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Trends in Agent-Based Computational Modeling of Macroeconomics

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Abstract Based on the 50 papers surveyed in Reference,[2] this paper addresses general research trends in agent-based macroeconomics. On the aspect of *agent engineering*, we highlight two major developments: first, the extensive applications of computational intelligence tools in modeling adaptive behavior, and second the grounding of these applications in the cognitive sciences.

Keywords: Agent-Based Modeling of Macroeconomics (ABM), Computational Intelligence, Genetic Programming, Co-Evolution, Novelties.

§1 Motivation

In my AESCS'2002 survey article,[2] I presented a lengthy review of the literature on the agent-based modeling of macroeconomics (ABM). The paper reviewed the development of agent-based modeling in three classes of macroeconomic models, namely, the cobweb model, the overlapping-generations model, and the asset pricing model. 50 papers were included in that survey. By and large, the survey showed how the economy modeled as a complex adaptive system is able to demonstrate the process of *self-coordination* and *self-stabilization*, a core issue in macroeconomics. It also enhanced our understanding of the *robustness* of these processes with an extensive coverage of the experiments conducted in the literature, many of which in effect overthrew the conventional stability analysis based on the device of representative agents.

This paper, as a follow-up to the survey, attempts to provide an overview of these 50 articles from two perspectives which were not explicitly addressed in the original survey. The first is the aspect of *agent engineering*. The original survey article was mainly organized as a sequel of macroeconomic models, and the progresses made in modeling adaptive behavior was, therefore, not systematically discussed. Section 2 has this issue as a focus. Secondly, we try to address the issue – *does agent-based macroeconomic modeling have anything worthwhile to offer to economists in general?*[*1] Section 3 provides a list of distinguishing features, which should be of interest not only to economists, but also to social scientists in general as well.

§2 Developments in Agent Engineering

An essential element of the agent-based modeling of macroeconomics is *agent engineering*. Over the last decade, the progress made in models of adaptive behavior has been particularly noticeable. There seems to have been a general tendency to *enrich* agents' adaptive behavior from several different perspectives. This enrichment has been made possible mainly due to the extensive applications of *computational intelligence* to economics.

First, simple adaptive behavior has been extended to complex adaptive behavior. At the initial stage, agents' decisions were simply characterized by *parametric* models; usually, there were just numbers over a bounded real space. Jasmina Arifovic's publications are typical examples (see Reference[2] for details).[*2] All important decisions such as quantity supply, labor supply, savings, financial portfolios, and investment in human capital were characterized by *numbers* rather than *rules*. As a result, the things revealed by the adaptive processes were best viewed as a series of *number crunching* exercises. Sophisticated learning or adaptive behavior were not able to appear in these simple adaptive models.

Later on, the notion of using *rules* instead of *numbers* to characterize agents' decisions was brought in by John Bullard, John Duffy, Reiner Franke, and many others. These series of efforts brought about a discernible progress: they formally introduced agents *who are able to forecast with rules (models)*. Nonetheless, their forecasting behavior was largely confined to *linear regression models*. This restriction was unavoidable because at that stage economists did not know much about dealing with non-parametric adaptive behavior, and linear regression models seemed to be the natural starting point. However, there is neither sound theoretic nor empirical support for the assumption that agents' adaptive behavior may be parameterized.

A breakthrough was made by Martin Andrew, Richard Prager, Shu-Heng Chen, Chia-Hsuan Yeh and Terje Lensberg via genetic programming (GP). The use of genetic programming not only makes agents able to engage in nonlinear and non-parametric forecasting, but it also makes them able to *think* and *reason*. This last virtue is crucial because it helps us to represent a larger class of cognitive capabilities, such as making plans and strategies. This development contributes to the advancement of the agent-based models which are full of the

[*1] This is the issue originally proposed by Steve Gilbert in his plenary speech delivered at the first Lake Arrowhead conference, entitled "Does agent-based modeling have anything worthwhile to offer to social science in general, or is it only of interest to practitioners of its own paradigm?"

[*2] Due to the page limitations imposed on this submission, we shall skip the bibliographical details of those citations which have already been cited in Reference.[2]

non-trivial strategic behavior of agents, e.g., games, auctions, and financial markets. The AI-ECON Research Center in Taipei has now launched a research project, referred to as *the functional-modularity foundation of economics*, that has further enlarged the adaptive behavior to encompass preferences, commodities, technology, human capital, and organizations.

