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Abstract:

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It is plain that the Austrian revival that began in the 1970s has yet to succeed in convincing the mainstream of the academy to jettison their physics-based mathematical models in favor of the sort of models and forms of argumentation that contemporary Austrians advocate. Agent-based computational modeling is still in its relative infancy but is beginning to gain recognition among economists disenchanted with the neoclassical paradigm. The purpose of this paper is to assuage concerns that readers might have regarding methodological consistency between agent-based modeling and Austrian economics and to advocate its adoption as a means to convey Austrian ideas to a wider audience. I examine models developed and published by other researchers and ultimately provide an outline of how one might develop a research agenda that leverages this technique. I argue that agent-based modeling can be used to enhance Austrian theorizing and offers a viable alternative to the neoclassical paradigm.

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1 Introduction

Austrian economists have provided a rich and unique perspective of economic science since the time of Carl Menger and Eugen Bohm-Bawerk. While there is some controversy over the extent to which mainstream economists have assimilated Austrian ideas, it is plain that the revival that began in the 1970s has yet to succeed in convincing the mainstream of the academy to jettison their physics-based mathematical models in favor of the sort of models and forms of argumentation that contemporary Austrians advocate. This paper is an attempt to demonstrate how Austrian economists might employ agent-based computational models as a means to complement research on traditional Austrian themes as well as improve the possibility of reaching a wider audience for those ideas.

Whether you believe the label “Austrian” economics remains useful, or prefer to think in terms of ‘good’ economics and ‘bad’ economics, the primary methodological tenets of Austrian economics are an adherence to methodological individualism, subjectivism, and the notion of the market as a process through time. Recent advances in the broader fields of social science offer economists the opportunity to maintain consistency with respect to these methodological tenets while applying new tools that not only may provide insight into topics of concern to Austrians, but also positively influence the mainstream regarding Austrian ideas. For example, through their research agenda in cultural economy, Emily Chamlee-Wright and Virgil Storr (2009) are pioneering ways in which economists use qualitative field studies to examine such important concepts as individual’s expectations of government actions and capabilities. A number of researchers such as Vernon Smith (2005), Kevin McCabe (2005), and Randall Hollcomb (2009) have pointed out areas where Austrian ideas overlap with advances in experimental and behavioral economics. Likewise, agent-based modeling is gaining traction among economists as an interesting alternative to strict neoclassical doctrine. All three threads of research offer great potential to breathe new life into the broader Austrian narrative.

While ABM is still in its relative infancy, it is gaining recognition among economists disenchanted with the neoclassical paradigm. A significant amount of criticism of neoclassical economic theory has to do with the fact that the assumptions required in order to maintain tractable mathematics also render the resulting model as woefully unrealistic. Agent-based modeling offers an alternative that enables researchers to examine the process of the emergence of complex phenomena while maintaining tractability. The purpose of this paper is to discuss the methodological consistencies between agent-based modeling and Austrian economics and chart a 'way ahead' of how one might develop a research agenda that leverages this technique. I argue that agent-based modeling can be used to enhance Austrian theorizing and offers a viable alternative to the neoclassical paradigm.

2 Austrian Flirtations with Agent-Based Modeling

Austrians have recognized the possibility agent-based modeling could be fruitfully brought to bear for many years now. As early as 1990, Lavoie et al, suggest that "Computer 'simulations' of spontaneous order processes might prove to be the kind of modeling approach that is process-oriented enough to help rather than obstruct economic theorizing" and recognize it as a potential complement to extant economic theorizing. They mapped out several different areas of inquiry that might be of interest to Austrians and other process oriented theorists, to include the evolution of knowledge, the spontaneous order of artificial intelligence, and using such models to model discovery procedures. In regards to the possibility of modeling artificial economies, the authors note "We might be able at least to illuminate existing ideas in market process economics, and we might conceivably develop substantive new ones, by doing mental experiments within artificial minds (Lavoie, et al, 1990)." This article will outline how previous researchers have used these tools to illuminate existing ideas and examine the prospects for the advancement of Austrian ideas in particular.

In their review article of Roger Garrison's "Time and Money", Ryan Oprea and Richard Wagner (2003) suggest an alternative analytic framework based upon the concept of the catallaxy as an ecology of plans, which they call enterprise-based macro. They suggest that to truly revive macroeconomics, a paradigm that emphasizes the coordination or discoordination of the plans of market participants is required. From this perspective, macroeconomic phenomena such as aggregate demand or the rate of unemployment would emerge as a result of the interactions of goal-seeking individuals. Such a framework would not only allow Austrians to leverage their unique ideas concerning market process, but enable them to shed their own historic reliance on equilibrium as an integral component of business cycle theory. The authors note that researchers such as Peyton Young (1998) are pioneering alternatives to Walrasian General Equilibrium theory built on dynamic, evolutionary concepts and analysis of institutions within which exchange takes place. The Oprea and Wagner lament the fact that:

> Austrian contributions have been missing from the subsequent development of this literature. The absence is particularly puzzling because the primary analytical techniques that have propelled this literature, evolutionary games and stochastic dynamical systems, are particularly suitable vehicles for exploring these classical Austrian themes, vehicles, moreover, that were not available two generations ago when these Austrian themes were first articulated (2003, p. 105).

