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On the Need and Use of Models to Explore the Role of Economic Confidence: A Survey

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Abstract

Empirical studies suggest that consumption is more sensitive to current income than suggested under the permanent income hypothesis, which raises questions regarding expectations for future income, risk aversion, and the role of economic confidence measures. This report surveys a body of fundamental economic literature as well as burgeoning computational modeling methods to support efforts to better anticipate cascading economic responses to terrorist threats and attacks. This is a three part survey to support the incorporation of models of economic confidence into agent-based microeconomic simulations. We first review broad underlying economic principles related to this topic. We then review the economic principle of confidence and related empirical studies. Finally, we provide a brief survey of efforts and publications related to agent-based economic simulation.

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On the Need and Use of Models to Explore the Role of Economic Confidence: A Survey

1.0 Introduction

Bird (2002) points out that "many commentators have suggested that the world changed on 11 September 2001. The terrorist acts in New York and Washington made the future more uncertain." Just one month after the 911 attacks, John Virgo, Executive Vice President of the International Atlantic Economic Society, chaired the *September 11th Panel Discussion* of the 52nd International Atlantic Economic Conference. Virgo observed that consumer confidence for September was at a five year low and in October slid to nearly an eight year low. He also observed that October [employment] figures showed the largest one-month decline in more than 21 years. "This makes it difficult for the rate cuts by the Federal Reserve to have the desired impact" (Virgo 2001 p355). Virgo reminds us that the economy was already slowing down before September 11th. The Federal funds rate had been cut 7 times in 2001 before the attack and three more times by November. At a Fed funds rate of only 2%, many economists worried that the Fed was running out of room to use monetary policy.

William J. Baumol, a panelist at the same International Atlantic Economic Conference, presented a more optimistic outlook, stating "The long-run benefits for the economy of the catastrophe are a Keynesian stimulus and replacement of obsolete facilities thereby improving the efficiency and effectiveness" (Virgo 2001 p353). Most economists would probably agree that events like September 11, 2001, do affect how people behave, but how people react to "increased uncertainty" and what that means for the economy is an issue at the heart of the debate over economic theory and policy.

The issue of uncertainty undoubtedly has broad implications for public policy, not the least of which will be those of the Department of Homeland Security (DHS). Indeed, Homeland Security Secretary Tom Ridge stated in a speech at the New York Federal Reserve on July 8, 2003 that "Safeguarding the integrity of America's financial systems is a key part of homeland security." Clearly, DHS must understand the potential effects of terrorist events on economic confidence and financial markets in order to make comprehensive comparisons of the relative effectiveness of mitigation and response strategies.

Confidence and financial markets are governed largely by the economic forces at work within the consumption and savings decisions of discrete microeconomic agents, such as firms, households, and financial intermediaries. Economists provide a rigorous framework for investigating these forces, based largely on the groundbreaking work of Milton Friedman, Franco Modigliani, et al in the 1950s and 60s and culminating in hypotheses that form the foundation for much of our nation's monetary and fiscal policy. However, modern empirical research finds that actual consumer expenditures are more sensitive to current income than forecast by these hypotheses, suggesting the need for models of consumer confidence and precautionary savings. These issues have clear implications for modeling the effects of terrorist attacks on confidence and financial markets.

Fortunately, the aforementioned theoretic framework integrates nicely into the discrete agent-based simulation framework, providing a powerful algorithmic foundation upon which to incorporate discrete models of confidence. This approach surpasses the analytical capability afforded by traditional economic modeling methods in two ways. First, agent models can be very complex and are less constrained by the need for simplifying assumptions, as is generally the case for theoretical economic models. Second, agent models can explore behavior under extreme circumstances that have never occurred in history, which is never the case with empirical economic models.

2.0 Risk and Uncertainty

Without information, consumers and producers cannot successfully make rational decisions. Economic models of perfect competition and market equilibrium depend on knowledgeable economic participants. However, information about the future and about the actions of others is usually imperfect, and most decisions are subject to some uncertainty. In order to understand how economists have tried to incorporate incomplete or imperfect information into their models it is useful to review the development of the tools economists use to describe uncertainty and risk.

2.1 Probability and Statistics

The risk that uncertainty imposes on decision makers has been acknowledged throughout human history, but it is only recently that man has begun to study this problem from a scientific perspective. Before the use of modern techniques in statistical analysis, decision theory, and economics, the future was considered beyond the realm of human understanding. Some evidence of man's familiarity with risk comes from early archeological evidence of gambling. For example, in an early form of dice played with *astragali*, or the rectangular-shaped ankle bone of a hoofed animal, players gambled on which side the bone would land. Recognizing that the outcome of rolling the bones was uncertain, individuals were willing to exchange the possibility of a loss for the chance of a win, or, in other words, they were willing to accept some risk. The rules associated with this game, however, also provide anecdotal evidence that, although the players were aware of facing a risk, they did not fully understand the nature of the risk. Despite the greater likelihood of landing on some sides than others, more difficult throws weren't always given higher value. Even with the later development of "fair" dice, it was most likely well known among gamblers that the chances of throwing a seven with two dice were better than throwing a two, but the exact difference between those chances wasn't formally developed until the 16th century, when the concept of probability was introduced.

Although there are some situations in which probabilities may not be suited to decision making, gambling and the purchasing of insurance are examples where the decision to participate involves a mathematical expectation of loss. "Gambling is exemplified by preferring the small probability of a large gain and the large probability of a small loss to the certainty of an income greater than the mathematical expectation of the gamble; insurance means preferring a certain small loss to the small chance of a large loss" (Arrow 1971 p5). That people have participated in gambling and are willing to buy insurance suggests that individuals are able to make decisions about risky situations. A first step, then, in understanding how we choose which actions to take when the consequences of those actions is uncertain is to understand probabilities.

A famous Italian physician and self-admitted compulsive gambler, Girolamo Cardano, was the first author to represent probability as a fraction. In his book, *Liber de Ludo Aleae* written in 1525 and published post-humously in 1663, Cardano showed that the chances of throwing any number with only one die are all equal: one out of six. He then continued with two dice and developed a table showing the chances of throwing each number from two to twelve, with the highest chances being centered on seven. Cardano then went on to experiment with larger numbers of dice. Being a gambler, Cardano distinguished between chances, and odds. "As Cardano put it, the *probability of* an outcome is the ratio of favorable outcomes to the total opportunity set. The *odds on* an outcome are the ratio of favorable outcomes to unfavorable outcomes. The odds obviously depend on the probability, but the odds are what matter when you are placing a bet" (Bernstein 1998 p53). If the odds offered on a bet are less than the ratio of unfavorable to favorable outcomes, it is not a good bet. By the end of the century, Cardano's ideas had spread across Western Europe. Today, these principles form the basis of logistic statistics and discrete choice theory.

A few years before Cardano's book was published, Blaise Pascal and Pierre de Fermat also stumbled upon probability when they developed Pascal's triangle. In 1654, the two began a correspondence discussing the problem of the points, introduced by Luca Paccioli in his 1494 book, *Summa de arithmetic, geometria et proportionalita*. "This brain-teaser appears repeatedly in the writings of mathematicians during the sixteenth and seventeenth centuries. There are many variations, but the question is always the same: How do we divide the stakes in an uncompleted game?" (Bernstein 1998 p43). Pascal's triangle of numbers, with each element equaling the sum of the two numbers above, describes the frequency of possible combinations of two outcomes.

1
1 1
1 2 1
1 3 3 1
1 4 6 4 1
1 5 10 10 5 1

Figure 1. Pascal's Triangle.

Each row adds to the total number of combinations. Dividing the frequency of a possible combination by the total number of combinations gives the probability. The top row describes an event with certainty. The second row describes an equal probability situation like flipping a coin or having a boy or girl, or winning or losing a game. Adding across, the total number of outcomes is 2 and the probability of each outcome is ½ or 50%. The probability of winning two games can be found in the third row. There are four possible results: one chance of winning both games, two chances of winning one and losing win (win then lose or lose then win), and one chance of losing both games. Because winning appears in three of the four possible outcomes, the probability of winning at least one game is 75%. The probability of winning one and losing one is 50% (see Bernstein p64). The stakes in Paccioli's theoretical game should be divided according to the probability of each player winning the remaining number of games required.

