has offered flood insurance at rates which are well below their actuarial value... Under the usual hypothesis of risk aversion, any

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[40] Edward Leamer's work (1978) illustrates another issue about the reliability of model testing and formulation, which can be viewed as methodological rule-mechanisms to restrict "specification searches" used to claim empirical support for a theory. See Thomas Cooley and Stephen LeRoy (1981) for an application of Leamer's methodology to evaluating previous work on the demand for money.

[41] See Rawls, 1971, pp. 18–19, 137–38, 140, 149.

[42] See Rawls, 1971, pp. 150, 154–55. Notice in these passages how Rawls believes that a crucial feature of the veil of ignorance is the inability to formulate reliable probability information about the impact of social contingencies on particular individuals.

> individual should certainly be willing to undertake a favorable bet.... Yet, until the government increased the pressure by various incentives, very few took out this insurance.... The main distinguishing characteristic of those who took out flood insurance was acquaintance with others who took out insurance. This might be taken as an explanation in terms of information costs, but the information seems so easy to acquire and the stakes so large that this hypothesis hardly seems tenable.
> [1981, p. 2]

In contrast, the above analysis immediately suggests that even costless information will be ignored if the behavior resulting from its use will not satisfy the Reliability Condition, (recall that solving procedures for Rubic's cube systematically ignore costless information available simply by looking at the cube while unscrambling it). The real issue is why are agents reluctant to engage in behavior that might be prompted by such information.

Consider a brief sketch of the insurance behavior phenomenon. As the probability, p, of a disaster goes to zero, the number of such extremely rare but conceivable events grows indefinitely large. Given any positive setup costs of insuring against each of these possibilities, the total insurance cost will eventually exceed a person's (finite) wealth. Thus, it is clearly not appropriate to insure against all of them. (What do we call someone who is constantly trying to protect against rare but serious sickness; and what would happen to total output net of the demand for medical services if everyone exhibited this propensity?)

The above argument implies that the probability of the right time to insure, π, is bounded by the ratio of a person's wealth to total insurance cost; so that π approaches zero as p approaches zero. Thus, the required reliability will steeply rise for sufficiently rare disasters (i.e., the tolerance limit T will begin to accelerate toward infinity as p approaches zero—see Figure 1).[43] Note also that rare events are precisely those which are remote to a person's normal experience, so that uncertainty in detecting which rare disasters to insure against increases as p approaches zero. Such greater uncertainty will reduce the reliability of insurance decisions (i.e., reduce the ration r/w) as disasters become increasingly remote to a person's normal experience.

As a result of the above factors, the required reliability of when to insure increases sharply just when the actual reliability is dropping. Thus, at some point as p approaches zero, the Reliability Condition will be violated (i.e., T will rise above the falling r/w ratio). This implies people will switch from typically buying to typically ignoring insurance options, which is just the pattern documented in Kunreuther's 1978 study.

We can also show that after a person switches to ignoring insurance, he will be very reluctantly convinced to insure by any information source, *except those local to his normal experience* (for example, a neighbor, a relative, or an "acquaintance" as suggested in the above quotation). Note further that ignoring insurance does not necessarily mean a person consciously decides to ignore all the various potential insurance options—either those obtainable by contacting an insurance agent, or many other ones for which no market insurance is available.

This is a simple example of a more general implication: agents will only become alert or sensitive to information about options whose selection is reliable; or conversely, they will fail to become aware of information about options whose selection is unreliable. Another example of selective alertness to information is the use (or disuse) of marginal cost information to make production decisions, discussed next.

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[43] Consider also very briefly the behavior of the l/g ratio of the tolerance limit. The loss l will be a negative function of the expected value of the disaster losses (denoted $E(p)$) relative to the expected value of the insurance costs (denoted $C(p)$); that is, l is a negative function of $E(p)/C(p) = v(p)$, denoted $l(v(p))$. Similarly, g is a positive function of $v(p)$, denoted $g(v(p))$. Now think of a sequence of actuarily fair or "pure" insurance options for which $v(p) \equiv 1$. If the estimated $v(p)$ is close to zero, then the l/g ratio will not deviate substantially from $l(1)/g(1)$. When this result is coupled with a steeply rising $(1-\pi(p))/\pi(p)$ ratio as $p \rightarrow 0$, we have the same acceleration implied for $T(p) \equiv l(1)/g(1) \times (1-\pi(p))/\pi(p)$.

B. *Spontaneous Alertness to Marginal Cost Information in Simple Production Environments*

A memorable episode in the history of economics was the marginalist controversy about whether businessmen use marginal cost calculations to guide their production decisions. The debate prompted Alchian to write "Uncertainty, Evolution, and Economic Theory" (1950). This was the article that first explicitly justified optimization theory as an explanatory tool to predict the outcome of selection processes (i.e., selection processes will produce simulations to optimizing behavior, which claim is contradicted by the above analysis). Regardless of how one views this debate, it is clear that businessmen typically do not use or are even aware of the kinds of marginal calculations discussed in standard production theory (this lack of awareness is itself an empirical regularity). But what would happen in a relatively simple production environment in which such information could be readily monitored and used with little uncertainty in directing production decisions?

The Reliability Condition implies the spontaneous development (without any special training in economic theory) of alertness and sensitive reaction to marginal cost information for sufficiently simple production environments. This will not be the usual situation, but are there cases that would naturally fit this hypothesis? An example is summarized in the following passage from Hirshleifer's price theory text:

> Electricity is typically generated by companies that operate a number of separate producing plants, with a transmission network providing connections to consumers as well as ties among the generating plants... the operating problem at any moment of time is to assign output most economically among the generating plants....
>
> Fred M. Westfield investigated the operating practices of a leading American electric utility. He discovered that this company employs a dispatcher to actually "assign the load" from moment to moment among the different plants. The dispatcher is guided by a Station-Loading Sliderule that shows what the economist would regard as the Marginal Cost function of each plant. By mechanically manipulating his Sliderule, the dispatcher automatically equates Marginal Cost for all plants in operation in such as way as to meet the total generation requirement....
>
> The company's method of division of output, and the Sliderule itself, were developed by engineers lacking the slightest acquaintance with economic theory. The company's engineers thus independently "discovered" Marginal Cost analysis.... [1980, pp. 286–87]

The engineers did not discover marginal cost analysis, but rather developed a way of reacting to what we as economists would call marginal cost information. Nevertheless, the development of a Station-Loading Sliderule is confirming evidence for the hypothesis of spontaneous sensitivity to marginal cost information in simple production environments. On the other hand, within standard price theory, it can only represent an isolated special case that illustrates a clearly noticeable use of such information.

C. *Uncertainty Implies "Corridor" Dynamics for Macroeconomic Shocks*

A major issue in macroeconomic theory has a direct parallel with the insurance behavior phenomenon discussed above. Instead of deciding whether to insure against various natural disasters, think of a repertoire of activities to prepare for the negative effects of macroeconomic "shocks"; or more generally, anything that produces a coordination failure in an economic system.

When will an economic system evolve so as to "self-insure" against these potential sources of unemployment and other symptoms of coordination failure? Costly shock-preparation activities are beneficial if they are appropriately timed to mitigate the effects of a shock, but otherwise there is a loss from the reduction in output otherwise attainable.

Now suppose, analogous to the insurance case, that there are different types of shocks, some more severe than others; where larger shocks are possible but less and less likely to happen. In addition, the reliability of detecting when and how to prepare for large shocks decreases as their determinants and repercussions are more remote to agents' normal experience.

In a similar manner to that discussed for the insurance case, we can derive that the economy's structure will evolve so as to prepare for and react quickly to small shocks. However, outside of a certain zone or "corridor" around its long-run growth path, it will only very sluggishly react to sufficiently large, infrequent shocks. This is essentially the "corridor hypothesis" for macroeconomic systems recently advanced by Leijonhufvud (1981, pp. 103–29).

In this paper, I have not gone into the specific microprocesses involved (individual agent behavior, intra- and intermarket structures, transmission mechanisms, etc.). Nevertheless, even without adding more specific assumptions we can still derive this general qualitative feature as a necessary consequence of uncertainty. Standard economic theory has been unable to do so, as summarized by Leijonhufvud:

> ...general equilibrium theorists have at their command an impressive array of proven techniques for modelling systems that "always work well". Keynesian economists have experience with modelling systems that "never work". But, as yet, no one has the recipe for modelling systems that function pretty well most of the time but sometimes work very badly to coordinate economic activities. [1981, p. 103]

D. *A Clear Prediction of the Law of Demand*

Suppose consumers do not have well-defined preference relations, but instead must deal with uncertainty in trying to detect when to buy more or less of particular commodities. Myriad "internal" perceptual and "external" environmental factors come together to determine the relative value of particular commodities. In a prospective sense, there is no reliable information to compare all the margins of choice to calculate the most preferred response for each future situation. Rather, consumers must try to react appropriately to various influences that might prompt them to purchase more of particular commodities.