In areas of macroeconomics and other areas of political economy, Wagner has offered approaches that lend themselves to an agent-based implementation (2006, 2007; 2008; 2010).

Robert Axtell is another researcher contributing to the development of an alternative to Walrasian economics and in 2007 he published in this journal a description of how agent-based modeling helps researchers to unravel the neoclassical “sweet spot” (pp. 106-108). The sweet spot consists of assumptions of agent rationality and homogeneity, as well as non-interaction and equilibrium, which are necessary to achieve the researchers’ desired model performance in terms of formality, generality, and tractability. He demonstrates that in attempting to relax any one of the assumptions, typically leads to all assumptions unraveling. For example, allowing for agents to interact necessarily implies (at least transient) disequilibrium and heterogeneity as agents accumulate unique local experiences. Neoclassical theory is one attempt to make sense of the spontaneous order that individuals collectively form when participating in the catallaxy. Axtell shows agent-based computational modeling is another framework available to examine these spontaneous orders without sacrificing realism to as great an extent. Unraveling the sweet spot enables the researcher to trace emergent macro-level phenomena back through the genetic-causal chain of interactions to its origin in individual behavior.

Guinevere Nell’s (2010) recent article is the latest effort to advocate for the benefits that agent-based modeling could bring to the Austrian perspective. Her piece highlights the centrality of competition and entrepreneurship in Austrian theorizing, especially in terms of the socialist calculation debate, and argues that agent-based modeling provides a useful tool for analysis of these concepts. Perhaps the most important attribute of agent-based modeling is its ability to model out of equilibrium behavior. Whereas mainstream neoclassical theorizing asks which agents’ behavior are consistent with a final equilibrium outcome, ABM [Agent-Based Modeling] facilitates analyzing how agents' behaviors endogenously change with each others' (Arthur, 2006, p.1534). The equilibrium approach lends itself to a closed form analytical solution, with which one may achieve generality and syntactic clarity. However, as discussed below, the ability to articulate closed form equations that describe these outcomes often requires the sacrifice of detail and complexity in order to maintain mathematical tractability. The advent of agent-based modeling provides the researcher with a tool that can make the modeling of complex phenomena more tractable while attaining improved levels of realism. This paper is an attempt to reconcile this methodology with Austrian economics and offer suggestions for pursuing a research agenda that exploits their complementary features.

3 Spontaneous Order Economics and Agent-Based Modeling

Spontaneous orders are also known as complex adaptive systems in the artificial intelligence and computational economics literatures. Complex systems are composed of interacting agents that exhibit emergent properties (Tesfatsion, 2006, p.836). A system is complex if it is composed of interacting units and exhibits emergent properties that cannot simply be deduced from aggregating the system's components while emergent properties are those "properties arising from the interactions of the units that are not properties of the individual units themselves (p.836)." Further, a compex adaptive system is one that contains goal-directed or purposive agents. Agent-based models, properly constructed, are themselves complex adaptive systems in that goal-directed agents interact to exhibit emergent properties. Thus, to the extent that phenomena exhibit complexity, agent based modeling represents a potential tool to facilitate the development of an invisible hand explanation of such phenomena.

Epstein (2006, p.1588) describes the following are some general features typical of most agent based models:

a. Heterogeneity. Every individual is explicitly represented and their instance variables are allowed to differ in substantial ways in relation to other agents. The manner in which agents are allowed to differ from other agents is limited only in the number of characteristics modeled.

b. Autonomy. There is no leader in charge of agents' behavior. Agents alter their behavior as a result of interactions with other agents and their environment.

c. Explicit space. Events transpire in an explicitly defined environment, which means the notion of "local" is well posed.

d. Local interactions. Agents are allowed to interact with other agents, i.e. neighbors, and their environment on the basis of particular rules of conduct.

e. Bounded rationality. Agents possess neither global information nor infinite computational capacity. While they may be purposive or goal seeking, agents are typically unable to strictly maximize their behavior.

f. Non-equilibrium dynamics. The process through which agents coordinate their activities is the focus of the research, as opposed to the end state.

At least superficially, these features appear to overlap with ideas with which Austrians are familiar. The three core methodological tenets of Austrian theorizing are methodological individualism, subjectivism, and the notion of the market as a process (Boettke, 1994). Austrian theorists, perhaps more than many other economists embrace the notion of the market as a process through which the subjective demands of consumers are met with the scarce resources available. The fact that process, individual choice under uncertainty, and subjectivism are in the foreground of their analyses has led the scholars following this tradition to turn their attention to the coordinating effects of entrepreneurship, money, and social institutions that enable individuals to better cope with uncertainty.