By manipulating a set of primitives with genetic operators, one can *grow* a great variety of human cognitive processes. In principle, there is no limit for those growing processes. It is the *survival pressure* endogenously generated via agents' interaction that determines the size of them. In this case, neither do we need to assume that the agents follow simple rules, as the KISS principle suggests, nor do we assume that they are sophisticated. Simplicity or complexity is not a matter of an *assumption* but a matter of *emergence*. For example, in a simple deterministic agent-based cobweb model, the literature shows that all surving firms have indeed followed simple and myopic rules to forecast price. However, their behavior became more complicated when speculators were introduced into the markets. In addition, when turning to the stock market, agents' behavior could switch between simple rules and sophisticated rules.[*3] In a nutshell, in ABM, what determines the survivability of a type of agent is not the model designers, but the *natural law* of the models. We shall see more on this in Section 3.

The second development is concerned with the *behavioral foundations* of agent engineering. While the CI tools have been extensively applied to agent engineering, their ability to represent *sensible* adaptive behavior has been questioned since agent-based economic models became popular. Since 1999, a series of efforts have been made in an attempt to justify the use of genetic algorithms in agent-based modeling. However, most of these studies are mainly built upon theoretical arguments. Kiyoshi Izumi and Kazuhiro Ueda are the first to use the evidence from *interviews* and *questionnaires* to justify the use of genetic algorithms in their agent-based foreign exchange markets. Their study highlights the significance of the *field study*, an approach frequently used by sociologists, to agent engineering. Duffy's agent-based model of a medium of exchange applied the data from laboratory experiments with human subjects to justify the use of *reinforcement learning*. His study showed how agent-based economic models can benefit from *experimental economics*.

Another related development has occurred in the use of *natural language*. People frequently and routinely use natural language or linguistic values, such as high, low, and so on, to describe their perception, demands, expectations, and decisions. Some psychologists have argued that our ability to process information efficiently is the outcome of applying *fuzzy logic* as part of our thought process. Evidence on human reasoning and human thought processes supports the hypothesis that at least some categories of human thought are definitely fuzzy. Yet, early agent-based economic models have assumed that agents' adaptive behavior is *crisp*. Nicholas Tay and Scott Linn made progress in this direction by using

[*3] In plain English parlance, they sometimes regarded George Soros as their hero, while at other times they developed a great admiration for Warren Buffett.

the *genetic-fuzzy classifier system* (GFCS) to model traders' adaptive behavior in an artificial stock market.

Tay and Linn provided a good illustration of the *non-equivalence* between the acknowledgement of the *cognitive constraint* and the assumption of *simple agents*. It is well-known that the human mind is notoriously bad at intuitively comprehending exponential growth. However, there is no evidence that traders on Wall Street are simple-minded. Tay and Linn's work recognized the difference, and appropriately applied the GFCS to *lessen* agents' reasoning load via the use of natural language.

Izume's, Duffy's and Tay's works can all be regarded as a starting point for a more remarkable development in agent engineering: the CI tools employed to model agents' adaptive behavior are grounded in strong evidence within the cognitive sciences. It is at this point that agent-based modeling should have closer interactions with the *field and panel study*, *experimental economics* and *behavioral economics*.[*4]

§3 Distinguishing Features

While the progress made in agent engineering is evident, the second part of this paper tackles a more subtle issue of ABM: *does agent-based macroeconomics have anything worthwhile to offer economists in general, or is it only of interest to practitioners of its own paradigm?* In this section, we shall argue that the development of ABM has already demonstrated some distinguishing features with insightful lessons which are generally not available from neoclassical macroeconomics. The distinguishing features, which may interest economists in general, are two-fold. First, ABM helps build a *true* micro-foundation of macroeconomics by enabling us to study the *micro-macro relation*. This relation is not just a linear scaling-up, but can have a complex "chemical" effect, known as the *emergent property*. Consequently, macroeconomics becomes a part of the *sciences of emergence*. Second, ABM is able to demonstrate a lively *co-evolution* process, which provides a new platform for testing economic theories. Moreover, what comes with the co-evolution process is a *novelty-generation* process. The latter is, in particular, the weakest area of neoclassical economics.

3.1 Micro-Macro Relation and Emergent Properties

Agent-based modeling provides us with a rich opportunity to study the so-called *micro-macro relation*, which is beyond the feasibility of the neoclassical economics that consists of only a few representative agents. The first type of micro-macro study involves laying the *foundation* for the aggregate behavior upon the *agents' interacting adaptive schemes*. A series of efforts were made by Arifovic, Bullard, Duffy and Herbert Dawid to attribute, in an analytical way, the appearance of some interesting macroeconomic phenomena, such as the fluctuations in foreign exchange rates, the bid-ask spread, hyperinflation and economic take-off, to the adaptive behavior driven by GA. Elements, such as

[*4] Mentioning this is particularly appropriate when the 2002 Nobel Laureates in economics just happen to be pioneers of these two fields of research: Vernon Smith and Daniel Kahneman.

self-reinforcement and *critical mass*, upon which the conventional arguments are built, are actually encapsulated into GA. Chen, Duffy and Yeh, on the other hand, showed the significance of the *survival of the fittest principle* to the convergence to Pareto optimality. In their agent-based cobweb model, OLG model of saving and inflation, and coordination games, it was shown that the property of converging to Pareto optimality will break down if *survival pressure* is removed.