Now suppose the price of a commodity x rises. In order to benefit from continued purchases, the actual value of successive units of the commodity must exceed the now higher opportunity cost implied from the price increase. The likelihood of this situation arising is less than before, given the same structure of motivational influences affecting the value of x. Thus, the probability π of the right situation to buy more x is smaller. For the same reason, even when the right situation arises, the average excess of actual value over the higher price of x (denoted g) is less than before. In addition, the average loss from purchasing more x at the wrong time (denoted l) is now higher than before the price of x went up. Each of these factors will increase the required reliability for purchasing x (i.e., the tolerance limit for purchasing x, $T = (l/g)(1-\pi)/\pi$, will rise).

Given that T has risen, *how is the consumer to change his behavior to be more reliable in purchasing x*? A general answer is suggested in an extensive literature in behavioral psychology about signal detection experiments.[44] The earliest experiments were similar to hearing tests where a person tries to detect the presence of a signal amid background noise (over a sequence of trials where the signal's occurrence is randomly distributed). A variety of other detection skills have been tested, which involve pattern recognition situations and various information processing and other cognative skills. All of the experiments exhibit a key feature: a person can increase the reliability of his detection behavior only by being more cautious in detecting the signals. That is, greater reliability requires a person to reduce the probabil-

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[44] See David Green and John Swets, 1974; James Egan, 1975. A brief appendix on the signal detection experiments (plus some further material on reliability principles suggested by these experiments) is available on request from the author.

ity of reacting regardless of whether the signal is present or not. Note that reliability in these experiments is measured by the r/w ratio used in the Reliability Condition (and reported in graphical form with *ROC* curves).[45]

Now apply this principle to detecting when to buy more of a commodity x. A person can be more reliable in purchasing x only by reducing the probability that potential influences will successively prompt him into purchasing (whether they be internal promptings, advertising, behavior of other consumers, or whatever).

Thus, we have a simple two-step syllogism: *a higher price requires purchasing behavior to be more reliable, which can be achieved only by reducing the probability of purchase.* This implication is essentially the law of demand for consumer behavior, yet without any qualification for income effects; nor must we use complicated Slutsky derivations, or other technical maximizing conditions. To some of us, the logic involved might even seem "too simple" compared to our intellectual investment in n-dimensional consumer theory. Nevertheless, in its simplicity is a clear, unambiguous implication of the Law of Demand, which we have never been able to derive with traditional optimizing methods.[46]

E. *Evolution of Property Rights, Trading, and Market Structure*

Let me sketch a scenario about the evolution of an exchange system. Suppose initially that the reliable range of flexibility of agents' behavioral rules is more than sufficient to handle the complexity of the social environment (say in the primitive beginnings of human society). As a result, agent interactions evolve into more complex relationships in which the consequences from each agent's individual behavior depend on the actions of more and more other agents. In addition, the behavior of these other agents will become increasingly remote to the local experience of each agent as the network of social interdependencies broadens. Consequently, uncertainty in determining the consequences from selecting particular actions will successively increase for each agent in the society.

At some point, the evolution of more complex social interdependence will stop, unless social structures also evolve that reduce the scope of nonlocal information that individual agents must know to reliably forecast the consequences of their own behavior. (In more precise terms, the scope of information over which agents can reliably interpret successively narrows as the social environment becomes more complex.)

In general, further evolution toward social interdependence will require institutions that permit agents to know about successively smaller fractions of the larger social environment. That is, *institutions must evolve which enable each agent in the society to know less and less about the behavior of other agents and about the complex interdependencies generated by their interaction.*

One of the basic ways of accomplishing this is to divide up the decision authority to use resources so that only particular agents (or small groups of agents) have the right to control their use. With such a right-to-control institution, individual agents no longer have to know how other agents might use their "privately owned" resources. A whole range of factors that are within an agent's local experience can now be used to determine the consequences of particular use decisions. Two of the more important possibilities are decisions about whether to consume or delay the use of a resource, and about whether to transfer the right-to-control resources to other agents. Obtaining the right to control itself becomes valuable, given that

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[45] *ROC* stands for "receiver operating characteristic"; see Green and Swets, pp. 31–34.

[46] The Reliability Condition also implies a number of other key empirical regularities that are not derivable from basic maximization theory (see fn. 5 above). Another implication is that behavior will be relatively sensitive to information that defines an agent's local frame of reference within the environment. This will produce "framing effects" studied by Kahneman and Tversky, and a number of other anomalies now widely recognized in the risk-behavior literature (see fn. 30 above). Still other examples include the "excessive reaction" of securities and futures markets to "current information"; the "tendency to ignore prior information" used in Bayesian probabilities; and the "insensitivity of judgments to sample size"; even by "professionally trained" econometricians (see Arrow, 1981, pp. 3–7).

only local information is now required to control the use of a resource.

In more basic terms, the question is whether agents will be willing to cooperate with each other through increasingly complex interdependencies that have the potential—if properly coordinated—to increase average output per agent. As the society becomes more complex, agents will cooperate only in ways that enable them to use increasingly local information to detect whether they will individually benefit. That is, they will exhibit a "propensity to cooperate" only in situations where increasingly local experience indicates a benefit—even if such restriction cuts off a whole range of benefits that might result from more subtly interconnected forms of cooperation. A major way of satisfying this restrictive criteria is to cooperate only in situations where agents immediately reciprocate the cooperative actions of each other, such that each perceives a net benefit based on his own self-evaluation of the forsaken and received items.

This form of reciprocation enables agents to decide based on immediately local experience about the results from cooperating. Thus, their tendency to cooperate in such situations will be relatively great compared to myriad other possibilities that would require the reliable use of more nonlocal information to avoid mistakes. (In more precise terms, we can show that the probability of agents cooperating in such situations will be much higher than for other forms of cooperation.) This limited tendency to cooperate can itself be regarded as a behavioral regularity, one that Adam Smith recognized as the "propensity to truck or barter." Notice also that such a propensity depends on a structure of property rights that enables agents' self-evaluations to determine the use of resources without knowing the behavior of other agents.

The above discussion is only a brief illustration of a large number of implications about legal and market institutions. These institutions will evolve so as to provide predictable opportunity for mutual reciprocation situations; and so as to reduce the scope and complexity of information that must be reliably interpreted for agents to benefit from these situations. For example, a few implications include: a restriction to more centralized market organization and to financial instruments that enable agents to avoid knowing the particular circumstances, attributes, and identity of potential reciprocators and the items reciprocated; a severe restriction of futures markets and auction markets to certain strategic locations within a larger network of inventory markets structured so as to reduce price fluctuations;[47] and ownership structures that enable agents to avoid detecting whether continued reciprocation will be maintained, especially when this is necessary for particular reciprocators to realize longer term benefits or to prevent certain losses.[48] The essential factor in all of these institutional regularities is uncertainty in deciphering the complexity of the social environment.[49]

Finally, let me mention another key feature about the possibility of coordination failures. A complex cooperative system must somehow limit the occurrence of serious coordination failures. Nevertheless, its very complexity can evolve only to the extent that it enables agents to benefit without deciphering more than a tiny fraction of its overall structure. As a result, a complex system can-

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[47] A few modern references on the above topics are: Alchian, 1969, 1977; Robert Clower, 1967; Clower and Leijonhufvud, 1975; Robert Jones, 1976; Seiichi Kawasaki et al., 1982; Lester Telser, 1981.

[48] The reliability model can be used both to predict the likelihood of opportunistic behavior (discontinuing reciprocation), and how the likelihood of such behavior affects the required reliability of various kinds of contractual arrangements. In many cases, the only solution is to structure ownership of assets in a way that eliminates having to detect when to engage in certain contracts. This will produce a stable regularity in contractual and market ownership patterns, which are also studied under the rubric of "transaction costs" (see Williamson, 1975, 1979, 1981, 1983; Benjamin Klein et al., 1978; also Alchian and Demsetz, 1972; Coase, 1937, 1960; Demsetz, 1969, 1967; Dahlman, 1980).

[49] Standard choice theory concentrates exclusively on the potential gains from trade (via Edgeworth exchange boxes, etc.), rather than on the effect of uncertainties created in trying to realize that potential. Consequently, we now have an elaborate general equilibrium theory of exchange which is devoid of the very institutional regularities necessary for complex exchange economies to evolve in the first place (see the epilogue of Vernon Smith, 1982, p. 952).

not prevent coordination failures that would require agents to understand a sizeable fraction of its complexity in order to avert them.