Hayek dedicated the vast majority of his life's work elucidating the intricacies of spontaneous order. According to him, order is achieved when the individuals in a society adjust their behavior such that accurate expectations might be formed regarding their future conduct (Hayek, 1973, p.36). The price mechanism is one social institution responsible for enabling individuals to pursue and achieve coordination of consumption and production plans in a decentralized manner. The division of labor is a grown order in which individuals pursue their own goals and are able to coordinate their behavior by sending, receiving, and interpreting price signals communicated as a result of their participation in the market. Alternatively, an organization is a made order, where relationships are formed exogenously and information flows through consciously developed channels (Hayek, 1973, p.37). In organizations, subordinate units carry out the plans of superior units and execute only the tasks assigned them.

The quintessential organization is a military unit. The members of the organization constantly look for guidance from their leader, as they are rarely delegated the authority to make decisions based purely on their local knowledge. Rather, they feed this local knowledge up the chain-of-command so that the commander may make his decision based on the aggregation of all the subordinate knowledge. The nature of organizational decision making and the concomitant limitations of the human mind's ability to process information place significant constraints on the complexity of organizations and their ability to adapt to rapidly changing situations. In an organization, order is maintained by the unitary action of the leader and the alacrity with which his commands are executed.

Order is grown endogenously in a spontaneous order as individuals adhere to rules of conduct on the basis of particular information of time and place (Hayek, 1973, p.37). Outcomes emerge as result of purposive action on the part of agents, rather than the result of the design of any one particular mind. Hayek argues that it is the nature of the rules that govern individual interaction that determine whether order is grown, made, or achieved at all. While the rules that govern an organization tend to be concrete and provide relatively specific instructions to specific individuals with the intent of accomplishing a stated goal of the organization, the rules that govern a spontaneous order are abstract, purposeless in the sense that particular collective outcomes are not pursued, and equally applicable to all individuals. Such rules enable individuals to make the most appropriate use of their specific knowledge of time and place while enabling order to emerge spontaneously.

While spontaneous orders may achieve any degree of complexity imaginable, those of concern to social scientists are arguably complex enough to defy exhaustive understanding due to the limitations of human intelligence. Due to the multiplicity of interactions between various individuals all acting on the basis of dispersed knowledge, only (estimates of) global or summary variables might be obtainable by an outside observer, such as the aggregate unemployment rate or the consumer price index as an estimate of inflation. And while certain global variables might display a particular statistical relationship over a period of time, these variables do not "act" on each other, they are not true objects of choice, and the underlying statistical relationship is ultimately transient and bound to change with the underlying conditions.

As Hayek (1964) points out concerning the study of complex phenomena, often the best one can achieve is an explanation of the principle which governs the emergence of outcomes. "[T]he science of complexity is about revealing the principles that govern the ways in which these new properties appear (Vicseck, 2002, p.131)." Simulation facilitates the understanding of the inner workings of complex phenomena and helps to illuminate the process through which outcomes emerge. While simulation begins from a necessarily arbitrary and reductionist foundation, the process of following interconnected chains of causation from the actions of individuals through the macro-level phenomena parallels Menger's compositive methodology.

Positivist social scientists hold that the true measure of a theory is how well that theory's predictions match the empirical data (Friedman, 1953). Alternatively, Hayek holds that while scientists may obtain an analytical description of simple phenomena which lends itself to empirical falsification, complex phenomena defy such description and the best a scientist may hope to achieve is an explanation of the principle in operation. As Gilbert and Troitzsch remind us, nonlinear interactions are inherently difficult to predict. "Complexity theory shows us that even if we were to have a complete understanding of the factors affecting individual action, this would still not be sufficient to predict group or institutional behavior (2005, p.11)." Simulation models assist researchers to base theoretical behavior on relatively more realistic assumptions and to think through the chain of logical reasoning to deduce the outcomes that may emerge.

While agent-based simulation as a method, properly employed, appears capable of complementing Hayek's spontaneous order economics, there are certain aspects of the body of Austrian work that may not be as accommodating. For instance, it would appear that the extreme apriorism of praxeology as a method of inquiry should cause Austrians to reject agent-based modeling as too empirically oriented and arbitrary. However, I intend to show that most of the apparent differences can be adequately resolved.

It is difficult to argue that agent-based modeling is as rigorous as the demanding methodological constraints of praxeology. Praxeology begins with the action axiom that states that human beings act to remove a certain felt uneasiness (Mises, 1996; Rothbard, 1997). This axiom is held to be true *a priori*. Any theories deduced from the axiom are held to be true with didactic certainty, as long as the chain of logical reasoning is valid. Certain postulates may also be added, such as the notion that individuals perceive a disutility of labor, which change only the domain under which the resultant theories are operative. Thus, any theories derived from such a postulate are held to be true, but only in those instances where individuals prefer leisure to labor.