Probabilities were very useful for keeping track of information and relating the likelihood of some events to others, but it still remained to discover the characteristics of these probabilities that would make them useful in formulating decisions about the unknown. The term "statistics" wasn't actually used until around 1748, when a German political geographer named Gottfried Achenwall used it as a contraction for "State Arithmetic". Despite the late appearance of the name, statistics had been in use for some time. By 1279, the King of England had declared rules and procedures for sampling the currency to determine the reliability of the mint. These rules did not have a mathematical background, however, and it would be many years before they would be improved upon.

In 1662, John Graunt's study on the causes and number of deaths was published. *Natural and Political Observations made upon the Bills of Mortality* was based on the compilation of statistics Graunt had obtained from available church records and government documents. Despite inaccuracies in the data, Graunt was able to make fairly accurate calculations of life expectancy, cause of death, male to female ratios, and total population. In 1693, a paper by Edmund Halley continued work based on Graunt's method. Using more complete statistics than Graunt, Halley was able to determine the life expectancy of people at different ages and suggested the logical effects that should have on life insurance premiums.

By the 18th century, the methods of using sample data to draw conclusions about the population from which they were drawn were quickly expanded. In 1713, Nicholas Bernoulli finished editing and published *Ars Conjectandi*, a book that had been written by his late uncle, Jacob Bernoulli. In the book, Bernoulli states what has come to be known as the law of large numbers. "In its simplest form…the law states that in a sequence of independent trials in each of which a given event E may occur with a constant probability p, the probability that the relative frequency of occurrence of E in n trials differs from p by more than any assigned positive quantity can be made as small as desired by making n sufficiently large" (Arrow 1971 p14).

Despite the value of this discovery, Bernoulli's method would still require a very large number of samples to be drawn. Bernoulli presented the problem to a well known mathematician, Abraham de Moivre. De Moivre concluded that if a large number of samples are taken, most of them will be close to the mean and very few significantly far away. Based on this, he developed the "normal" or "bell shaped" curve to describe the distribution of errors in sampling about the mean.

Two people are particularly responsible for the popularization of normal distribution. The first, Carl Friedrich Gauss, applied the idea to astronomy. In his 1809 book, *Theoria Motus*, Gauss advocated observing the most common path of heavenly bodies in order to estimate their orbits. The Marquis Pierre Simon de Laplace applied the normal distribution to estimates of the population of France as well as the mass of Jupiter. He also expanded the theory to his central limit theorem around 1809. He stated that by taking the average of a set of averages obtained from a large number of samples, the variation about the overall mean would be less than that of the individual observation.

Thomas Bayes' *Essays Towards Solving a Problem in the Doctrine of Chances,* published in *Philosophical Transactions* in 1764, investigated essentially the opposite of Bernoulli's sampling question. Bayes asked: Given historical evidence that a sample will produce a certain result, what is the probability that any one trial will vary within a certain range from the average? "The primary application of the Bayseian system is in the use of new information to revise probabilities based on old information, or, in the language of the statisticians, to compare posterior probability with the priors" (Bernstein 1998 p132). Bayes clearly formulated how people could make use of information to derive probabilities, but his method still required the process to start from somewhere. What should these original beliefs about probability be? Here Bayes relied upon what many statisticians before him had settled with, Jacob Bernoulli's Principle of Insufficient Reason: "…it states that if there is no evidence leading us to believe that one of an exhaustive set of mutually exclusive events is more likely to occur than another, then the events should be judged equally probable" (Arrow 1971 p12).

2.2 Risk and Economics

By the time Adam Smith introduced the world to economics in 1776 (see Smith 1937), much of the foundations for describing individual choices under uncertainty were in place. With the Law of Large Numbers, the Normal Distribution, the Central Limit Theorem, and Bayes' Method, statisticians were prepared to measure and study risk.

Before proceeding further, it is necessary to distinguish between uncertainty and risk, at least in the economic sense. Kenneth Arrow describes in his 1971 *Essays in the Theory of Risk Bearing* the situation of individuals facing decisions with unknown consequences as follows. "It is known that one out of a number of hypotheses about a given situation is true. The statistician has the choice of one of a number of different experiments, the outcome of any one of which is a random variable with a probability distribution depending on which of the unknown hypotheses is correct. On the basis of that outcome, the statistician must take some action (accept or reject a hypothesis, estimate the mean of a distribution to be some particular value, accept or reject a load of goods, recommend a change in production methods, etc.) the consequences of which depend on the action taken and on the hypothesis which is actually true" (Arrow 1971 p8). In other words, when faced with uncertainty people will make decisions based on their perceptions of the risk. In addition, Arrow requires that risk can be described by individual expectations of the outcome and the degree of certainty in that expectation. Uncertainty arises when the outcome of an event is unknown; risk is the condition that is imposed on the decision-making process of choosing without complete information.

Accepting Arrow's assumption that uncertain events are random but governed by a probability distribution, probability and statistics seem to be the perfect tools for modeling risk. But there is more at work when it comes to analyzing the effects of uncertainty on decision theory, even when it comes to playing games. "The principles at work in roulette, dice, and slot machines are identical, but they explain only part of what is involved in poker, betting on the horses, and backgammon" (Bernstein, 1998 p14). In the latter set, choice, and thus preferences, plays a part in addition to chance. In 1738, Daniel Bernoulli made his contribution to the history of decision making. In *Papers of* *the Imperial Academy of Sciences in St. Petersburg*, Bernoulli suggested that in addition to probability, which can be publicly known or estimated and is therefore potentially identical for everyone, utility or expected satisfaction, which varies across individuals, comes into play when formulating decisions. Useful examples are peoples' reactions to lightning. Prior to the concept of utility, fear of being struck by lightning would have been considered irrational because according to probability, the chances are very small. "Bernoulli saw the situation more clearly: people with a phobia about being struck by lightning place such a heavy weight on the consequences of that outcome that they tremble even though they know that the odds on being hit are tiny" (Bernstein 1998 p105). Daniel Bernoulli also hypothesized that the gain in utility one experiences is inversely proportionate to the wealth one already possesses. He also thought, along the same lines of reasoning, that the amount of utility lost due to a negative outcome would be greater than the amount of utility gained due to a positive outcome.

Bernoulli's ideas lay dormant for quite some time. In the early 19th century, however, they were revived by a popular English philosopher, Jeremy Bentham. Bentham suggested that people make decisions based on their expectations of both pleasure and pain, or utility. William Stanley Jevons took Bentham's ideas and explained them mathematically. In *The Theory of Political Economy*, "Jevons opens his analysis by declaring that 'value depends entirely upon utility'… Jevons was confident that he had solved the question of value, claiming that the ability to express everything in quantitative terms had made irrelevant the vague generalities that had characterized economics up to that point. He brushed off the problem of uncertainty by announcing that we need simply apply the probabilities learned from past experience and observation" (Bernstein 1998 p190). To paraphrase again, choices are made according to an individual's value of the expected outcome, which is determined by the probability of occurrence for each outcome.

Probability and economics would be forever intertwined. Utility theory led directly to the foundations of modern economics: laws of supply and demand and the static economic model of price determination in competitive markets.

Despite the valuable contribution to decision theory, some economists have pointed out fundamental problems with utility. In 1921, in *Risk, Uncertainty and Profit*, Frank Knight distinguishes between risk and uncertainty in his model of a competitive market system. "It is *conceivable* that all changes might take place in accordance with known laws, and in fact very many changes do occur with sufficient regularity to be practically predictable in large measure. Hence the justification and the necessity for separating in our study of the effects of change from the effects of ignorance of the future" (Knight, p198). Probability can account for the risky prospect of some foreseen changes, but the future remains uncertain.

In that same year, John Maynard Keynes' *A Treatise on Probability* reiterated Jules - Henri Poincare's point that what appears to be chance is really the result of some unforeseen cause and effect. Keynes pointed out that because of man's limited knowledge, what is thought to be probable today, is not necessarily so tomorrow. Our forecasts, according to Keynes, are only degrees of belief in an uncertain future.