VI. Switching and Punctuation Dynamics

Recall the notation introduced above in Section IV, Part E, where $\mathbf{z}=(\mathbf{s},\mathbf{c},\mathbf{m},\mathbf{e})$ represents an agent's sensory ($\mathbf{s}$), cognitive ($\mathbf{c}$), and morphological ($\mathbf{m}$) components (hereafter denoted by $\mathbf{y}=(\mathbf{s},\mathbf{c},\mathbf{m})$), along with the environmental variables $\mathbf{e}$. Using these variables, we can analyze how uncertainty affects the dynamic response of behavioral rules, and how agents' internal components interact with each other and with the environment to generate evolutionary change in themselves and in the surrounding environment. Two key dynamic properties are conditioned by the transition point between satisfying or violating the Reliability Condition (i.e., the point at which $r/w=T$).

First: Changes in the environmental variables $\mathbf{e}$ may shift the reliability ratio r/w or the tolerance limit T of an action; causing them to "cross over" each other from their initial positions (i.e., shift r/w from below T to above it, or vice versa). If this happens, rule-governed behavior will switch from allowing to severely restricting that action. Thus, a relatively sudden "switching" between different behavior patterns may occur.

Second: If the reliability ratio of an action is initially bounded below its tolerance limit, then behavioral rules will prohibit that action. Now consider a small change in a particular component, $y^0 \in \mathbf{y}$, which would shift r/w and T for such an action closer together, but not enough for them to cross over each other. So long as this is the case, there will be no change in an agent's behavior that might improve or worsen his performance, because the Reliability Condition for selecting that action is still violated. Suppose, however, that movement in some of the *other* $\mathbf{z}$ variables besides y^0 (which might include the $\mathbf{e}$ variables) shift r/w and T sufficiently for them to cross over each other.

At the point of transition, greater reliability from changes in y^0 will now allow selecting the action to improve an agent's performance; which may initiate evolutionary adjustment of y^0 in the appropriate direction. This means that the $\mathbf{y}$ attributes may exhibit relatively sudden increases or decreases in the speed of evolutionary change. Thus, evolutionary adjustment in the $\mathbf{y}$ attributes may be "punctuated" with a variety of sudden changes, especially as a large number of such attributes interact through an agent's behavioral rules, or the environment is itself influenced by the actions of other agents.

It is significant that a simple "crossover" mechanism will generate irregular dynamic movement in the outward behavior or internal attributes of an agent, and suggests an alternative to the recent attempts to account for such effects via catastrophe theory.[50] A recursive use of the Reliability Condition can also generate systematic hysteresis effects, in which the crossover point depends on the past history and direction of a variable's movement.[51]

A few examples to illustrate the above two dynamic properties are the following:

1) A number of implications characterize sudden switching of animal behavior between different actions, such as aggressive behavior in either attacking or retreating, or territorial behavior in either attack or defense strategies. A common example in economics involves switching between buying and selling strategies in financial markets, resulting in sudden movement in stock prices. In general, a wide range of behavior in economics is governed by such switching and hysteresis effects and has been obscured by the use of traditional optimization theory.

2) A specific economic illustration of the crossover mechanism is the "corridor hypothesis" for macroeconomic systems discussed above in Section V. Another example

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[50] See E. C. Zeeman, 1977; Rene Thòm, 1975; David Berlinski, 1975; Hector Sussman, 1975.

[51] Consider very briefly a two-stage use of the Reliability Condition. First, $r/w=T$ is used to characterize a transition point between different behavior patterns. Second, introduce uncertainty about an agent trying to detect unstable shifts in this transition point. An agent may fail to switch once the transition point is reached, or he might mistakenly switch too early. A second application of the Reliability Condition implies that an agent will delay switching until he rarely switches too early; so that the observed switching point will shift depending on the action selected before the switch occurred.

is a structure of expectation "stages" during inflations (ranging from initially "sluggish" to eventually "explosive" expectation adjustment), which contrasts with recent rational expectations modeling.[52]

3) Growing evidence supports the "punctuation hypothesis" recently advanced in evolutionary biology, which claims that irregular bursts in the pace of evolutionary change have produced speciation and macroevolution of dramatic morphological changes (see Stephen Gould and Niles Eldredge, 1977; Steven Stanley, 1979).

4) An example of the latter which has been of considerable interest is the dramatic expansion of the cerebrum responsible for the higher thought processes of humans. Of all the various y attributes, the cerebrum most directly tends to prompt increasingly sophisticated behavior patterns. Right situations for selecting particular actions within a behavioral repertoire will become increasingly rare as the complexity of that repertoire increases.[53] This will cause a steeply rising acceleration in the required reliability for selecting these actions. Thus, if the second dynamic property above ever triggers rapid expansion of the cerebrum, then its sudden leveling off at a larger size is also implied. This dynamic pattern has been of interest and puzzlement in the biology literature.[54]

VII. Hierarchical Structure and Evolution of Reliable Complexity

We can also characterize how uncertainty may generate hierarchical structures of increasingly flexible rules. Such rule-hierarchies have far reaching applications, some of which are briefly discussed in the following remarks:

1) For example, consider a system of components that interact with each other at level v, while these interactions comprise a larger system that interacts within a surrounding environment at level $v+1$. For simplicity, the relationship between a system and its subcomponents is functionally written, $s_{v+1}(\mathbf{s}_v)$, where s_{v+1} denotes the system and $\mathbf{s}_v$ denotes its subcomponents. Thus, we have a recursive structure of rule-governed systems, $s_{v+1}(\mathbf{s}_v)$, where each element of $\mathbf{s}_v$ is itself a system of components at the next lower level $v-1$, denoted $s_v(\mathbf{s}_{v-1})$.

2) Now, suppose that more simply structured subcomponents decrease the reliability of a system in administering more complex interactions with its environment. For example, such components might be more vulnerable in distinguishing nonlocal phenomena. For any given level of subcomponent structure, viable performance requires a minimum degree of behavioral rigidity. Thus no system composed of similarly structured components can allow greater flexibility without hindering its viability. Consequently, the only way more sophisticated behavior could arise from such systems is for a number of them to evolve into the subcomponents of a still larger system. Since the components of the larger system are recursively built up from smaller subsystems, additional structure may be permitted which enables them to reliably guide more complex behavior of a larger system. When this is possible, the behavior of the larger system can be less rigidly constrained than its component subsystems.

3) Recent discoveries in microbiology dramatically illustrate this implication. They show how molecular mechanisms direct the embryological unfolding of living systems. The essential feature of all of these mechanisms are large molecular structures (containing hundreds or thousands of atoms) that interact with each other literally by recognizing each other's shape. That is, they interact with noncovalent bonds which are very much weaker than the covalent bonds (i.e., the merging of electron clouds) of physical chemistry. Thus, stable bonding requires a relatively large surface closely matched to

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[52] The explosive stage could refer to the final phase of a hyperinflation in which agent's expectations so quickly adjust that trying to counteract this reaction by further money supply acceleration will drive real balances toward zero.

[53] As an agent's behavior becomes more complex, each additional action must compete against more and more other actions. Thus, the likelihood of an additional action being more preferred than other actions is conditional on the behavioral complexity of an agent; and in general will decrease as the complexity of his repertoire increases.

[54] See, for example, Edward Wilson, 1975, pp. 547–50; Jerison, 1973, pp. 402–43; D. Pilbean, 1972.

the shape of another molecule (which large surfaces require many atoms within each molecule).[55] Molecular shape enables the precise calibration of "stereo-specific" bonding, which permits a much more complex structure of interaction possibilities than otherwise possible with the more rigid constraints of physical chemistry. Moreover, the precise recognition properties of stereo-specific bonding enables the reliable direction of complicated molecular mechanisms, as evidenced in the biochemistry of cell regulation and embryological processes.[56] The significance of this is summarized by Nobel Prize biochemist Jacques Monod:[57]

> [Stereo-specific bonding gave] molecular evolution a practically limitless field for exploration and experiment, [which] enabled it to elaborate the huge network of cybernetic interconnections which makes each organism an autonomous functional unit, whose performances appear to transcend the laws of chemistry if not to ignore them altogether. [1972, p. 78]

4) If the recursive structure, $s_{v+1}(s_v)$, is continued to higher or lower levels ($v+2, v+3,\ldots$; or $v-1, v-2,\ldots$) we obtain a hierarchical structure of increasingly sophisticated systems, where later stages are governed by successively more flexible rules. Such hierarchical structures represent a basic way systems conditioned by uncertainty can evolve into allowing successively more sophisticated behavior without hindering their viability in the process.

This pattern of hierarchical development is systematically evidenced in nature at a number of intertwining levels. For example, there are the invariable behavior patterns of atoms, which are composed of successively more basic subatomic particles; and which are themselves components of larger cosmological systems whose behavior is also synonymous with highly predictable laws.[58] Above this level, there is another hierarchy of organic molecules (discussed above) that eventually form components in living cells. Such cells in turn are subcomponents of still larger organs and tissues that permit relatively more flexible behavior of yet another hierarchy of increasingly sophisticated living organisms. Finally, there is the subtle, usually difficult to predict, behavior of humans and their social institutions. Looking back on this structure, the particular course of its evolution may be extremely improbable. Nevertheless, what did evolve has been through a hierarchical process from very predictable to relatively much less predictable phenomena.