Agent-based models are representations of particular sets of assumptions instantiated in computer code. Each simulation run is a realization of the chain of deductions based on the set of assumptions, or as Epstein (2006) notes, every simulation replication is essentially a sufficiency theorem. Upon completion of an experimental design, the researcher uses inductive techniques and statistical analysis to choose among the population of candidate theories that the simulation has produced. While this process of induction is not necessarily of the same character as the scientistic empiricism that Austrians tend to criticize and seek to avoid with aprioristic techniques, it is possible a model may produce competing theories. The criteria developed to select between competing theories would not be immune from the arbitrary opinions of the researcher and thereby limit the theory's universality. However, it does represent a step in the direction of greater realism relative to the neoclassical framework. And, while the conclusions arrived at would not necessarily be true with didactic certainty, the goal of such research would be to achieve pattern predictions and explanation of principles rather than universal laws.

Conducting an agent-based modeling study requires a unique combination of deductive and inductive considerations. Lavoie, et al (1994), recognized that this approach involved theoretical and empirical approaches:

> [I]t would be more experimental, in a sense, than most theoretical research is today… [T]he aim would be to set up constraining conditions, specifying institutional environments or decision rules for agents, and then to run the simulation in order to see what happens. The idea … is to run the simulations as mental experiments, where what is of interest is not what the end results are so much as how the process works. And we, the programmers, would not know how the process was going to come out until we ran the mental experiments. (Lavoie, et al, 1994)

The results of such mental, or rather artificial, experiments would not necessarily hold with didactic certainty, but they could be sufficiently realistic so as to gain an understanding of previously inaccessible social processes.

A computational model, such as an agent-based simulation, must be built upon much narrower assumptions than the action axiom. As such, it is necessary to make arbitrary decisions regarding the assumptions that govern agents' behavior. For instance, in their Sugarscape model, Epstein and Axtell (1996) found it necessary to make assumptions regarding the particular characteristics of the agents' motivation for collecting and consuming sugar. Among the infinite number of mechanisms to govern agent behavior, one must be chosen and instantiated in the model. So, a critic might argue that the conclusions arrived at in the Sugarscape study are only valid for humans that eat only sugar and have significantly restricted vision, etc. However, that charge misses the point of a simulation study of simply gaining an understanding of the complex mechanism under examination.

Mises developed his methodology to study praxeology in an attempt to craft a universal theory of human action independent of time and place. As such, it was necessary to purge any ad hoc or contingent elements from the framework, since the presence of arbitrary premises would ultimately limit the application of the theory. Given the fact that a human must use discretion to determine what features of reality are relevant to include in any model, arbitrary designs will creep into its development, and thus limit its application to only that domain in which the peculiar notion is operational. However, it is important to note that there is much more to good economic theorizing than praxeology. After all, as Lavoie (1994a) states, "doing economics in an Austrian way is tracing systemic (spontaneous order) patterns of events to the (subjectively) meaningful purposes of (individual) human actors (p.56; parentheticals in the original)." As such, I intend to show that agent-based simulation is consistent with much of *the rest* of Austrian economics.

Mises recognized that the science of human action has a theoretical and a historic aspect (Mises, 2003; 2006). Properly understood, theory is a tool that the student of human action employs in order to make sense of history. The employment of conjectural history, is a technique with which the theorist develops historically contingent theory. When conducting conjectural history, reference is made to specific institutions, policies, or other arrangements that were present in reality at the time.

> Such conjectural histories therefore make use of the ideal-type constructs (these constructs, to be sure, never refer to ideal-typical *people*, but only to ideal-type *objects* or *consequences* of action), although their truth follows apodictically where all the real-life equivalents of the specified ideal-types are present in a given historical circumstances. Causal-genetic or "evolutionary" theories such as Menger's theory of the origin of money fall into this category of conjectural history (Selgin, 1988, p.27; emphasis his).

Theory developed in this manner is highly contingent on the underlying assumptions, but it is indispensable to the analysis of economic phenomena that appear in reality. Agent based simulation can assist researchers in the conduct of conjectural history by facilitating the examination of complex processes. It is capable of employing ideal-types, both agents and institutions, and ultimately assists the researcher in providing a genetic-causal explanation of social phenomena.

In his discussion of the use of ideal types in economics, Koppl (1994) notes that ideal types are "intelligible" representations of actions or actors (p.72). He goes on to explain that the generality of an argument based on the use of ideal types depends upon the anonymity of the ideal type used. "The anonymity of a personal ideal type is the degree to which it is empty of particular content (p.73)." Thus, the more anonomously the agents inhabiting artificial societies are developed, while remaining recognizable to human beings as actors, the more effective will be their employment as ideal types.

In Cowan (1994) and Cowan and Rizzo (1996), the authors elucidate the importance of the notion of causation in economic analysis. The genetic-causal approach they outline embraces the notion that the cause of an outcome "creates a unidirectional *process* the outcome of which is the effect (1996, p.274)." Purposive human behavior, traced back to the tastes and expectations of individuals, are the endogeneous causes of these outcomes. Typical mainstream equilibrium economics eschews notions of causations. After all, in order for a cause to originate, a change must occur, but change is essentially precluded in the equilibrium framework. Agent-based modeling is uniquely suited to illuminate these complicated chains of causation that result in emergent unintended outcomes. The models are capable of providing researchers with comprehensive information regarding the state of each individual agent in the population, which enables the researcher to follow chains of causation from their inception to their ultimate end. However, it should be stressed that such endeavors are truly only fruitful if they lead to greater understanding of actual processes.