It is probably no mistake that the man who introduced us to probability was a gambler. He relied on his dice playing experience, the repeated sampling process of throwing dice, to make observations about risk in a similar way to that described by Bayes. In many situations, however, we are not afforded the luxury of such an easy experiment as rolling dice. There are many situations that we face every day that suggest risk, but are not so easily addressed by simple probability distributions. Arrow (1971 p5) provides examples, such as "…the existence of legally guaranteed incomes, variation in the rate of return on securities, and the holding of inventories beyond those demanded by pure transfer cost consideration. In a world of certainty, contractual obligations such as leases, bonds, and long-term labor contracts would have no significance, except possibly as a protection against dishonesty". Here, again, it is reasonable to assume that we make assessments of risk in these situations based on experience and information, but these risk assessments get at the heart of the debate between probabilities as an objective measure and probability as a measure of belief. We can use statistics to make reasonable estimates of the probability of many events, but these are still estimates. The validity of statistical estimates is related to the number of observations available, but in addition to the daily risks we face (like the weather) there are infrequent or even one-time events that pose a risk.

Theorists were divided. The followers of Jevons and Menger on one hand, and Knight and Keynes on the other: those that believed in an objective, measurable utility, and those who believed in a weaker, subjective utility.

2.3 Game Theory

In 1926, John von Neumann presented a paper on game theory to the Mathematical Society at the University of Gottingen that would eventually have a profound effect on the study of decision theory. Before the introduction of game theory, economists relied on the assumption of "perfect information" to model the interactions of economic agents. Game theory looked at competition from a more primitive point of view.

Von Neumann described a game he had played as a young boy, match penny. In the game, two players choose a side of a coin and then reveal their choices to one another. If they match one player wins and if they don't, the other does. Von Neumann determined that the best strategy was to choose heads or tails randomly and equally. He argued that if one player chose to reveal heads six out of every ten times, the other player would catch on and choose his strategy accordingly. His analysis showed that the odds of 50/50 were not only derived from the coins themselves, but from free choice as well. His results suggest that the best strategy of play is not to *win* the game, but rather to *not lose* the game; this was a novel idea for decision theory.

In 1944, *Theory of Games and Economic Behavior* was released by von Neumann and Oscar Morgenstern. Being interested in von Neumann's ideas, Morgenstern had encouraged him to apply his ideas to economics. The result was a new way to look at competition and analyze decision making. The authors developed new rules for determining outcomes when two, three, and many agents interact and how those outcomes vary as information is made available to all or some of the agents. A useful tool that was developed was the concept of the zero-sum game, in which the winnings of one player are the losses of another. In this situation the authors were able to characterize the necessary conditions for a "solution" to the game. Imagine a game in which each of two players is to select one of two strategies available to them. The outcome of the game is determined by the combination of strategies chosen by the two players. If the game is a zero-sum game, a solution will only exist if the strategy with the largest minimum payoff for each player leads them to pick the strategies that will result in both players receiving that largest minimum payoff. If there is not this coincidence of strategies, the results of the game are indeterminate. There are two problems with finding the solution to games: (1) they must be zero-sum, and (2) they must have payoffs that make the players want to choose particular strategies. The authors deal with the first problem by introducing an additional player, "nature." Their idea was that the residual payoffs in a two person game go to an imaginary third player. In this way, all games could be conceived of as zero-sum games. In order to deal with the requirements of the payoff-strategy alignment needed to solve the game, the authors introduced "mixed strategies." If it was not clear what an opponent would choose by the design of the game, a player could calculate the expected payoff of each of their own strategies by applying a subjective probability to each of their opponents' choices. Here, the authors do not hesitate to apply probabilities to obtain expected values and, in fact, rely on them as a means of solving otherwise ambiguous games. (see Von Neumann-Morgenstern 1944, Hurwicz, Marschak)

To support their use of expected utility, von Neumann and Morgenstern reintroduce cardinal utility theory. The two authors asked an individual to choose an order of preference between three goods: coffee, tea and milk. If the individual preferred coffee to tea and tea to milk, then when asked: given a choice between coffee for certain and a 50/50 chance of tea or milk, what would you choose? Obviously the person would choose coffee since he prefers it to either of the other two options. However, when the question is altered: given a choice between tea and a 50/50 chance of coffee or milk, what would you choose? The answer is not so straight forward. By varying the probability in the second part of the choice, von Neumann and Morgenstern were able to measure the relative utility that individual placed on the three goods. They also adjusted their experiment to analyze money. The choices were then between a certain sum of money for certain, and the chance of either more or less money at some probability. By altering the amounts and the probabilities, they were able to measure the degree of risk aversion, "…that is, how far we are willing to go in making decisions that may provoke others to make decisions that will have adverse consequences for us" (Bernstein 1998 p239). The final result was an axiomatic approach to defining cardinal utilities that describe how individuals order their preferences over a variety of gambles.

2.4 Measuring Risk Aversion

Von Neumann and Morgenstern went to great lengths to validate their theories in their book, but one thing seemed certain, expected utility and its measurement was here to stay. In the 1960's, both John Pratt and Kenneth Arrow, independently, developed a measure of local risk aversion based on the slope and curvature of mathematically defined utility functions. For a utility function $u(x)$, the Arrow-Pratt measure of absolute risk aversion is $r(x) = \frac{-u''(x)}{u'(x)}$. When x is money or wealth, this measure of risk aversion has the convenient characteristic that a higher value indicates greater risk aversion characterized by the difference between the utility of the expected value of a gamble and the expected utility of the gamble. Following von Neumann and Morgenstern, the authors reason that there should exist some amount, a certainty equivalent, that a risk averse individual should be willing to accept without risk in order to avoid being faced with a gamble. The difference between this certainty equivalent and the expected value of the gamble is the individual's risk premium. Higher measures of risk aversion indicate smaller certainty equivalents and, therefore, larger risk premiums. Relative risk aversion, or $\frac{r(x)}{x}$, is a useful measure when the gamble described is relative to one's existing wealth. (see Arrow 1971 chapter 4 and Pratt 1964)

Following Pratt's example, Roger Bowden (1972) suggested replacing the "stochastic life-cycle problem with a certainty equivalent problem in which expectations of future income receipts are adjusted by the subtraction of risk premiums, as a manifestation of risk aversion on the part of the individual" (p211). Bowden suggests that consumers decide how much to spend and how much to save in each period by evaluating their current and future expectations of income. Because of uncertainty about the future, consumers base their decisions on a certainty equivalent rather than actual income. Bowden also suggests that the risk premium is endogenous to the allocation problem and posits possible implications for the time profile of lifetime consumption.

2.5 The Principal-Agent Problem

It seemed as if economics had made great progress in dealing with risk, but in 1970 George Akerlof reminded us of the limitations of using statistics to describe risk. "There are many markets in which buyers use some market statistic to judge the quality of prospective purchases. In this case there is incentive for sellers to market poor quality merchandise, since the returns for good quality accrue mainly to the entire group whose statistic is affected rather than to the individual seller" (Akerlof, 1970 p488). Akerlof was essentially applying the *tragedy of the commons* to a competitive market. He argued that in a market driven by quality statistics, there would be an incentive on the part of producers to make inferior products in order to cut costs. The inferior products, valued at the market average, would enjoy the reputation of the larger market as well as benefit from cheaper production methods. As more and more inferior products enter the market, the market statistic would be dragged down and the "lemons" would drive out the quality products. Akerlof extends this problem of "adverse selection" to the insurance, labor, and credit markets. In each case the principle, or business, must make a decision based on limited information about the agent with which they wish to do business. Using insurance as an example, if an insurance company sets its premiums based on some market statistic, taking into account the insured's risk premiums, the company runs the risk of encouraging only the individuals with higher risk than the market average to purchase the insurance.

Another example of how relying on statistical evidence may cause the purchaser of risk to inadvertently create undesirable incentives is moral hazard. Again, it is useful to think of insurance. By charging a premium based on market statistics, "*The insurance policy might itself change incentives and therefore the probabilities upon which the insurance company has relied*. Thus, a fire insurance policy for more than the value of the premises might be an inducement to arson or at least to carelessness" (Arrow 1971 p142).