5) Hierarchical structures may also have systematic importance in the design of cognitive and related (natural and artificial) learning processes.[59] For example, there may be

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[55] See J. Monod, 1972, pp. 45–46.

[56] See J. Monod, 1972, chs. 4–7.

[57] For a recent more technical overview of the subject, see James Watson, 1976.

[58] The body of this paper has only briefly alluded to the physical sciences. At issue is whether the invariable regularities exhibited by natural phenomena can be regarded as "rule-mechanisms" to cope with extreme uncertainty in avoiding destabilizing interactions between the components of a system that might disintegrate its structure? More generally, what patterns of component interaction are viable in the sense of generating their own continuation, or the continuation of larger interactive patterns between components which are themselves systems? Many topics in the physical sciences could be discussed, but only three topics are mentioned here. First, we can analyze uncertainty in producing stable macrostructures to characterize relationships between the "particles" of matter and the "forces" that interconnect them. Second, we can consider uncertainty in maintaining the structural stability of tightly compacted systems to characterize symmetry properties, and other statistical regularities studied in quantum mechanics. Third, we can analyze the effects of violating the general relativity postulate of modern physics, especially about uncertainties in dealing with complex interdependencies permitted without the constraint of generally covariant interactions. On these three topics see respectively: P. C. W. Davies, 1979; J. P. Elliot and P. G. Dawber, 1979; Enrico Cantore, 1969; Albert Einstein, 1952, 1956.

Underlying these regularities is a persistent theme about the unity of science, as suggested in the following remark by Einstein: "The most incomprehensible thing about the universe is why it is so comprehensible." (See also the closing remarks of Kuhn's 1962 essay, p. 173.) The answer may lie in how extreme uncertainty affects the structure of self-continuing physical systems.

[59] See Simon, 1969, 1979a; Newell and Simon, 1972; J. R. Anderson, 1980; G. T. Miller et al., 1960.

resistance to knowledge not built up in recursive stages. For example, explicitly hierarchical methods have evolved in the abovementioned strategy books on playing blackjack, and more recently on how to solve Rubik's cube.[60]

6) It has also been argued by Kohlberg, with extensive supporting experimentation, that the moral development of children as they mature into adults follows a highly patterned hierarchical structure of six stages. The first stage is guided by "blind obedience to rules and authority...," which proceeds though intermediate steps to stage six, which is "guided by self-chosen ethical principles."[61] A pattern of successively more complex moral judgments is clearly suggested in this hierarchy.

7) The viability of an evolving system, (for example an ecological system of organisms, or an exchange system of competing agents), which originates truly novel change (whose interactive possibilities are largely unrelated to the system's past history) may be quite sensitive to uncertainty in avoiding disruptive novelty. If this is the case, the very processes which generate and select such novelty will themselves be organized in a hierarchical structure of increasingly flexible rule-mechanisms. An important illustration is the structure of relationships that connect the rigidly patterned molecular design of DNA to the more visible interactions comprising natural selection.[62]

Other implications characterize the diversity and pace of novel change that can be reliably controlled by an evolving system. For example, a more rapid average pace is permitted as the reliability of selective processes increases. These implications underly the major differences in the qualitative nature and average speed of cultural compared to biological evolution.

VIII. Conclusion

I have argued that uncertainty is the basic source of predictable behavior, and also the main conditioning factor of evolutionary processes through which such behavior evolves. Uncertainty exists because agents cannot decipher all of the complexity of the decision problems they face, which literally prevents them from selecting most preferred alternatives. Consequently, the flexibility of behavior to react to information is constrained to smaller behavioral repertoires that can be reliably administered. Numerous deviations from the resulting behavior patterns are actually superior in certain situations, but they are still ignored because of uncertainty about when to deviate from these regularities.

In contrast, standard economics analyzes the special case of no uncertainty in selecting most preferred options. This way of understanding behavior forces the determinants of uncertainty into the residual "error term" between observed behavior and the more systematic patterns claimed to result from optimization. I am thus suggesting a reversal of the explanation assumed in standard economics: the factors that standard theory places in the error term are in fact what is producing behavioral regularities, while optimizing will tend to produce sophisticated deviations from these patterns. Hence, the

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[60] A good example of a hierarchical method is Kosniowski, 1981, especially in contrast to David Singmaster, 1979 (called the "definitive treatise" by *Scientific American*), which follows a complex, cyclical development of ideas that switches back and forth between different parts of the book. Singmaster's book is also several times longer than later books (cited above in fn. 14), both in terms of number of words and notational density.

[61] See Kohlberg, 1976, pp. 30 and 32; and 1963, 1969.

[62] Consider the extreme uncertainty of tiny molecular structures directing the construction of living systems. Maurice Wilkin's 1953 paper (which accompanied Watson and Cricks' original paper in *Nature*) begins: "While the biological properties of deoxypentose nucleic acid suggest a molecular structure containing great complexity, X-ray diffraction studies described here show the basic molecular configuration has great simplicity" (p. 738). The Reliability Condition implies the opposite presumption; namely, that precisely because DNA is the ultimate source of larger biological systems, whose complexity cannot be reliably manipulated from any interaction local to its tiny structure, its internal design must be both rigidly patterned and engineered to replicate virtually without guidance from its local chemical environment.

observed regularities that economics has tried to explain on the basis of optimization would disappear if agents could actually maximize.

Another basic conclusion is that appropriately structured behavioral rules will not necessarily arise. Rather, they will evolve to the extent that selection processes quickly eliminate poorly administered behavior. This will more likely occur when agents are involved in highly competitive interactions that themselves indirectly result from scarcity. However, if weak selection processes are present, relatively vulnerable or dysfunctional behavior may evolve.

One area of major normative significance is the development of human social institutions; in particular, political institutions that have the opportunity to influence the outcomes generated by exchange competition. This is especially important if human agents are able to foresee numerous potential cases where the cooperative results of exchange institutions could be improved, but without being able to reliably administer the additional complexity necessary to realize those improvements.

Think of this issue in terms of the Reliability Condition. People may be able to identify government actions where situations exist in which a society will benefit (i.e., the probability of right circumstances π for selecting these actions is positive). Nevertheless, they may be unable to administer these actions with sufficient reliability to benefit the society by adding them to the government's repertoire of authorized activities (i.e., $r/w<T$ even though $\pi>0$). If this is the case, the society will benefit by appropriately limiting the scope and complexity of government behavior.

But how is such limitation to arise? It is here that we enter the area of "constitutionalism," defined broadly as the design of rule-mechanisms to restrict the flexibility of government to react to whatever influences might prompt it to engage in vulnerable activities. The writings of seventeenth- and eighteenth-century political philosophers and statesmen were primarily concerned with these issues. Out of their efforts came a number of features incorporated in the United States Constitution, such as the separation of powers mechanism.[63]

On a wider scale, the history of civilization can be organized around a theme of groping for social rule-mechanisms.[64] Nevertheless, the understanding of such mechanisms is only in its rudimentary beginnings; and in the last hundred years, the general trend has been away from these topics—especially for analysts trained in mainstream economic theory.[65] The reason is that mainstream theories have systematically directed attention away from the study of processes that limit flexibility to choose potentially preferred actions. A refocusing of research on such processes—with the appropriate analytical framework to guide us—may have practical consequences for the viability of existing institutions.

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[63] The basic source materials on these issues are the Federalist Papers by Hamilton and Jefferson (for example, numbers 10, 47, 48, 51). For a modern reference, see Martin Diamond, 1981.

[64] The often seemingly bizarre practices of religion and cultural ritual may also represent the design technologies of social rules crucial to the coordination and intensification of social bonds. For some interesting readings about ritual, symbolism, and comparative religion, see William Lessa and Evon Vogt, 1979, and M. Gluckman, 1962.

[65] Notable exceptions to this general trend are the writings of Buchanan and Hayek (see fn. 31 above).

REFERENCES

Abernathy, William J., *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*, Baltimore: Johns Hopkins University Press, 1978.

______, **Clark, Kim and Kantrow, A.,** "The New Industrial Competition," *Harvard Business Review*, September-October 1981, *59*, 68–81.

Alchian, Armen A., "Uncertainty, Evolution and Economic Theory," *Journal of Political Economy*, June 1950, *58*, 211–21.

______, "Information Costs, Pricing and Resource Unemployment," *Western Economic Journal*, June 1969, *7*, 109–28.

______, "Why Money?," *Journal of Money*, *Credit, and Banking*, February 1977, *9*, 133–40.

______ and **Demsetz, Harold,** "Production, Information Costs, and Economic Efficiency," *American Economic Review*, December 1972, *62*, 777–95.

Alcock, John, *Animal Behavior: An Evolutionary Approach*, Sunderland: Sinauer Associates, 1979.

Aldrich, R., *Organization and Environments*, Englewood Cliffs: Prentice-Hall, 1979.