It is difficult in the extreme to imbue artificial agents with the full character and quality of purposive human action. The inability to capture the open-endedness of how humans manage their subjective means-ends framework is a shortcoming that agent-based modeling as a method may never fully overcome. To the extent that the agents in the model capture relevant characteristics of the action axiom, then the more effective the simulation model is bound to be in illuminating the phenomena under consideration. While it is true that the artificial societies depicted in agent-based models lack the complexity and richness of human society, and the agents that populate these virtual worlds lack the intelligence of human beings, it is also true that the agents' relative ability to act within their society might be comparable (Lavoie, 1994b, p.554). Virtual agents certainly are not as creative or innovative as the individuals they mean to portray, but relative to their world, they could be considered creative as they are capable of learning from experience and adopting courses of actions as a result of trial and error (Lavoie, 1994b, p.554). Thus, artificial agents are subject to the criticism that they are not and perhaps never will be capable of achieving the intelligence and creativity of human beings, but they are capable of innovation relative to the worlds they inhabit.

Mises makes clear that "specific method of economics is the method of imaginary constructions (1996, p.236)." Of course some imaginary constructions are more useful than others when it comes to promoting the understanding of social phenomena. In this section I have argued that agent-based modeling can assist in the development of such imaginary constructions. To date, most Austrians have chosen refrain from exploiting the capabilities inherent in agent-based modeling, though some have recognized its potential contribution.

4 Some Examples of Useful Models

In this section, I provide a brief overview of two models that may be of interest to Austrian and other process oriented economists. Interested readers might also find Gilbert and Troitzsch (2005) valuable, as these authors outline a number of reasons why simulation is useful to the social scientist. Chief among these, and the one most consistent with the purposes discussed in this paper, is the ability to gain an understanding of complex social phenomena. They also review several agent-based simulation studies, such as Epstein and Axtell (1996), Drogoul and Ferber (1994), Doran *et al* (1994), and Jager *et al* (2001). Additional examples of the successful application of agent-based simulations to the study of spontaneous phenomena abound. Vriend (2006) provides a cursory survey of a wide range of agent-based models with special emphasis on those employing assortive interactions. Agent-based models can also fruitfully be applied to research problems that are not strictly of an economics nature. Axelrod (1997) contains examples of agent-based models applied to numerous multidisciplinary problems such as variations of the Iterated Prisoners' Dilemma, promoting norms, conflicts and transmitting culture. For an extensive survey of the use of agent-based simulations to examine social dilemmas, see Gotts et al (2003).

4.1 Sugarscape

Epstein and Axtell's (1996) Sugarscape model marks a seminal application of agent-based simulation to the study of spontaneous order social science. The authors leverage the capabilities of this technique and eschew common assumptions such as homogeneous agents and equilibrium in an effort to endogenously generate phenomena like trade, culture, disease transmission, and war.

The model is comprised of an environment, or sugarscape, on which sugar grows naturally in varying proportions. Agents, who require sugar to survive, inhabit the environment and possess heterogeneous levels of parameters such as vision, metabolic rate, speed, and maximum age. In subsequent variations, they may also possess gender, cultural attributes, and a metabolic rate for a second good known as spice. In the most basic implementation, agents move around the grid, each following the simple rule of identifying the unoccupied grid square in their field of vision with the greatest amount of sugar and moving to it.

<< Fig 1 about here >>

While the authors study a range of social phenomena, among those perhaps most interesting to the readers of this journal would be the chapter on trade. In this section, spice, an additional good that the agents require for life is added to the environment. Agents possess a utility function that depends on their endowed metabolic rates of the two goods and the current levels of goods in their possession, so that the good which they would “run out of’ first, thus dying as a result, they find relatively more valuable. Agents are allowed to bargain with the individuals in their neighborhoods, and trade occurs in a decentralized manner. In subsequent implementations they even allow agents to borrow wealth and attempt to model externalities as a result of pollution. The authors find that the system behavior most closely approaches that envisioned in neoclassical economic theory when infinitely lived agents with fixed preferences trade with each other for long periods of time. They find that trade increases the number of agents the environment can sustain, and that trade tends to increase income inequality as measured by the Gini coefficient. Perhaps more importantly, they note that as the agents in their model diverge from those embodied in neoclassical models, i.e. allow finite lives, possess culturally dependent preferences, etc, the behavior of the system tends to further diverge from the general equilibrium solution. They notice that agents trade until no further gains are possible locally, but end up falling short of the general equilibrium ideal, mostly due to the limitations with whom individuals may trade. The authors take this to mean that the First Fundamental Theorem of Welfare Economics (Varian, 1984: 198-203) may not apply to decentralized traders and suggest that this erodes justification for laissez faire policy. While justification of laissez faire does not necessarily rest on the operational integrity of the theorems of welfare economics, this brings up two important points. First, it is a demonstration of how the methodology can call into question doctrine held sacred by segments of mainstream economics. Secondly, in scientific discourse it takes a theory to replace a theory. To the extent that Austrians could use ABM as an additional means with which to levy criticism against certain aspects of neoclassical theory, it could generate opportunities to offer Austrian perspectives a viable alternative.