The problems associated with contracts and incentives have become known as the principal-agent problem. "Consider two individuals who operate in an uncertain environment and for whom risk sharing is desirable. Suppose that one of the individuals (known as the agent) is to take an action which the other individual (known as the principal) cannot observe. Assume that this action affects the total amount of consumption or money which is available to be divided between the two individuals. In general, the action which is optimal for the agent will depend on the extent of risk sharing between the principal and the agent. The question is: What is the optimal degree of risk sharing, given this dependence?" (Grossman and Dart, 1983 p7; also see Holmstrom 1979.)

2.6 Rational Expectations

The study of economics has, from the beginning, been aimed at understanding rational behavior. Faced with scarcity, mankind must make many choices and the rational way to make those choices necessarily involves risk. As we have seen, economists have introduced risk into many of their models over the years and it has become common practice to describe risk with probabilities based on statistical distributions. There is some disagreement about whether the probabilities used should be subjective or objective, but there is general agreement that expectations play a crucial role in economic models.

Following the great depression, economists began to question the complete reliance on free markets of the classical economists. Eventually, econometric models of aggregate supply and aggregate demand became the bedrock of Keynesian Macroeconomics. Keynes argued that the government could influence aggregate demand and therefore actively resist economic downturns like the great depression. Elaborate models of the economy were built to analyze data and estimate parameters, but Keynesian models and associated monetary policy performed poorly in the face of the oil shocks of the 1970's.

In "Expectations and Neutrality of Money", Robert Lucas (1972) introduced what has become known as the Lucas Critique. "For policy analysis, the traditional macroeconomic models were used to describe the laws of motion of the economy in much the same way as an engineering model would describe the laws of motion of a rocket ship. The economic policymaker, like the engineer, was assumed to be playing a game against nature, because the economic agents in the model could not react (adjust their decision rules) to the policymaker's moves. The new analysis changed the policy game to one against other players, where the other players, the private agents, are allowed to adjust to the moves of the policymaker" (Miller 1994 p3). By controlling taxes or the money supply, policymakers were adjusting one of the inputs just as an engineer might change the mix of rocket fuel in a spaceship to adjust its flight path. How the model would change was predicted by the coefficients. Lucas argued, however, contrary to the engineering analogy, when the government made changes to the inputs in an economic model, those changes might affect the coefficients. That is, when the government changed taxes of the money supply, they were essentially changing the rules by which economic agents play. And when the rules change, the players change their expectations and the way they behave.

The rational expectations doctrine was extended by Sargent (1973) and Barro (1974, 1976, 1978, 1979, 1984). Miller (1994) states "The economist in the Minneapolis Fed's research team… argue[d] that the Lucas critique was fatal and that new approaches had to be developed." Despite the perceived failure of Keynesian macro-econometric models, neo-classicists such as Lucas and Sargent pursued equilibrium models based on the assumptions that agents are rational, reacting to policy changes in a way which is in their best interests privately, and that the impulses which trigger business fluctuations are mainly unanticipated shocks. The neo-classical rational-expectations economists concluded that economic agents respond to policy formation and form expectations in such a way to yield monetary policy neutral. That is, only relative prices matter and that expansive monetary policy will only cause inflation, not real growth.

However, neo-Keynesian economists also developed models using rational expectations that predicted the possibility of effective government intervention leading to real growth. The conflicting results of neo-classicists and neo-Keynesians raised new questions. As with microeconomics, the introduction of risk and the expectations that economic agents form about an uncertain future in macroeconomic models relaxes an unnecessarily rigid assumption: that information is complete, free, and equally available to all agents. But rational expectations theory of business fluctuations, and the corresponding empirical work, did not provided a definitive analysis of monetary non-neutrality and business cycles.

3.0 Consumer Confidence

As their understanding of risk, uncertainty, and expectations advanced, economists began to incorporate these ideas into the formal models of consumption. Of particular interest for many decades, no more so than after 911, is how general uncertainty about world events affects individual consumption decisions. The popular press often cites consumer confidence measures as indices of risk perception, implying that aggregate consumption reflects these measures in some way. But do these indices measure risk perceptions in a way that is useful for economic analysis? Or do they reflect agents' knowledge of more traditional economic indicators? Before any link between consumer confidence measures and consumption can be developed, an understanding of the various theories of how uncertainty affects consumption is necessary.

3.1 Psychological Economics

An explanation of uncertainty and its role in determining consumer behavior began with George Katona of the University of Michigan's Institute for Social Research. A psychologist by training, Katona developed a survey that asked people about their current financial situation, the business climate, and their expectations of their job and earnings prospects in the future. Using this survey, Katona created an index of consumer confidence; higher values indicated that the economic situation is good and projected by individuals to get better; lower values show pessimism about the economy and the future. Such an index is consistent with the expected utility theories discussed in the previous section; changes in the index value may reflect changes in perceptions of probabilities of future outcomes.

The survey and confidence index reflected Katona's view (and a budding vein of research) that psychology plays a role in individual consumption decisions. The psychological impact on consumption can be summed up by saying that consumption is determined by agents' ability and willingness to buy. At its heart, psychological economics recognizes that agents are not "marionettes pushed around by external forces," (Katona date p8). Rather than acting as automatons to changes in prices, wages, and income, agents determine their level (and type) of consumption based on "attitudes, aspirations, and expectations" (Katz 1972 p65).

This thesis stems from the notion that consumption as a function of only prices and income is not well suited to the affluent post-World War II American economy. Consumers after WWII found themselves with discretionary income and the power to choose among a broad range of products and investments. Thus consumption in the U.S. reflected tastes, preferences, and the willingness-to-buy as much as prices and income.

A specific representation of the consumption function is not developed as a result of Katona's work. This appears to be a deliberate implication of joining psychology and economics; if behavior is governed by laws and is measurable, then the empirical observation of behavior should uncover those laws. Instead of theoretically reasoning and testing the hypothesis that a change in income will create predictable changes in consumption, the psychological economist would observe agents' behavior (and perhaps motives or perception) in response to income changes and then reason a theory to explain the behavior.

3.2 Life-Cycle Theory and Permanent Income Hypothesis

Although Katona's work provided a framework for understanding the psychology of choice, the lack of a formal model of consumption would not do for most economists. In the years following the publication of John Maynard Keynes' *General Theory* in 1936, an impressive literature was devoted to his hypothesis of the relationship between income and consumption. While this literature did not explicitly recognize the psychological forces involved, economists increasingly recognized that a simple model of consumption, one based on current income and prices was inadequate. Synthesizing this literature, Franco Modigliani and Richard Brumberg developed a model of consumption where individuals derive utility from current and future consumption, and consumption in the current period is a function of current income, expected income, and the individual's initial set of assets. This model, known as the life-cycle hypothesis (LCH) model describes household behavior as an attempt to smooth consumption patterns over one's lifetime somewhat independent of current levels of income; households do this by borrowing, saving, and lending. The model is typically represented as the following constrained maximization problem:

$$\max U_{t=0} = \sum_{t=0}^{T(t)} \delta(U_t(C_t))$$
$$s.t. \sum_{t=0}^{T(t)} \rho(C_t) = B_{t=0} + \sum_{t=0}^{L(t)} \rho(Y_t), \tag{1}$$

where C_t and Y_t are respectively the levels of consumption and income in period t, $U_t(C_t)$ is the *utility* received from consumption in time period t, B_0 is an initial wealth endowment, and $\delta(\cdot)$ and $\rho(\cdot)$ are discount functions; $\delta(\cdot)$ discounts the value of future utility according to the household's internal time preference, and $\rho(\cdot)$ discounts the value of future consumption and income according to the market interest rate. Also, $L(t) \leq T(t)$, where $L(t)$ denotes the number of remaining periods in which the household can work in the labor market to earn income, and $T(t)$ denotes the number of remaining periods in the household's life cycle.

The main implication is that consumption and income need not coincide in any given period; individuals have motives to save or dissave. The primary purpose of saving is to cushion against future income fluctuations, though the inclusion of uncertainty in the model would introduce two additional motives. First, individuals might have a precautionary motive, or a "desire to accumulate assets…to meet possible emergencies," (Modigliani and Brumberg, 1955 p392). Second, individuals may feel the need to acquire an equity stake in durables in the face of uncertainty. In this case, individuals would save in anticipation of a consumer durables purchase so that less debt would be incurred for the purchase. If consumers are uncertain of their ability to repay debts in the future, paying a larger share out-of-pocket would reduce the impact of such uncertainty.