Alexander, Richard, *Darwinism and Public Affairs*, Seattle: University of Washington Press, 1979.

______ and **Borgin, G.,** "Group Selection, Altruism, and the Levels of Organization of Life," *Annual Review of Ecology and Systematics*, September 1978, *9*, 449–75.

Anderson, Ian, *Turning the Tables on Las Vegas*, New York: Harper & Row, 1975.

Anderson, J. R., *Cognitive Psychology and Its Implications*, San Francisco: W. H. Freeman, 1980.

Archer, John, *The Archer Method of Winning at 21*, Hollywood: Wilshire Book Company, 1973.

Arrow, Kenneth J., "Risk Perception in Psychology and Economics," *Economic Inquiry*, January 1981, *20*, 1–9.

______, "Vertical Integration and Communication," *Bell Journal of Economics*, Spring 1975, *6*, 173–83.

Ashby, W., *An Introduction to Cybernetics*, New York: Wiley, 1956.

Athos, Anthony G. and Pascale, Richard T., *The Art of Japanese Management*, New York: Simon & Schuster, 1981.

Axelrod, Robert, (1980a) "Effective Choice in the Prisoner's Dilemma," *Journal of Conflict Resolution*, March 1980, *24*, 3–25.

______, (1980b) "More Effective Choice in the Prisoner's Dilemma," *Journal of Conflict Resolution*, September 1980, *24*, 379–403.

Barlow, B. W., *The Cube: A Short and Easy Solution*, Salt Lake City: Hawkes Publishing, 1981.

Berlinski, David, "Mathematical Models of the World," *Synthese*, August 1975, *31*, 211–27.

Black, M. R. and Taylor, H., *Unscrambling the Cube*, Burbank: Zephyr Engineering Design, 1980.

Blackwell, David and Girshick, M. A., *Theory of Games and Statistical Decisions*, New York: Dover, 1979.

Bookstaber, Richard and Langsam, Joseph, "Coarse Behavior and Extended Uncertainty," Working Paper 83–1, Graduate School of Management, Brigham Young University, 1983.

Boland, Lawrence, A., "On the Futility of Criticizing the Neoclassical Maximization Hypothesis," *American Economic Review*, December 1981, *71*, 1031–36.

Bradshaw, C. M., Szabadi, E. and Bevan, R., "Behavior of Humans in Variable-Interval Schedules of Reinforcement," *Journal of the Experimental Analysis of Behavior*, September 1976, *26*, 135–41.

Brown, Roger and Herrnstein Richard, *Psychology*, Boston: Little-Brown, 1975.

Buchanan, James M., *Freedom in Constitutional Contract*, College Station: Texas A&M University Press, 1977.

______, *The Limits of Liberty: Between Anarchy and the Leviathan*, Chicago: University of Chicago Press, 1975.

______ and **Brennan H. G.,** *Monopoly in Money and Inflation*, London: Institute for Economic Affairs, 1981.

Buskist, William F. and Miller, Harold L., Jr., "Concurrent Operant Performance in Humans: Matching When Food is the Reinforcer," *Psychological Record*, January 1981, *31*, 95–100.

Bussert, Patrick, *You Can Do the Cube*, New York: Puffin Books, 1981.

Cagan, Phillip, "The Monetary Dynamics of Hyperinflation," in M. Friedman, ed., *Studies in the Quantity Theory of Money*, Chicago: University of Chicago Press, 1956.

Caldwell, B., *Beyond Positivism: Economic Methodology In the Twentieth Century*, London: Allen & Unwin, 1982.

Campbell, Donald C., "On the Conflicts Between Biological and Social Evolution and Between Psychology and Moral Tradition," *American Psychologist*, December 1975, *30*, 1103–26.

______, "Downward Causation in Hierarchically Organized Biological Systems," in F. J. Ayala and T. Dobzhausky, eds., *Studies in the Philosophy of Biology*, New York: Macmillan, 1974.

Canfield, Richard A., *Blackjack: Your Way to Riches*, Secaucus: Lyle Stuart, Inc., 1979.

Cantore, Enrico, *Atomic Order: An Introduction to the Philosophy of Microphysics*, Cambridge: MIT Press, 1969.

Cardoza, Avery D., *Winning Casino Blackjack for the Noncounter*, Santa Cruz: Cardoza School of Blackjack, 1981.

Carter, C. F. and Williams, B. R., *Industry and Technical Progress: Factors Governing the Speed of Application of Science*, New York: Oxford University, 1957.

Cavelli-Sforza, L., and Feldman, Marcus, *Cultural Transmission & Evolution: A Quantitative Approach*, Princeton: Princeton University, 1981.

Chandler, Alfred D., *Strategy and Structure: Chapters in the History of Industrial Enterprise*, Cambridge: MIT Press, 1962.

______, *The Visible Hand: The Managerial Revolution in American Business*, Cambridge: Belknap Press, 1977.

Cheung, Steven, "Transactions Costs, Risk Aversion, and the Choice of Contractual Arrangements," *Journal of Law and Economics*, April 1969, *12*, 23–42.

Chew, S. H. and MacCrimmon, K. R., (1979a) "Alpha-Nu Choice Theory: A Generalization of Expected Utility Theory," Working Paper No. 669, University of British Columbia, 1979.

______ **and** ______, (1979b) "Alpha Utility Theory, Lottery Composition, and the Allais Paradox," Working Paper No. 686, University of British Columbia, 1979.

Chomsky, N., *Language and Mind*, New York: Harcourt, Brace & Jovanovich, 1972.

Clark, R., *The Japanese Company*, New Haven: Yale University Press, 1979.

Clower, Robert W., "The Keynesian Counterrevolution: A Theoretical Appraisal," in F. Hahn and F. Brechling eds., *The Theory of Interest Rates*, London: Macmillan, 1965.

______, "A Reconsideration of the Microfoundations of Monetary Theory," *Western Economic Journal*, December 1967, *6*, 1–8.

______ **and Leijonhufvud, Axel**, "The Coordination of Economic Activities: A Keynesian Perspective," *American Economic Review Proceedings*, May 1975, *65*, 182–88.

Coase, Ronald H., "The Nature of the Firm," *Economica*, November 1937, *4*, 386–405.

______, "The Problem of Social Cost," *Journal of Law and Economics*, October 1960, *3*, 1–44.

______, "Adam Smith's View of Man," *Journal of Political Economy*, October 1976, *19*, 529–46.

Cohen, Michael D. and Axelrod, Robert, "Coping with Complexity: The Adaptive Value of Changing Utility," *American Economic Review*, forthcoming.

Conner, M., *The Tangled Wing: Biological Constraints on the Human Spirit*, New York: Basic Books, 1982.

Conrath, D., "From Statistical Decision Theory to Practice: Some Problems with the Transition," *Management Science*, April 1973, *19*, 873–94.

Cooley, Thomas F. and LeRoy, Stephen F., "Identification and Estimation of Money Demand," *American Economic Review*, December 1981, *71*, 825–44.

Cooter, Robert, (1982a) "The Cost of Coase," *Journal of Legal Studies*, January 1982, *11*, 1–34.

______, **Marks, Stephen and Mnookin, Robert**, (1982b) "Bargaining in the Shadow of the Law: A Testable Model of Strategic Behavior," *Journal of Legal Studies*, June 1982, *11*, 225–52.

Dahlman, Carl, *The Open Field System and Beyond*, Cambridge: Cambridge University Press, 1980.

Davies, P. C. W., *The Forces of Nature*, Cambridge: Cambridge University Press, 1979.

Demsetz, Harold, "Information and Efficiency: Another Viewpoint," *Journal of Law and Economics*, April 1969, *12*, 1–22.

______, "Toward a Theory of Property Rights," *American Economic Review Proceedings*, May 1967, *57*, 347–59.

de Villiers, P., "Choice in Concurrent Schedules and a Quantitative Formulation of the Law of Effect," in W. K. Honig and J. E. R. Standdon, eds., *Handbook of Operant Behavior*, Englewood Cliffs: Prentice-Hall, 1977, 233–87.

Diamond, Martin, *The Founding of the Democratic Republic*, Itasca: Peacock, 1981.

Diamond, Peter and Rothschild, Michael, *Uncertainty in Economics*, New York: Academic Press, 1978.

Dornbusch, Rudiger and Fischer, Stanley, *Macro-Economics*, New York: McGraw-Hill, 1978.

Drèze, Jacques H., "Axiomatic Theories of Choice, Cardinal Utility, and Subjective Probability," a review in his *Allocation Under Uncertainty: Equilibrium and Optimality*, New York: Wiley, 1974, 1–23; reprinted in P. Diamond and M. Rothschild, eds., *Uncertainty in Economics*, New York: Academic Press, 1978, 37–57.

Dubey, Leon B., Jr., *No Need to Count: A Practical Approach to Casino Blackjack*, San Diego: A.S. Barnes & Co., 1980.