The model provides a tool to facilitate tracing emergent phenomenon back through the genetic-causal process to the purposive behavior of individuals. While the authors do not use this term, their analysis is generally consistent with the concept. For example, the authors note that the network through which individual agents trade is an emergent structure. Agents are only capable of trading with their neighbors, but agents may be connected economically with agents who are geographically distant. Thus, purposive agents seeking to improve their welfare through trade under the given rules cause the creation of a social structure that was not of their design. In this case, the causation can be explained both in terms of individual decision making as well as the process through which the sequences of decisions caused the overall effect. The preferences and actions of individuals, in terms of their willingness to trade and selection of trading partners, coupled with the institutional rules governing with whom agents may trade and the specific bargaining algorithms cause the emergence of trading network. This is just one such example that demonstrates how agent-based modeling is well suited for studying systems composed of interacting agents which exhibit emergent properties "arising from the interactions of the agents that cannot be deduced simply by aggregating the properties the properties of the agents (Axelrod and Tesfatsion, 2006, p.1649)."

The model is certainly a substantial distillation of anything we might observe in reality. At most only two economic goods exist and the only productive activity included in the model involves collecting an exogenously provided commodity. There is no entrepreneurship, no economic calculation of profit and loss, and no medium of exchange. However, the authors are able to demonstrate the emergence of numerous phenomena such as migration, culture, conflict and trade are possible as a result of very simple agents "acting" with purpose in accordance with simple rules and on the basis of local information.

4.2 Howitt and Clower

In Howitt and Clower (2000), the authors implement a model of decentralized market activity in which agents follow simple rules in trading various commodities with each other. The agents are allowed to "shop around" in order to gain information about prices and availability, shops enter and exit the system endogeneously, and shop owners select prices to offer in a manner that attempts to obtain a normal profit. Agents only trade with each other through intermediaries (shops), they are limited in the number of shops with whom they can trade at any one time, and shops can only trade in two goods at any time.

Figure 2 outlines the circular pattern of trade that is induced for a representative shop. In the diagram y_{ik} denotes a quantity y of good g_{ik} sold/offered at shop k, while p_{ik} is the price of that good.

<< Figure 2 about here >>

The shop offers prices, p_{0k} and p_{1k} for the goods. The individuals who come to buy y_{1k} of the first commodity (g_{ok}) simultaneously sell $p_{1k}y_{1k}$ of the second commodity (as depicted in the right half of the diagram. The trading shop accumulates a surplus of any positive difference between the outflow and inflow of either commodity, which is applied to the shop's operating costs.

The authors conducted 500 replications for each of 12 different values of the parameter that determines the overhead-cost schedule, with each run lasting up to 400 years of simulation time. If at least 99% of the agents were either shop owners or had profitable trading relationships for ten years in a row the economy was deemed to have reached full employment. Monetary exchange was deemed to have emerged if the number of agents trading indirectly was within 1% of the maximum possible number for at least ten years (pp 69-70). Thus, in monetary exchange, one commodity is involved in (nearly) every transaction that takes place. The authors show that in approximately 90% of the cases, their artificial economy achieves full employment, and of those occasions, 99% exhibit monetary or indirect exchange. In most cases, the commodity that emerges as money is the least costly to trade, but not always. The actual outcome is the result of a path-dependant process that due to stochastic variation and interactions of agents, may or may not result in selecting the most saleable asset to be money.

Process oriented economists observe the phenomenon of money and imagine the evolution of behavior that brought it about. Menger offered a praxeological yet historically contingent explanation of how a medium of exchange might emerge, in that individuals discover that trading for a more "saleable", or universally desired item improves their ability to overcome the double coincidence of wants that challenges direct exchange. Howitt and Clower's model demonstrates that the given conditions are sufficient for indirect exchange to occur, and the exchange tends to be mediated by the least costly (most saleable) commodity under consideration.

This model differs from other attempts to model the emergence of money, such as Marimon, McGraten and Sergeant (1990) in that in Howitt and Clower model the trade is mediated through specialist traders and the possibility of the proverbial double coincidence of wants is not precluded as an assumption of the model as it is in Marimon, et al. Considering that Mises referred to Menger's description of the emergence of money as "an irrefutable praxelogical theory of the origin of money (1996, p405)", Howitt and Clower's model does not achieve nearly the same universality in application as Menger's analysis. Arbitrary assumptions include the necessity of trading through specific firms, limitations and parameters concerning the number of firms with whom an individual might have a trading relationship, the number of commodities in which a shop may transact. However, it does succeed in demonstrating how the phenomenon of money might emerge in such a world.