Modigliani and Brumberg find that Keynes' hypothesis – that individuals will increase consumption in proportion to an increase in income – is explained by their model. Further, they contend that the rate of savings is constant across levels of income.

Although a specific role for expected income appears in the model, no discussion is made of how those expectations are formed or how consumption changes in response to a change in expected income. This shortcoming is addressed to some degree by the Permanent Income Hypothesis (PIH) and its variant the Rational Expectations Permanent Income Hypothesis (REPIH).

The basic idea of PIH is that current period consumption is determined by lifetime resources, not measured income at a given point in time. Permanent income, then, is the annuity value of lifetime net worth. Consumption in a given time period is proportional to permanent income. Incorporating rational expectations explicitly states that agents' expectations of future income are formed using all available information and with full knowledge of the structure of the economy.

Under PIH, individuals determine their permanent income, and thus consumption, by evaluating their expectations of future income. Uncertainty exists in the path of future income, but the assumption of rational expectations gives rise to certainty equivalence with respect to contemporaneous consumption decisions; agents do not know the nature of future income shocks, so decisions are made as though the uncertainty does not exist.

An implication of certainty equivalence is that only changes in expected income can change permanent income (and thus consumption) in the current period. For example, an agent who observes a higher income in the current period (perhaps the result of a wage increase) might expect that the higher level of income will occur in future periods, changing their expected future income. As a result, consumption would contemporaneously change.

The response of consumption to expectations provides the most logical and developed role for consumer confidence in determining consumption. The strength of this role depends on the information consumer confidence indices contain about expected income. If consumer confidence adequately summarizes agents' beliefs about future income, then its role is consistent with PIH. But if consumer confidence predicts current consumption, then it is not consistent with PIH; recall: consumption can only change as a result of changes in expected income.

Several assumptions of PIH require explicit treatment. Foremost, households are assumed to be forward-looking. Second, credit markets must be perfect; agents must be able to borrow and save against future income. If an individual expects a higher future income, they might consume more now by borrowing against future income. Credit market constraints will inhibit this process and consumption would not increase until future income is realized. Thus the link between expectations and consumption would be broken, and PIH would not be valid.

Finally, the interest rate is assumed to be constant over time. This eliminates changes in consumption due the risk of interest rate fluctuations, though these concepts can be added to the model.

3.3 Empirical Testing of PIH

Though the PIH theory of consumption has been well fleshed-out, most studies reject the pure PIH or REPIH for a myriad of reasons. An oft-cited reason for rejection is Flavin's (1981) "excess sensitivity to current income." An implication of Flavin's consumption model is that the revision in permanent income is proportional to the observed error of forecasted income (i.e. "innovation in current income"). REPIH is then tested by whether or not the marginal propensity to consume (MPC) out of current income is zero (i.e. MPC = 0 implies acceptance of REPIH). Flavin finds that the MPC is significantly not equal to zero, and so determines that consumption is excessively sensitive to current income, thus rejecting REPIH.

Flavin's findings are supported by Campbell and Mankiw (1990), who finds in addition that the rejection of REPIH cannot be explained by relaxing the assumptions of constant interest rate or separability of the consumers' utility function.

Acemoglu and Scott (1994) also reject REPIH, but do so by incorporating a measure of consumer confidence. They use confidence as a proxy for individuals' expectations and find that confidence is a leading indicator of consumption changes. This finding is inconsistent with REPIH, where only changes in income expectations can change consumption.

Acemoglu and Scott's work is also noteworthy because it defines a different role for consumer confidence measures. In their attempt to explain the rejection of REPIH, they test whether imperfect capital markets or the precautionary saving motive might account for confidence predicting consumption. Precautionary saving (and not imperfect capital markets) is found to explain the relationship. Their finding suggests a role for confidence measures, not for modeling income expectations, but for explaining risk aversion.

3.4 Forecasting

The exact link between uncertainty, expectations, and consumption is still up for debate, but the impact of consumer confidence on the economy and consumer expenditures has been thoroughly investigated. A prodigious literature is dedicated to the question of whether consumer confidence measures contain information important for economic forecasting and predicting consumer expenditures. Most of these studies, using various econometric models, test whether consumer confidence by itself has predictive content or whether adding consumer confidence improves the predictive ability of forecasts based on leading economic indicators.

The literature is divided on the predictive content of consumer confidence. When confidence measures are found to be significant predictors of expenditures, they often add little in terms of predictive ability. Some studies find no predictive value in confidence measures, or that consumer confidence, on it own, is a poor predictor of consumption. Table 1 summarizes some of the findings in the literature.

Table 1. Summary of Findings for Confidence-Related Studies

Study	**Did consumer confidence improve forecasting model?**	**Is consumer confidence modeled alone or in conjunction with other variables?**
Garner (1991)	Not a good predictor of consumption.	Both
Batchlor and Dua (1998)	Would have helped predict 1991 recession but not 1982 recession.	With other variables
Eppright, Arguca, and Huth (1998)	Consumer confidence has some predictive power not in other economic indicators	With other variables
Howrey (2001)	Consumer confidence modestly increases accuracy of forecasting models.	Both
Desroches and Gosselin (2002)	Not helpful in predicting consumer spending.	Modeled alone
Garner (2002)	Improved forecasting models slightly.	With other variables

These findings are not heartening for researchers seeking a role for consumer confidence in forecasting shocks to the economy, but additional findings provide some hope. Batchelor and Dua (1998) find that consumer confidence may contain important non-economic information. For example, they find that including a measure of consumer confidence in forecasting models would have help predict the 1991 recession, but not the 1982 recession. They hypothesize that this reveals the “special circumstances” surrounding the 1991 recession more than does predictive ability of consumer confidence.

According to Batchelor and Dua, information about shocks that are non-economic in nature, like the 1991 Gulf War, are contained in consumer confidence measures. In these cases the ability of consumer confidence to predict expenditures would be increased.

The findings in Garner (1991) support this view. Garner compares forecast models with and without consumer confidence indices over times of "ordinary circumstances," (late 1987 to the first half of 1990) and "exceptional circumstances," (late 1990 and 1991). Forecasts with consumer confidence performed worse during the ordinary times, but much better during the Gulf War time period. He suggests that the improved forecast ability of the models with consumer confidence is due to the fact that the Gulf War was an unanticipated, non-economic event.

This line of reasoning logically leads to the role of consumer confidence after a terrorist attack. Consumer confidence should be an important indicator of the economy following a terrorist attack; a shock to the economy of this sort leaves individuals little basis for forming expectations and making decisions using more traditional economic indicators. This view is not, however, borne out by the evidence following 911. Garner (2002) finds that the fall in consumer confidence (and the worsening recession) was not a result of these exceptional circumstances. Rather, the consumer confidence measures likely reflected the available economic information.

Garner's apparent contradiction of his 1991 findings points the way for further research into the role (if any) of consumer confidence in the economy. There is clearly a relationship between consumer confidence, as currently measured, and other economic indicators. The nature of that relationship is yet undiscovered. In particular, if consumer confidence does in fact contain important information in the wake of non-economic shocks, then it remains to be answered why consumers were so resilient after 911.

3.5 Conclusions

In a simplified model of the economy, individuals and firms respond to changes in prices by altering consumption and supply decisions based on maximizing individual utility or profit. This model abstracts from reality in that it gives little role to the decision-making process and has the implication that agents behave rationally. If it is acknowledged that agents often make decisions based on little or faulty information, or that the future is uncertain, then the model poorly explains economic outcomes.

Introducing uncertain outcomes into an economic model necessitates the consideration of how individuals perceive risk. By looking at individual choices as choices between different risky situations, decisions can be characterized as satisfying agents' desire to seek or avoid risk. Uncertainty also necessitates an understanding of expectations. Whether considered subjectively or objectively, individual expectations of event probabilities ultimately determine choices between different risky situations.