Edwards, Ward, "Subjective Probabilities Inferred from Decisions," *Psychological Review*, March 1962, *69*, 109–35.

Egan, James P., *Signal Detection Theory and ROC Analysis*, New York: Academic Press, 1975.

Einstein, Albert, *The Meaning of Relativity: Including the Relativistic Theory of the Non-Symmetric Field*, Princeton: Princeton University Press, 1956.

______, *The Principle of Relativity*, New York: Dover, 1952.

Elliot, J. P. and Dawber, P. G., *Symmetry in Physics*, Vols. 1; 2, London: Macmillan, 1979.

Elster, John, *Ulyssess and the Sirens*, Cambridge: Cambridge University Press, 1979.

Fellner, William, "Distortion of Subjective Probabilities as a Reaction to Uncertainty," *Quarterly Journal of Economics*, November 1961, *75*, 670–90.

Ferguson, Thomas S., *Mathematical Statistics: A Decision Theoretic Approach*, New York: Academic Press, 1967.

Fishburn, Peter C., "Transitive Measurable Utility," Discussion Paper No. 224, Bell Laboratories, 1981.

Fischer, Stanley, "Long Term Contracts, Rational Expectations, and the Optimal Money Supply Rule," *Journal of Political Economy*, February 1977, *85*, 191–206.

Friedman, Milton, "The Methodology of Positive Economics," in his *Essays in Positive Economics*, 1953; reprinted in W. Breit and H. M. Hochman, eds., *Readings in Microeconomics*, New York: Holt, Rinehart & Winston, 1968, 23–47.

______, *A Program for Monetary Stability*, New York: Fordham University Press, 1969.

______ **and Savage, L. J.,** "The Utility Analysis of Choices Involving Risks," *Journal of Political Economy*, August 1948, *56*, 279–304.

Gibson, J., "The Theory of Affordances," in R. E. Shaw and J. Bransford, eds., *Perceiving, Acting, and Knowing*, Hillsdale: Lawrence Erlbaum Assoc., 1977.

Gluckman, M., *Essays on the Ritual of Social Relations*, Manchester: Manchester University Press, 1962.

Gould, Stephen J. and Eldredge, Niles, "Punctuated Equilibria: The Tempo and Mode of Evolution Reconsidered," *Paleobiology*, January 1977, *3*, 115–51.

Graham, Virginia L. and Tulcea, C. Ionescu, *A Book on Casino Gambling*, New York: Pocket Books, 1978.

Green, David M. and Swets, John A., *Signal Detection Theory and Psychophysics*, New York: Robert Kriegur, 1974.

Grinder, R., "Parental Childrearing Practices, Conscience, and Resistance to Temptation of Sixth-Grade Children," *Child Development*, December 1962, *33*, 802–20.

Hahn, Frank, *On the Notion of Equilibrium in Economics*, Cambridge: Cambridge University Press, 1973.

Hamilton, W. D., "The Genetical Evolution of Social Behavior," *Journal of Theoretical Biology*, 1964, *7*, 1–17.

Hayek, F. A., *Studies in Philosophy, Politics, and Economics*, Chicago: University of Chicago Press, 1967.

______, *Law, Legislation, and Liberty*, Chicago: University of Chicago Press, 1973.

Heiner, Ronald A., "A Theory of Predictable Behavior: Application to Insurance Behavior Anomolies," Department of Economics, Brigham Young University, February 1982.

Heisenberg, Werner, *The Physical Principles of the Quantum Theory*, New York: Dover, 1949.

Herrnstein, Richard J., "On the Law of Effect," *Journal of the Experimental Analysis of Behavior*, November 1970, *13*, 243–66.

______, "Relative and Absolute Strength of Response as a Function of Frequency of Reinforcement," *Journal of the Experimental Analysis of Behavior*, 1961, *4*, 267–72.

______, "Secondary Reinforcement and Rate of Primary Reinforcement," *Journal of the Experimental Analysis of Behavior*, January 1964, *7*, 74–91.

______ **and Heyman, Gene M.**, "Is Matching Compatible with Maximization in Concurrent Variable Interval, Variable Ratio?," *Journal of the Experimental Analysis of Behavior*, March 1979, *31*, 209–23.

______ **and Vaughan, W.**, "Melioration and Behavioral Allocation," in J. E. R. Staddon, ed., *Limits to Action: The Allocation of Individual Behavior*, New York: Academic Press, 1980, 143–76.

Hess, W. R., *Imprinting: Early Experience and the Developmental Psychobiology of Attachment*, New York: Van Nostrand 1973.

Hetherington, E. Mavis and Park, Ross D., *Child Psychology: A Contemporary Viewpoint*, 2d ed., New York: McGraw-Hill, 1979.

Hey, John D., *Uncertainty in Microeconomics*, New York: New York University Press, 1979.

Heyman, Gene M. and Luce, R. Duncan, "Operant Matching is not a Logical Consequence of Maximizing Reinforcement Rate," *Animal Learning and Behavior*, May 1979, *7*, 133–40.

Hicks, John, "A Suggestion for Simplifying the Theory of Money," *Economica*, February 1935, *2*, 1–19.

Hirshleifer, Jack, "Evolutionary Models in Economics and the Law: Cooperation Versus Conflict Strategies," *Research in Law and Economics*, 1982, *4*, 1–60.

______, "Economics from a Biological Viewpoint," *Journal of Law and Economics*, April 1977, *20*, 1–54.

______, *Price Theory and Applications*, 2d ed., Englewood Cliffs: Prentice-Hall, 1980.

______ **and Riley, John**, "The Analytics of Uncertainty and Information," *Journal of Economic Literature*, December 1979, *17*, 1375–421.

Hoffman, Eric and Spitzer, Mathew, "The Coase Theorem: Some Experimental Tests," *Journal of Law and Economics*, April 1982, *25*, 73–98.

Hogarth, R. M., "Cognitive Processes and the Assessment of Subjective Probability Distributions," *Journal of the American Statistical Association*, June 1975, *70*, 271–94.

Holmes, Warren G. and Sherman, Paul W., "Kin Selection in Animals," *American Scientist*, January-February 1983, *7*, 46–56.

Howard, N., *Paradoxes of Rationality*, Cambridge: MIT Press, 1971.

Jerison, Harry, *Evolution of the Brain and Intelligence*, New York: Academic Press, 1973.

Jones, Robert, "On the Origin and Development of Media of Exchange," *Journal of Political Economy*, August 1976, *84*, 757–76.

Judson, Horace F., *The Eighth Day of Creation*, New York: Simon & Schuster, 1979.

Kahneman, Daniel and Tversky, Amos, "Prospect Theory: An Analysis of Decision Under Risk," *Econometrica*, March 1979, *47*, 263–91.

______ **and** ______, "The Framing of Decisions and the Psychology of Choice," *Science Magazine*, January 30, 1981, *211*, 453–58.

______ **and** ______, "The Psychology of Preferences," *Scientific American*, January 1982, *246*, 160–73.

Kawasaki, Seiichi, McMillan, John and Zimmerman, Klaus F., "Disequilibrium Dynamics: An Empirical Study," *American Economic Review*, December 1982, *72*, 992–1004.

Keeney, Ralph L. and Raiffa, Howard, *Decisions with Multiple Objectives: Preference and Value Tradeoffs*, New York: Wiley, 1976.

Keeton, William, *Biological Science*, 3d ed., New York: Norton, 1980.

Kirzner, Israel M., *Competition and Entrepreneurship*, Chicago: University of Chicago Press, 1973.

Klein, Benjamin, Crawford, Robert and Alchian, Armen, "Vertical Integration, Appropriable Rents, and the Competitive Contracting Process," *Journal of Law and Economics*, October 1978, *21*, 297–326.

______ **and Leffler, Keith**, "The Role of Market Performance in Assuring Contractual Performance," *Journal of Political*

Economy, October 1981, *89*, 810–34.

Knight, Frank, *Risk, Uncertainty and Profit*, Boston: Houghton Mifflin, 1921.

Kohlberg, Lawrence, "Stage and Sequence: The Cognitive-Developmental Approach to Socialization," in D. A. Goshn, ed., *Handbook of Socialization Theory and Research*, New York: Rand McNally, 1969, 347–480.

______, "The Development of Children's Orientation Toward Moral Order: Sequence in the Development of Moral Thought," *Vita Humana*, January 1963, *3*, 11–33.

______, "The Domain and Development of Moral Judgment: A Theory and Method of Assessment," in his et al., eds., *Assessing Moral Judgment States: A Manual*, New York: Humanities Press, 1976, 14–45.

______, "Cognitive Stages and Preschool Education," *Human Development*, January 1966, *9*, 5–17.

______, "Justice as Reversibility," in P. Laslett and J. Fishkin, eds., *Philosophy, Politics, and Society*, New Haven: Yale University Press, 1979.

Konner, M., *The Tangled Wing: Biological Constraints on the Human Spirit*, New York: Basic Books, 1982.