5 Mapping Out a Way Ahead

As discussed above, Austrian scholarship provides an alternative to the neoclassical paradigm that currently dominates mainstream academia. They have lodged countless criticisms against the physics-based underpinnings of Walrasian General Equilibrium theorizing, but have only had moderate success in influencing mainstream economists. A method of employing agent-based modeling in which Austrians may have a particular comparative advantage is in "agentizing" legacy analytical models. In this treatment, a phenomenon that is typically modeled with a representative agent or general equilibrium model is examined using an agent-based computational approach. The performance of the two approaches is then compared to determine the circumstances under which the models' conclusions agree or differ.

Seagren (2010a; 2010b) is an attempt to agentize the standard neoclassical treatment of tort law. An artificial society of agents is constructed in which individuals are occasionally involved in destructive accidents with each other in the course of pursuing otherwise productive activity. They face a tradeoff in that taking action that reduces the chances of accidents occurring also endogenously reduces their productivity. The research question of what sort of liability regime is optimal for this society is first answered using neoclassical techniques on the basis of empirical data generated from the model. This analysis is then compared with an approach that enables agents' strategies to evolve in a decentralized manner and the two methodologies are compared and contrasted. Not only does this approach enable the researcher to answer common neoclassical questions such as the optimal liability rule, but also demonstrates how new questions might be generated, especially concerning population dynamics and out of equilibrium behavior.

As discussed above, neoclassical theorizing essentially examines individual behavior in equilibrium. As such, typical neoclassical research questions involve determining the existence of market clearing price vectors, deducing optimal or rational individual behavior, and deducing the effects of quantifiable uncertainty. In agentization efforts, it is common to find that the mainstream neoclassical model accurately describes the outcomes that are obtained under a variety of circumstances. In this sense, agentization is implemented as a complementary technique which assists the researcher in determining the robustness of neoclassical theory to particular foundational assumptions. Using experimental design, a wide variety of parameter combinations can be tested and the results examined to find the boundary of the parameter-space where the neoclassical model performs adequately, and where it fails to do so. From a rhetorical perspective, such an approach may be beneficial in the sense that the intent of the research is not necessarily to attack the neoclassical model, per se, but to examine it closely and test its limits.

Perhaps the most beneficial aspect of the agentization approach is that it opens up new avenues of investigation, or alternatively, it makes Austrian avenues more accessible. Because the notion that the market is a process is in the foreground of Austrian analysis, and because agent-based models facilitate process oriented analysis, agentizing traditional neoclassical models is one way to highlight the interesting and significant phenomena that neoclassical theory tends to disregard. In other words, the fact that out-of-equilibrium trades are allowed to occur necessarily leads researchers in the direction of examining concepts such as choice under uncertainty, heterogeneous perceptions, and the effect of individuals' expectations about the future – all of which are concepts with which Austrians have traditionally dealt.

As is typical for any scientific method of examination, there exist advantages and weaknesses to any particular means of analysis chosen. As many of the advantages of agent-based modeling were described above, it is important to outline some of the weaknesses. Some have been addressed by earlier scholars while others are still awaiting a conclusive answer.

First and foremost, it is important for practitioners of the computational modeling approach to not fall into the trap of creating elegant simulation models as an end in itself. Agent-based computational models are simply one of many means that one might use to examine social phenomenon. They can do some heavy lifting of working through the implications of large numbers of individual agents acting according to particular rules on behalf of localized information. They can assist the researcher in her attempt to answer the questions that concern her, but it is ultimately incumbent on the researcher to translate the conclusions of the analysis of the model output into a theory that helps to explain the world of human beings.

Properly constructed agent-based models exhibit the emergence of complex phenomena, which are, by definition, outcomes difficult to deduce simply from the activity of the component parts. As such, the researcher may often confront outcomes of the model that initially appear counterintuitive. Since many advances in economic science are counterintuitive on some level, this might be recognized as a good thing. However, great care must be taken to ensure that the emergent outcome in the model is truly the result of purposive agents acting on the basis of the rules enshrined in the code as intended by the researcher and not simply an artifact of either an erroneously coded algorithm or the researcher's accidental misconception of the appropriate way to model a given situation. In the former case, a bug in the code unbeknownst to the researcher causes an erroneous result. In the latter case, a programming rule that is implemented consistent with the researcher's vision artificially ensures an outcome that only appears spontaneous. For example, if a typo in the code goes unnoticed, it might result in agents possessing a different level of a particular parameter than the researcher intended. A thorough verification of the code will help ensure the computer program operates as intended and is free of bugs. Alternatively, a rule might be correctly implemented in the syntax of the code and conform to the researcher's intent, but the rule might be improperly concrete and artificially drive a particular outcome. A thorough validation of the model helps to ensure that it captures the relevant aspects of the phenomenon under examination and further ensures that emergent phenomena are sufficiently spontaneous.