Despite what economists know about risk and uncertainty, its meaning for modeling responses to large shocks or terrorist attacks is, in a word, uncertain. From the consumer point of view (and the same argument could be made from the producer side), a likely scenario is that a terrorist attack increases the perceived probability of future economic hardship, and consumers respond by reducing current consumption. But consumer response to a terrorist attack depends on agents' perceptions of how event probabilities change, the individual level of risk aversion, and how expectations are formed; thus, as recent history suggests, a large shock will not necessarily lead to a large economic impact. Uncovering the conditions for such an effect is the direction for future research in this field.

Although our survey has focused on the earlier fundamental literature, our research efforts will also incorporate more recent understanding of issues such as precautionary savings (Abel 1984, Wang 2004), unemployment and retirement insurance (Stiglitz and Yun 2002), and the role of social security.

4.0 Agent-Based Economics

The inconclusive empirical findings regarding the role of confidence suggest the exploration of alternative modeling paradigms. We are exploring the use of agent-based simulation for that purpose. Agent-based economic simulation is a computational approach for integrating models of social choice into complex systems of artificial decision makers that allow researchers to conduct controlled economic experiments. The methodology involves the use of computer programs to distribute information, decisions, and communications across many well-defined economic participants who follow certain rules while trying to optimize their user-defined objectives (e.g. utility functions). The experimenter's objective is to replicate the relevant economic activity of individuals, and thereby study complex collective behaviors.

Much of the seminal work in computer simulation of social systems helped to define the need and role for this novel approach to explore issues. Ostrom (1988) states:

> [Computer simulation] should be viewed as a medium through which theoretical propositions can be articulated and predictions can be generated. It is one of several symbol systems available to theorists for expressing theoretic ideas. The first symbol system acquired by students in social psychology is natural language and the second is mathematics. Computer simulation offers a third symbol system. Theorists express their ideas in a program, and a computer is used to facilitate the generation of predictions from the theory-as-a-program.

Gilbert and Terna (2000) expand on this statement as follows:

> The logic of developing models using computer simulation is not very different from the logic used for the more familiar statistical models. In either case, there is some phenomenon that we as researchers want to understand better. This is the "target". We build a model of the target through a theoretically motivated process of abstraction (this model may be a set of mathematical equations, a statistical equation, such as a regression equation, or a computer program). We then examine the behavior of the model and compare it with observations of the social world. If the output from the model and the data collected from the social world are sufficiently similar, we use this as evidence in favour of the validity of the model.

The *processes of abstraction* listed by Gilbert and Terna are well documented and broadly applied. For example, "a set of mathematical equations" might refer to linear or mixed-integer programming models, which are commonly used in applied economics. Such "mathematical equations" might also refer constrained optimization problems commonly defined in theoretical economics. Empirical economics conventionally employs "statistical equations" when conducting data analysis to obtain evidence for theoretic results. However, simulation is becoming more common in economic research for reasons explained by Luna and Stefansson (2000):

> Computer Simulations of economic systems are slowly gaining ground within the profession. Economists have become aware of the limitations of the standard mathematical formalism. On the one hand, when dealing with real world phenomena, it is often impossible to reach a `closed-form' solution to the problem of interest. One possible approach is to simplify the problem so that an elegant closed-form solution is synthesized. The implicit assumption is that the simplification process has spared all relevant elements and discarded only unnecessary ornaments. In case this *a priori* seems too strong, the

empirically oriented researcher may want to employ a simulation to study the dynamical properties of the system.

McCain (2000) describes the role for comparative computer simulation as a logically sufficient means to explain a result by constructing a process which gives rise to the result. This new paradigm is similar to the more common paradigm for economic research, in which axiomatic results are used as a logically sufficient means to explain observed behavioral relationships by employing empirical data analysis to estimate statistical relationships that are consistent with those suggested by the axiomatic results.

Tesfatsion (2001) states that decentralized market economies are complex adaptive systems defined by intricate feedbacks between microstructure and macrostructure. She suggests that economists (e.g. Smith 1937, Hayek 1948, and Schelling 1978) have long recognized this feedback, but have lacked the means to model it in its full complexity. However, agent-based computational economics (ACE) provides a means to "study a wide variety of complex phenomena associated with decentralized market economies, such as inductive learning, imperfect competition, trade network formation, and the open-ended co-evolution of individual behaviors and economic institutions."

4.1 Foundations

The principles of conventional economic theory and practice are founded in the incentives and constraints of individual economic actors, and the interaction of those actors, which is the exact "ground up" structural framework used in agent-based computational economics (ACE); see Epstein and Axtell (1996), Basu et al. (1998), Luna and Stefansson (2000), and Tesfatsion (2002).

Early contributions to computational methodology were provided by Holland and Miller (1991) and Axelrod (1997). Agent-based modeling has since been applied to analyze many fundamental social issues. Elliot and Kiel (2002) provide a brief but illuminating survey of agent-based models used to explore cooperative and competitive behavior, such as Danielson's (2002) study of reciprocity and cooperation in evolutionary games, Macy and Flache's (2002) study of reinforced learning and "stochastic collusion" in mixed-motive games, and Epstein's (2002) study of emergent macro-level dynamics related to societal breakdown.

Much of the agent-based modeling literature has focused on problems that are inherently computational, such as auction markets (Farmer 2001, Zovko and Farmer 2002, and Terna 2002), matching models such as labor markets (Sapienza and Fontana 2002; also Chaturvedi, Metha, Dolk and Ayer 2004), and a broad literature in game theory (e.g. Parsons et al. 2002, Ehlen and Glass 2003). Although markets, auctions, and games are clearly of interest in economics, the agent literature in these topics focuses primarily on local behavior of limited dimension, rather than on broader economic issues.

4.2 Framework: Object-Oriented Programming

Object-Oriented Programming (OOP) is a natural framework for building ACE simulations. Examples of OOP languages include C++ (foundation for the *Aspen* and *N*-

ABLE platforms discussed below), Objective C (foundation for the *Swarm* platform discussed below), and Java (foundation for the *RePast* platform discussed below).

Luna and Stefansson (2000, see Introduction) attribute the advantages of OOP to four properties of OOP: abstraction, encapsulation, inheritance, and poli-morphism. Luna and Stefansson state, "these properties allow the programmer to conceive an agent as a self-contained (encapsulated) object which is the `tangible´ instance of some initial template (abstraction), and which has inherited some general features that define its essence without `hindering´ its potential development."

4.2.1 Templates and Instances

OOP allows one to design agent templates, which generally include variables representing attributes, input parameters, or initial or boundary conditions. This feature affords the agent modeler the option of proceeding along two experimental paths.

In the first case, that modeler can specify that the initial values for such variables be drawn randomly from specified distributions upon instantiation of each agent. This approach allows for models in which agents' attributes are distributed according to some desirable distributions, which creates a population of desirably differentiated agents. This is the ACE analogue to much of theoretical economics, which is often comprised of mathematical models that require certain assumptions regarding the distribution of agent attributes.

In the second case, the modeler can explicitly specify the attributes for each `tangible' instance of a template. This is more analogous to empirically-driven models in applied economics, because each instantiated agent can be specified to represent actual known economic actors.

The distinction between agent templates (or *classes* in C++ jargon) and agent instances (or *objects* in C++ jargon) is explicitly defined in OOP, making OOP a particularly desirable framework for the design and development of ACE simulations.

4.2.2 Complex Agent Design

OOP allows the modeler to design and encapsulate elemental functions and knowledge components for use by agents, and combine such components laterally or hierarchically into increasingly complex economic actors, or complex corporations of differentiated actors, such as firms or households. Additionally, the OOP property of inheritance provides a powerful means to sequentially incorporate simpler templates into broader templates. See Schildt (2003).

4.2.3 Object-Oriented Software Packages

Free packages exist for general-purpose agent-based modeling, including SWARM and REPAST.

SWARM[1] was originally created at the Santa Fe Institute, but is currently managed by the not-for-profit Swarm Development Group, founded to support the development of the SWARM software package for multi-agent simulation of complex systems. SWARM is available in Java and Objective C. See Luna and Stefansson (2000) and Luna and Perrone (2002) for applications of SWARM to problem domains.