Kosniowski, Czes, *Conquer that Cube*, Cambridge: Cambridge University Press, 1981.

Kreps, David et al., "Rational Cooperation in the Finitely Repeated Prisoner's Dilemma," *Journal of Economic Theory*, August 1982, *27*, 245–52.

Kuhn, Thomas, *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press, 1962.

Kunreuther, Howard et al., *Disaster Insurance Protection*, New York: Wiley, 1978.

Kydland, Finn E. and Prescott, Edward C., "Rules Rather Than Discretion: The Inconsistency of Optimal Plans," *Journal of Political Economy*, June 1977, *85*, 473–91.

Lakatos, Imer and Musgrave, Alice, *Criticism and the Growth of Knowledge*, Cambridge: Cambridge University Press, 1970.

Langlois, Richard, "Internal Organization in a Dynamic Context: Some Theoretical Considerations," Economic Research Report No. 83–04, C. V. Starr Center for Applied Economics, New York University, January 1983.

Leamer, Edward, "'Explaining Your Results' As Access Biased Memory," *Journal of the American Statistical Association*, March 1975, *70*, 88–93.

______, *Specification Searches: Ad-Hoc Inference With Nonexperimental Data*, New York: Wiley, 1978.

Leblebici, Huseyin and Salanik, Gerald R., "Effects of Environmental Uncertainty on Information and Decision Processes in Banks," *Administrative Science Quarterly*, December 1981, *26*, 578–96.

______ **and** ______, "Stability in Interorganizational Exchange: Rulemaking Processes of the Chicago Board of Trade," *Administrative Science Quarterly*, June 1982, *27*, 227–42.

Leibenstein, Harvey, "Allocative Efficiency vs. X-Efficiency," *American Economic Review*, June 1966, *56*, 392–415.

Leijonhufvud, Axel, *On Keynesian Economics and the Economics of Keynes*, New York: Oxford University Press, 1968.

______, *Information and Coordination*, New York: Oxford University Press, 1981.

______, "Life Among the Econ," *Western Economic Journal*, September 1973, *11*, 327–37.

Lessa, William and Vogt, Evon, *Reader in Comparative Religion: An Anthropological Approach*, New York: Harper & Row, 1979.

Levins, Richard, *Evolution in Changing Environments*, Princeton: Princeton University Press, 1968.

Lippman, Stephen and McCall, John, "The Economics of Job Search: A Survey," *Economic Inquiry*, June 1979, *14*, 155–89.

Loomes, Graham and Sugden, Robert "Regret Theory: An Alternative Theory of Rational Choice Under Uncertainty," Department of Economics Working Paper, University of Newcastle-upon-Tyne, 1982.

______ **and** ______, "A Rationale for Preference Reversal," *American Economic Review*, June 1983, *73*, 428–32.

Lorenz, Konrad, *The Foundations of Ethology*, New York: Springer-Verlag, 1981.

Lucas, Robert E., Jr., "An Equilibrium Model of the Business Cycle," *Journal of Political Economy*, December 1975, *83*, 1113–44.

______, "Expectations and the Neutrality of Money," *Journal of Economic Theory*, April

1972, *4*, 103–24.

______, "Rules, Discretion, and the Role of the Economics Advisor," in S. Fischer, ed., *Rational Expectations and Economic Policy*, Chicago: University of Chicago Press, 1980, 199–210.

______, *Studies in Business Cycle Theory*, Cambridge: MIT Press, 1981.

Lumsden, Charles J. and Wilson, Edward O., *Genes, Mind, & Culture: The Coevolutionary Process*, Cambridge: Harvard University Press, 1981.

McFarland, David, *The Oxford Companion to Animal Behavior*, New York: Oxford University Press, 1982.

Machina, Mark, "Expected Utility Analysis Without the Independence Axiom," *Econometrica*, March 1982, *50*, 277–323.

March, James G., "Bounded Rationality, Ambiguity, and the Engineering of Choice," *Bell Journal of Economics*, Autumn 1978, *9*, 587–608.

Masterton, R., Hodos, William and Jerison, Harry, *Evolution, Brain, and Behavior: Persistent Problems*, New York: Wiley, 1976.

Maynard Smith, John, "Group Selection and Kin Selection," *Nature*, March 14, 1964, *201*, 1145–47.

Mayr, Ernst, *Populations, Species, and Evolution*, Cambridge: Belknap, 1970.

______ **and Provine, W.,** *The Evolutionary Synthesis: Perspectives on the Unification of Biology*, Cambridge: Harvard University Press, 1980.

Mazur, John E., "Optimization Theory Fails to Predict Performance of Pigeons in a Two-Response Situation," *Science*, September 1981, *214*, 823–5.

Menger, Carl, *Principles of Economics*, (1871), trans. by James Dingwall and Bert F. Hozelitz, eds., New York: New York University Press, 1981.

______, *Problems In Economics and Sociology*, (1883), trans. by F. J. Nock, Urbana: University of Illinois Press, 1963.

Michaels, C. F. and Carello, C., *Direct Perception*, Englewood Cliffs: Prentice-Hall, 1981.

Miller, G. T., Galanter, E. and Pribram, K. H., *Plans and the Structure of Behavior*, New York: Holt, 1960.

Miller, James G., *Living Systems*, New York: McGraw-Hill, 1978.

Mondon, Y., "What Makes the Toyota Production System Really Tick," *Industrial Engineering Magazine*, January 1981, *17*, 37–46.

Monod, Jacques, *Chance and Necessity*, New York: Random House (Vintage Books), 1972.

Montgomery, Viscount, *A History of Warfare*, Cleveland: World Publishing, 1968.

Montross, L., *War Through the Ages*, New York: Harper & Brothers, 1960.

Muth, Richard, "Rational Expectations and the Theory of Price Movements," *Econometrica*, July 1961, *29*, 315–35.

Nelson, Richard, "Research on Productivity Growth and Productivity Differences: Dead Ends and New Departures," *Journal of Economic Literature*, September 1981, *19*, 1029–64.

______ **and Winter, Sidney,** *An Evolutionary Theory of Economic Capabilities and Behavior*, Cambridge: Harvard University Press, 1982.

______ **and** ______, "Neoclassical Versus Evolutionary Theories of Economic Growth," *Economic Journal*, December 1974, *84*, 886–905.

Newell, A. and Simon, Herbert, *Human Problem Solving*, Englewood Cliffs: Prentice-Hall, 1972.

Nourse, James G., *The Simple Solution to Rubik's Cube*, New York: Bantam Books, 1980.

Okun, Arthur M., "Inflation: Its Mechanics and Welfare Cost," *Brookings Papers on Economic Activity*, 2: 1975, 351–401.

______, *Prices and Quantities: A Macroeconomic Analysis*, Washington: The Brookings Institution, 1981.

Ouchi, William, *Theory Z*, New York: Avon Publishers, 1981.

Pauli, Wolfgang, *Theory of Relativity*, New York: Dover, 1981.

Phelps, Edmond, "Okun's Micro-Macro System: A Review Article," *Journal of Economic Literature*, September 1981, *19*, 1065–73.

Piaget, J., *The Psychology of Intelligence*, London: Routledge & Kegan Paul, 1947.

______, *The Origins of Intelligence*, New York: International Universities Press, 1952.

Pianka, Eric R., *Evolutionary Ecology*, 2d ed., New York: Harper & Row, 1978.

Pilbean, D., *The Ascent of Man: An Introduction to Human Evolution*, New York: Macmillan, 1972.

Popper, Karl, *Conjectures and Refutations: The Growth of Scientific Knowledge*, 3d ed., rev., London: Routledge & Kegan Paul, 1969.

______, *The Logic of Scientific Discovery*, New York: Basic Books, 1959.

Posner, Richard, *Economic Analysis of Law*, 2d ed., Boston: Little-Brown, 1977.

______, "A Theory of Primative Society, With Special Reference to Primative Law," *Journal of Law and Economics*, April 1980, *23*, 1–54.

Prelec, D., "Matching, Maximizing, and the Hyperbolic Reinforcement Feedback Function," *Psychological Review*, March 1982, *89*, 189–230.

Premack, David, *The Mind of an Ape*, New York: Norton, 1983.

Priest, George L., "The Common Law Process and the Selection of Efficient Rules," *Journal of Legal Studies*, January 1977, *6*, 65–83.

Rachlin, Howard, Kagel, John H. and Battalio, R. C., "Substitutability in Time Allocation," *Psychological Review*, July 1980, *87*, 355–74.

Rawls, John, *A Theory of Justice*, Cambridge: Harvard University Press, 1971.

Revere, Lawrence, *Playing Blackjack as a Business*, Secaucus: Lyle Stuart, Inc., 1969.

Roughgarden, Jeffrey D., "Reasons and Rules in Choice: A Framework for Analysis," Department of Engineering Economics Systems, Stanford University, December 1982.