In what Epstein (2006) describes as "the indictment" of agent-based modeling, he notes the following common objections: agent-based models lack equations, the technique is not deductive, and they lack generality. His responds that agent models are computer programs that could be described by a set of recursive mathematical equations. However, such equations would be incredibly complex and barely intelligible whereas the agent model is immediately recognizable as a model (p.1591). In response to the charge that agent-based models are not deductive, Epstein notes that each realization of an agent-based model is in fact a strict deduction (p.1592). In answering the related charge that because the approach is computational, it does not constitute theory, Arthur (2006, p.1555) notes that "If working out the implications of a set of assumptions is theory, then whether it is done by hand or by computer does not matter. Both methods yield theory." Finally, against the charge that agent-based modeling lacks generality, Epstein, grants that agent modelers generally do not quantify their models over ranges of variables as wide as standard general equilibrium theory (i.e. the set of all consumers and assuming utility maximization for every agent) but suggests it is the price of empirical progress (p.1599). While these and other similar objections to agent-based modeling may persist, it is important to remember that the ultimate goal of employing such a tool in analysis is greater understanding of social phenomena.

6 Conclusion

Over fourteen years have passed since Epstein and Axtell developed Sugarscape. While still in its infancy, researchers working in the field of agent-based modeling are embarked on an agenda to provide the foundation of a post-Walrasian economics. Epstein and Axtell provide a hopeful vision of the power of agent-based modeling to improve our understanding of social processes:

> We can only hope that the field itself will display the evolutionary process it studies – new agents join, and intellectual heterogeneity grows; social networks of scientists endogenously take shape, selection pressures operate, and from the social enterprise of agent-based social science, interesting things emerge (p. 178).

Austrian economists, with their comparative advantage in the study of processes and spontaneous order are uniquely situated to take advantage of this technology and positively influence the trajectory of economic science.

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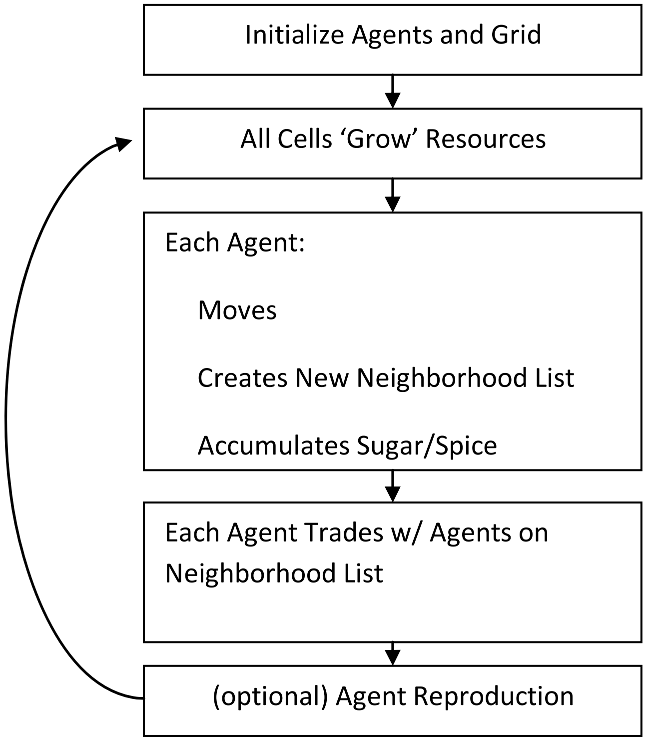

Figure 1. Outline of Sugarscape Model (Epstein and Axtell, 1996; Vriend 2006)

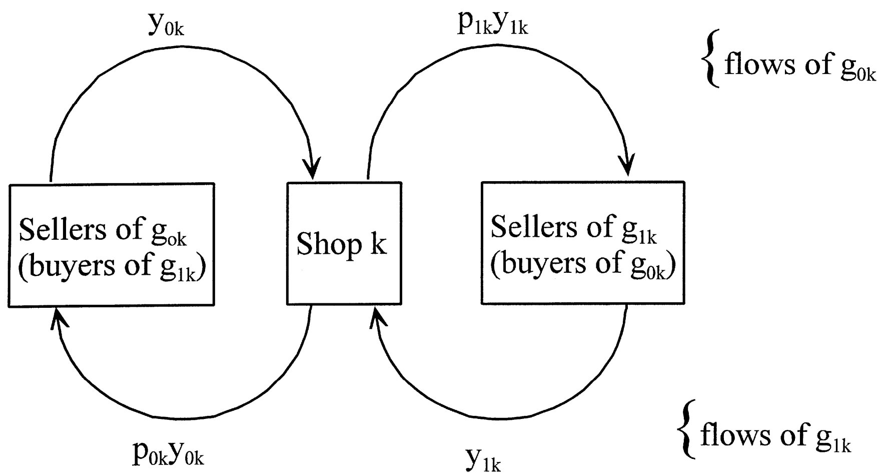

Figure 2. Outline of circular flow of commodities for representative shop (Howitt and Clower 2000, p. 61).