REPAST[2,3] was initially created at the University of Chicago, but is currently managed by the non-profit volunteer Repast Organization for Architecture and Development (ROAD). REPAST is used at Argonne National Laboratory's Center for Complex Adaptive Systems Simulation (CCASS). REPAST models can be developed in Java, C#, Managed C++, Visual Basic.Net, Managed Lisp, Managed Prolog, and Python scripting. REPAST claims utilities for discrete-event, system-dynamics, and social network models.

4.3 Key Application: Adaptive Agent Systems

One of the key areas of interest in the field are multi-agent models in which the agents are designed to learn and evolve in ways that are not specified a priori. This approach allows researchers to *discover* possible outcomes arising from a complex system.

Adaptive agent systems are systems of agents in which the agents adapt using information obtained in the course of the simulation. The principles of adaptive systems were largely explored by John Holland (1992, 1996, 1999) with his introduction of genetic algorithms.

4.3.1 Adaptive Agents

Adaptive agents are used in many types of industrial and scientific applications. Arizona State University Professor of Supply Chain Management Kevin Dooley, on his website, defines [adaptive] agents as "semi-autonomous units that seek to maximize some measure of goodness, or fitness, by evolving over time." We further refine this definition by stating that an agent is adaptive if a unique instantiation of the agent can process and use information obtained in the course of simulation to modify its internal algorithms (decisions) to better achieve a set of objectives (e.g. some measure of goodness or fitness). Adaptive agents are important for many problems and applications in the field of agent-based computational economics.

4.3.2 Evolutionary Agents

Evolutionary agents refer to a collection of semi-autonomous units, in which the characteristics of successful individual units are transferred to the population of units. The journal *Evolutionary Computation* describes this field to include "computational agent systems drawing their inspiration from nature, with particular emphasis on evolutionary algorithms, including, but not limited to, genetic algorithms, evolution

[1] Available at http://www.swarm.org.
[2] Available at http://repast.sourceforge.net.
[3] Also see http://www.econ.iastate.edu/tesfatsi/repastsg.htm.

strategies, evolutionary programming, genetic programming, classifier systems, and other natural computation techniques." See Basu et al (1998) and Marks (2001).

We distinguish *evolutionary* agents from *adaptive* agents in that the successful behaviors of individual evolutionary agents are transferred from the individual to the population of agents. In non-evolutionary agent-based systems, each agent learns or adapts independent from other agents. The following figure distinguishes agents as adaptive, evolutionary, or both.

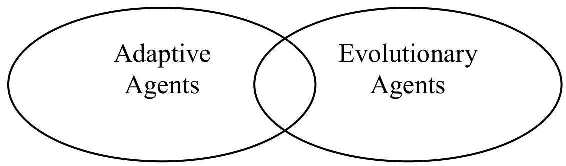

Figure 2. Types of Agents in Adaptive Systems

Evolutionary agents are appropriate for simulating some, but not all, economic phenomena. For example, repeated bidding in a competitive spot market would probably be better simulated by non-evolutionary adaptive agents who independently learn to identify the spot price. In contrast, evolutionary agents are probably more appropriate to simulate the inherently evolutionary process by which competitive industries bankrupt inefficient firms and adopt efficient technologies and effective business models. Often, economic simulations employs agents that are both adaptive and evolutionary.

4.3.3 Complex Adaptive Systems (CAS)

CAS is a common phrase used to describe many types of systems. Dooley defines a CAS as a system that "behaves/evolves according to three key principles: order is emergent as opposed to predetermined, the system's history is irreversible, and the system's future is often unpredictable." Dooley offers examples, including "economies, ecologies, weather, traffic, social organizations, and cultures."

There is a growing literature aimed at modeling economics within the context of complex adaptive systems. See Anderson et al. (1988), Arthur et al. (1997), and Tesfatsion (2001). Such adaptive ACE systems represent a subset of ACE, as illustrated in the figure below. Non-adaptive, or steady-state, agent-based systems are made up of fixed agents with static decision rules, in which the agents neither learn, nor transfer their characteristics to the rest of the population of agents.

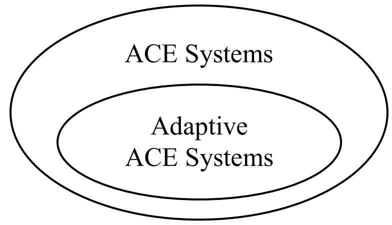

Figure 3. Adaptive versus Static ACE Systems

A system of non-adaptive agents can be an adaptive system if new agents can evolve from old agents in such a way that the new agents become increasing successful at achieving their objectives.

Although most of the emphasis in ACE has been on adaptive systems, an agent-based system need not be adaptive to identify meaningful and even emergence behavior. Steady-state ACE models can be used to explore the converge properties and identify emergent outcomes of economic systems. For example, Sprigg and Ehlen (2004) use static agents to demonstrate convergence to calculable theoretical economic equilibriums, but also discover unpredicted emergent behavior stemming from the complexity of the economic interactions.

4.4 Related Methods

The agent-based paradigm is often compared to systems-dynamics and discrete-events paradigms, which follow similar principles such as interacting objects with internal processes and rules.

4.4.1 System-Dynamics Models

Systems Dynamics (Sternman 2000) simulation is not unrelated to discrete-events simulations, but typically employ differential-equations and feedback loops, and usually afford a more macro-scale perspective to system problems than agent-based simulation. O'Donoghue (2001), Pylkkänen (2001), Spielauer and Vencatasawmy (2001), Baldini (2001), and Levy et al. (2001) apply dynamic microsimulation to classic problems in applied economics. Premier commercial packages include Stella and iThink[4] from ISEE Systems. Other packages include VenSim[5] and PowerSim[6].

4.4.2 Discrete-Events Models

Discrete-event and *agent-based* simulations follow similar principles and are fundamentally the same class of simulation. Information and rules are distributed among objects, which interact with each other and the [global] environment in the course of simulation. There arguably exist two subtle distinctions between what is usually inferred by the terms *discrete-event* and *agent-based*.

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[4] Available at http://www.iseesystems.com.
[5] Available at http://www.vensim.com.
[6] Available at http://www.powersim.com.

The first distinction derives from the degree to which information and behavior is embedded within the objects of the simulation. Agent-based models are largely designed for applications in which [nearly] all aggregate activity arises from local activity within the nodes, with little or no global control. Discrete-event simulations are often designed to model top-down control systems.

The second possible distinction derives from the intended use of the simulation. Discrete-event software packages seem geared for design of systems, where the user simulates the behavior of local objects under global controls. In contrast, agent-based models are often used to identify emergent behavior within a system of completely localized autonomous agents. Of course, whether or not this distinction is substantive is fundamentally irrelevant from a software perspective if all such simulations follow similar principles at both design-time and run-time.

4.5 Agent-Based Economics Today

This burgeoning field of agent-based computational economics (ACE) arose and expanded since the late 1990s partly due to increasingly powerful, cheap, and user-friendly programming environments, but also due to cross-fertilization of economics with other computation-intensive disciplines.

Although contained within the realm of economic research, ACE research is often conducted by and published in computational literature rather than social and economic literature. Therefore, ACE is defined by various literary contributions and research programs that transcend several disciplines.

4.5.1 Contributors and Programs

The following paragraphs identify several key contributors and programs in the field of agent-based computational economics. However, this list is by no means exhaustive, and might unintentionally omit some contributors at the forefront of the field.

Sandia National Laboratories

Richard Pryor is a retired Senior Scientist from SNL. He developed an agent-based simulation library called Aspen, which has been used for various efforts within DOE, DoD, DHS, and others (see Basu et al 1998, Barton et al 2000 and 2004, Slepoy and Pryor 2002, Sprigg and Ehlen 2004). The Aspen work has spawned the N-ABLE program currently sponsored by NISAC (listed below) and led to the formation of the Evolutionary Computing and Agent-Based Modeling Department at SNL. This department explores a myriad of problems in domains ranging from social and economic systems to logistics and supply-chain systems. See http://www.cs.sandia.gov/web9216/pubsagent/index.html.