Rowan, B., "Organizational Structure and the Institutional Environment: The Case of Public Schools," *Administrative Science Quarterly*, June 1982, *27*, 259–79.

Rozin, P., "The Evolution of Intelligence and Access to the Cognative Unconscious," in J. A. Spague and A. N. Epstein, eds., *Progress in Psychobiology and Physiological Psychology*, Vol. 6, New York: Academic Press, 1976, 245–80.

Sagan, Carl, *The Dragons of Eden*, New York: Random House, 1977.

Samuelson, Paul A., *Foundations of Economic Analysis*, Cambridge: Harvard University Press, 1947.

Sargent, Thomas J., *Macroeconomic Theory*, New York: Academic Press, 1979.

______, (1976a) "A Classical Macroeconometric Model for the United States," *Journal of Political Economy*, March-April 1976, *84*, 207–37.

______, (1976b) "The Observational Equivalence of Natural and Unnatural Rate Theories of Macroeconomics," *Journal of Political Economy*, May-June 1976, *84*, 631–40.

______ **and Wallace, Neil**, "'Rational' Expectations, the Optimal Monetary Instrument, and the Optimal Money Supply Rule," *Journal of Political Economy*, April 1975, *83*, 241–54.

Savage, L. J., *The Foundations of Statistics*, New York: Wiley, 1954.

Schelling, Thomas C., *Micromotives and Macrobehavior*, New York: W. W. Norton, 1978.

Schotter, Andrew, *The Economic Theory of Social Institutions*, New York: Cambridge University Press, 1981.

Schumpeter, Joseph, *Capitalism, Socialism, and Democracy*, New York: Harper & Brothers, 1942; Harper Colophon Edition, 1976.

Seligman, Martin E. P., "On the Generality of the Laws of Learning," *Psychological Review*, September 1970, *77*, 406–18.

Shackle, G. L. S., *Decision, Order, and Time in Human Affairs*, 2d ed., Cambridge: Cambridge University Press, 1969.

______, *Epistemics and Economics: A Critique of Economic Doctrines*, Cambridge: Cambridge University Press, 1972.

Simon, A. and Sikossy, L., *Representation and Meaning: Experiments With Information Processing Systems*, Englewood Cliffs: Prentice-Hall, 1972.

Simon, Herbert, "A Behavioral Theory of Rational Choice," *Quarterly Journal of Economics*, February 1955, *69*, 99–118.

______, *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization*, 2d ed., New York: Macmillan, 1959.

______, *The Sciences of the Artificial*, Cambridge: MIT Press, 1969.

______, "From Substantive to Procedural Rationality," in S. Latsis, ed., *Method and Appraisal in Economics*, Cambridge: Cambridge University Press, 1976, 129–48.

______, *The New Science of Management Decision*, Englewood Cliffs: Prentice-Hall, 1977.

______, "On How to Decide What to Do," *Bell Journal of Economics*, Autumn 1978, *9*, 494–507.

______, (1979a) *Models of Thought*, New Haven: Yale University Press, 1979.

______, (1979b) "Rational Decision Making in Business Organizations," *American Economic Review*, September 1979, *69*, 493–513.

Singmaster, David *Notes on Rubik's Magic Cube*, Hillside: Enslow, 1979.

______ **and Frey, Alexander H., Jr.,** *Handbook of Cubic Math*, Hillside: Enslow, 1982.

Slovic, Paul and Tversky, Amos, "Who Accepts Savage's Axiom," *Behavioral Science*, November 1974, *19*, 368–73.

______ **and Lichtenstein, Sarah,** "Preference Reversals: A Broader Perspective," *American Economic Review*, September 1983, *73*, 596–605.

Smith, Adam, *The Theory of Moral Sentiments*, (1759), New Rochelle: Arlington House, 1969.

Smith, Vernon L., "Microeconomic Systems as an Experimental Science," *American Economic Review*, December 1982, *72*, 923–55.

Sowell, Thomas, *Knowledge and Decisions*, New York: Basic Books, 1980.

Stanley, Steven M., *Macroevolution: Pattern and Process*, San Francisco: W. H. Freeman, 1979.

Staw, Barry, Sanderlands, Lana and Dutton, Jane, "Threat Rigidity Effects in Organizational Behavior: A Multilevel Analysis," *Administrative Science Quarterly*, December 1981, *26*, 501–24.

Stigler, George, J., "The Economics of Information," *Journal of Political Economy*, June 1961, *69*, 213–25.

Strotz, R. H., "Myopia and Inconsistency in Dynamic Utility Maximization," *Review of Economic Studies*, November 1955, *23*, 165–80.

Sugimori, Y., Kusunoki, K. and Cho, S., "Toyota Production System and Kanban System: Materialization of 'Just in Time' Production and 'Respect for Human' System," *International Journal of Production Research*, December 1977, *15*, 553–64.

Sussman, Hector J., "Catastrophe Theory," *Synthese*, August 1975, *31*, 229–70.

Taylor, D., *Mastering Rubik's Cube*, New York: Holt, Rinehart & Winston, 1980.

Telser, Lester, "Why Are There Organized Futures Markets?," *Journal of Law and Economics*, April 1981, *24*, 1–22.

Thòm, Rene, *Structural Stability and Morphogenesis*, Reading: W. A. Benjamin, 1975.

Thorpe, Edward, O., *Beat the Dealer: A Winning Strategy for the Game of Twenty-One*, New York: Vintage Books, 1962.

Tinbergen, Nino, *The Study of Instinct*, London: Oxford University Press, 1951.

Toates, Fredric, *Animal Behavior: A Systems Approach*, New York: Wiley, 1980.

Tobin, James, "Are New Classical Models Plausible Enough to Guide Policy?," *Journal of Money, Credit and Banking*, November 1980, *12*, 788–99.

Trivers, Robert L., "The Evolution of Reciprocal Altruism," *Quarterly Review of Biology*, March 1971, *46*, 35–58.

Tversky, Amos, "Intransitivity of Preferences," *Psychological Review*, January 1969, *76*, 31–48.

Ullman-Margalitt, Edna, *The Emergence of Norms*, New York: Oxford University Press, 1978.

Varian, Hal R., "Catastrophe Theory and the Business Cycle," *Economic Inquiry*, January 1979, *17*, 14–28.

Vaughan, William, "Melioration, Matching, and Maximization," *Journal of the Experimental Analysis of Behavior*, September 1981, *36*, 141–49.

von Neumann, John and Morgenstern, Oskar, *Theory of Games and Economic Behavior*, Princeton: Princeton University Press, 1944.

Watson, James, D., *Molecular Biology of the Gene*, 3d ed., Menlo Park: W. A. Benjamin, 1976.

Weber, R., "The Allais Paradox, Dutch Auctions, and Alpha-Utility Theory," J. L. Kellogg Graduate School of Management Working Paper, Northwestern University, 1982.

Weiner, Norbert, *Cybernetics*, Cambridge: MIT Press, 1948.

Weintraub, E. Roy, "The Microfoundations of Macroeconomics: A Critical Survey," *Journal of Economic Literature*, March 1977, *15*, 1–23.

Wendt, Dirk, "Some Criticism of Stochastic Models Generally Used in Decision Making Experiments," *Theory and Decision*, May 1975, *6*, 197–212.

White, Andrew D., *Fiat Money Inflation in France*, New York: D. Appleton-Century, 1933; Los Angeles: Pamphleteers, Inc., 1945.

Wilkins, Maurice, "Molecular Structure of Deoxypentos Nucleic Acids," *Nature*, April 1953, *171*, 738–40.

Williamson, Oliver E., *Markets and Hierarchies: Analysis and Antitrust Implications*, New York: The Free Press, 1975.

______, "Transactions-Cost Economics: The Governance of Contractual Relations," *Journal of Law and Economics*, October 1979, *22*, 233–61.

______, "The Modern Corporation: Origins, Evolution, Attributes," *Journal of Economic Literature*, December 1981, *19*, 1537–68.

______, "Credible Commitments: Using Hostages to Support Exchange," *American Economic Review*, September 1983, *73*, 519–40.

Wilson, Edward O., *On Human Nature*, Cambridge: Harvard, 1978.

______, *Sociobiology: The New Synthesis*, Cambridge: Belknap, 1975.

Winter, Sidney G., "Economic 'Natural Selection' and the Theory of the Firm," *Yale Economic Essays*, May 1964, *4*, 225–72.

______, "Satisficing, Selection, and the Innovating Remnant," *Quarterly Journal of Economics*, May 1971, *85*, 237–62.

______, "Optimization and Evolution," in R. H. Day and R. Groves, eds., *Adaptive Economic Models*, New York: Academic Press, 1975.

Winterfeldt, Detlof, "Additivity and Expected Utility in Risky Multi-Attribute Preferences," *Journal of Mathematical Psychology*, February 1980, *21*, 66–82.

Zeeman, E. C., *Catastrophy Theory*, New York: Addison-Wesley, 1977.