National Infrastructure Simulation and Analysis Center

NISAC is a DHS sponsored joint program between Sandia National Laboratories and Los Alamos National Laboratories. Among its efforts, NISAC is developing a high-powered agent-based computing platform called the NISAC Agent-Based Laboratory for

Economics (N-ABLE). The N-ABLE effort specializes in economic simulations that require many agents and massive computational capacity. See http://www.csu836.sandia.gov/organization/div6000/ctr6200/6222/index.shtml.

Argonne National Laboratory

Argonne's Center for Complex Adaptive Systems Simulation (CCASS) has used Swarm and RePast for various agent-based applications. CCASS co-sponsors the agent-based social science conferences with the University of Chicago (see SSRCC). CCASS Deputy Director Michael J. North has related publications (e.g. Thomas et al. 2004, and North 2001). See http://www.dis.anl.gov/msv/cas.

Santa Fe Institute

SFI's stated objective, on its website, is to emphasize "multidisciplinary collaboration in pursuit of understanding the common themes that arise in natural, artificial, and social systems." Faculty and collaborators have explored various complex system approaches to the study of finance and economics (e.g. Arthur 1995, Arthur et al. 1997, Durlauf and Young 2001, Farmer 2001). See http://www.santafe.edu.

Purdue University

Visiting Associate Professor of Strategic Management Shailendra Raj Mehta is co-director of the SEAS laboratory for simulation, and has several publications (e.g. Chaturvedi et al. 1999, 2003-4) and working papers (e.g. Gupta et al. 2003 and Drenevich et al. 2004 and) related to agent-based synthetic economies. See http://www.krannert.purdue.edu/faculty/mehta/home.asp.

Associate Professor of Forestry and Natural Resources Bryan Pijanowski (see Alexandridis and Pijanowski 2002) advised in the development of the Multi Agent-Based Economic Landscape (MABEL) developed within the SWARM environment to study behaviors and markets related to land. See http://web.ics.purdue.edu/~bpijanow/publications.htm.

Iowa State University

Leigh Tesfatsion (2002) is Professor of Economics and Mathematics in the ISU Department of Economics. She teaches a course entitled *Agent-Based Computational Economics (ACE)*, maintains an ACE website, and has authored several articles and books, including Judd and Tesfatsion (2005). See http://www.econ.iastate.edu/tesfatsi/ace.htm.

University of Chicago

Chicago's Social Science Research Computing Center (SSRCC) has developed and used the Java-based agent-based software called RePast, which borrows from the Swarm simulation toolkit. See http://sscs.uchicago.edu and http://repast.sourceforge.net.

University of Michigan

Michigan's Center for the Study of Complex Systems (CSCS) is an interdisciplinary program to facilitate research of nonlinear, dynamical, and adaptive systems. CSCS hosts the SwarmWiki and supports an annual adaptive systems workshop in collaboration with the Santa Fe Institute. See http://www.cscs.umich.edu.

Swarm Development Group

This is a not-for-profit organization founded to support the development of the Swarm software package for multi-agent simulation of complex systems. Swarm programming language environments include Java and Objective C. See http://wiki.swarm.org.

Japan Defense Agency

Akira Namatame (2003) is a Professor in the JDA National Defense Academy Department of Computer Science. He has organized the following conferences and workshops: (1) The Japan-Australia Joint Workshop on Intelligent and Evolutionary Systems: 1997, 1998, 2000, 2002, 2003, (2) The Fourth International Conference on Computational Intelligence and Multimedia Applications: 2001, (3) The First International Workshop on Agent-based Approach in Economic and Social Complex Systems: 2002, (4) The Sixth International Conference on Complex Systems: 2002, (5) The Ninth Workshop on Economics with Heterogeneous Interacting Agents: 2004. See http://www.nda.ac.jp/~nama.

International Foundation on Multiagent Systems

This is a not-for-profit corporation that co-sponsors the annual *International Joint Conference on Autonomous Agents and Multiagent Systems*. See http://www.ifmas.org.

4.5.2 Journals, Books and Conferences

ACE publications have accelerated since the late 1990s. The following tables list some selected samples of journals, books, and conferences related to agent-based economics.

Table 2. Sample ACE Articles from Selected Journals

Journal	Article
Artificial Life	Janssen and Jager (2003)
	Tesfatsion (2002)
Autonomous Agents and Multi-Agent Systems	Bergman and Tennenholtz (2002)
	Tesauro and Kephart (2002)
Brazilian Electronic Journal of Economics	Bordini et al. (2000)
	Rivero et al. (1999)
	Leijonhufvud (1999)
Computational Economics	Meyer et al. (2003)
	Carpenter (2002)
	Edmonds (2001)
	Basu, Pryor, and Quint (1998)
Computational & Mathematical Organizational Theory	Buchta et al. (2003)
	Teitelbaum and Dowlatabadi (2000)
Electronic Commerce Research	Bertels and Boman (2001)
	Deveaux et al. (2001)
Evolutionary Computation, IEEE Transactions on	Izumi and Ueda (2001)
	LeBaron (2001)
	McFadzean et al. (2001)
Group Decision and Negotiation	Panzarasa et al. (2001)
Journal of Conflict Resolution	Bearce and Fisher (2002)
	Zott (2002)
Journal of Economic Behavior and Organization	Mizuta et al. (2003)
	Chen and Yeh (2002)
	DeCanio and Watkins (1998)
Journal of Economic Dynamics and Control	Kutschinski et al. (2003)
	Negroni (2003)

Proceedings of the National Academy of Sciences	Cedarman (2002)
	Elliott and Kiel (2002)
	Lempert (2002)
Proceedings of the Sixth International Conference on Artificial Life	Maza et al. (1998)
Social Science Computer Review	Sallach (2003)
	Bankes et al (2002)
	Moretti (2002)
	North (2001)

Table 3. Selected ACE-related Books & Reports

Successful Technical Trading Agents using genetic Programming (2004) Pryor et al.
Analysis of Price Equilibriums in the Aspen Economic Model under Various Purchasing Methods (2002) Slepoy and Pryor.
Agent-Based Methods in Economics and Finance: Simulations in Swarm (2002) Luna and Perrone eds.
Economic Simulations in Swarm: Agent-Based Modeling and Object-Oriented Programming (2002) Luna and Stefansson eds.
Agent-Based Computer Simulation of Dichotomous Economic Growth (2000) McCain ed.
Evolutionary Computation in Economics and Finance (2002) Shu-Heng Chen ed.
Modeling Requirement for Simulating the Effects of Extreme Acts of Terrorism: A White Paper (1998) Pryor et al.
Growing a Market Economy (1997) Basu and Pryor.

Table 4. Selected ACE-related Conferences

International Conference on Autonomous Agents and Multiagent Systems
International Conference on Complex Systems
International Conference on Computational Intelligence and Multimedia Applications
International Conference on Computing in Economics and Finance
International Workshop on Agent-based Approach in Economic and Social Complex Systems
Japan-Australia Joint Workshop on Intelligent and Evolutionary Systems
Symposium on Adaptive Agents and Multi-Agent Systems
Workshop on economics with Heterogeneous Interacting Agents

5.0 Remarks

Positive economics (Friedman 1953) generally involves the use of accepted axioms to formulate a theory that explains observed behavior and forecasts the response to changing economic conditions. Agent-based economic simulation replaces calculus with computation to provide a laboratory for extending this methodology.

Agent-based studies have largely focused on computationally intensive problem domains such as iterative game-theoretic applications, matching mechanisms, operations research, and short-run financial trading models. However, the appealing features of agent modeling also apply to our current efforts to model broader market decisions and interactions (Sprigg and Ehlen 2004, and Sprigg 2004).

Agent-based economics is allowing us to incorporate relevant economic theory of Friedman, Modigliani, Bowden, Lucas, Barro, Sargent, et al. into a simulation framework that is less encumbered by the need for simplifying assumptions.

We are thereby modeling a financial economy that incorporates life-cycle principles into a multi-market economic simulation, while simultaneously incorporating additional hypothetical complexity into the choices of agents to better understand and model the role of confidence for explaining observed behavior. Ultimately, this approach should allow for extrapolations to explore likely market reactions under rare and extreme conditions. Specific objectives include a capability to better anticipate cascading economic responses to terrorist threats and attacks.

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