The second type of micro-macro study is concerned with the *consistency* between the micro behavior and the macro behavior. A particular interesting thing is that the micro behavior can sometimes be quite different from the macro behavior. Both the work done by Franke on the cobweb model and Chen and Yeh on the asset pricing model showed that the time series of the market price (an aggregate variable) followed a simple stochastic process. However, there is no simple description of the population dynamics of individual behavior. The simple stochastic price behavior was, in effect, generated by a great diversity of agents whose behavior was constantly changing. Chen and Yeh proposed a measure for the *complexity* of an agent's behavior and a measure of the *diversity* of an agent's complexity, and it was found that both measures can vary quite widely, regardless of the simple aggregate price behavior.

In addition, using the micro-structure data, Chen and Chung-Chih Liao initiated an approach to study what is called the *emergent property*.[3] By that definition, they found that a series of aggregate properties, such as the efficient market hypothesis, the rational expectations hypothesis, the price-volume relation and the sunspot effect, which were proved by rigorous econometric tests, were generated by a majority of agents who did not believe in these properties. Once again, our understanding of the micro behavior does not lead to a consistent prediction of the macro behavior. The latter is simply not just the linear scaling-up of the former. Conventional economics tends to defend the policy issues concerned with the individual's welfare, e.g., the national annuity program, based on the macroeconometric tests, e.g., the permanent income hypothesis. Agent-based macroeconomics may invalidate this approach due to emergent properties.

3.2 Co-Evolution

Briefly, co-evolution means that everything depends on everything else. The performance of one strategy depends on the composition of the strategies with which it interacts, and the fundamental push for agents to adapt arises because other agents are adapting as well. This idea is by no means new to economists. Actually, it is the main subject of evolutionary game theory. However, what has not been shown explicitly in the evolutionary game theory or mainstream economics is that *it is the force of co-evolution which generates novelties*. We shall say a few words concerning their relation here, but more on novelty in the next subsection.

Novelties-generation, from its general characteristics to its formation process, is little known in mainstream economics. For example, there is no formal (mathematical) description of how the DOS system eventually leads to the Windows system. Neither is there an abstract description showing how commodities $A_1, A_2, ..., A_n$ in the early days lead to commodities $B_1, B_2, ..., B_m$ at a later stage, or how a population of behavior years ago leads to a different population of behavior at present. Quite ironically, the vision of the Father of neoclassical economics, Alfred Marshall, namely, "Economics, like biology, deals with a matter, of which the inner nature and constitution, as well as outer form, are constantly changing," was virtually not carried out at all by his offspring (neoclassical economists).

ABM attempts to recast economics along biological and evolutionary lines. Within the co-evolutionary framework, the system which an agent faces is essentially *open* and *incomplete*. The optimal kinds of behavior (strategies, rules,...) which interest most economists may not necessarily exist in this system. In his agent-based cobweb model, Franke used the *survival distribution function* of firms to show *waves of evolutionary activity*. In each wave, one witnesses the sudden collapse of a strongly dominating strategy, the "optimal" strategy. Very typically, the co-evolution demonstrated in the agent-based model is not a peaceful state of co-existence, but is an incessant struggle for survival where no strategy can be safe from being replaced in the near future. Novel strategies are spontaneously developed and old "optimal" strategies are continually replaced.

This feature casts doubt on the "optimal" economic behavior which is not derived from the agent-based co-evolutionary context. In this way, Chen and Yachi Hwang's agent-based model of investment lent support to the non-optimality of the capital asset pricing model (CAPM). The optimality of the CAPM was originally derived from a general equilibrium setting. However, Chen and Hwang simulated an agent-based multi-asset market, and showed that, in most of their simulations, the fund managers who followed the CAPM did not survive when investors with the constant relative risk aversion presented.

In Chen and Hwang's model, the CAPM traders and many different types of traders were all introduced to the market right at the beginning (at the initialization stage). They were competing with other agents whose portfolio strategies were evolving over time and which were characterized by GA. The annihilation of the CAPM traders was the result of this setting. This kind of test is referred to as the *formula-agent* approach. Formula agents are agents whose behavior or decision rules are inspired by economic theory. Based on this approach, the economic behavior predicted by the economic theory is tested by directly adding formula agents to the initial population. Doing so may be biased because the resultant co-evolution process may be determined by these initial *hints*, a common phenomenon known as *path dependence*.[*5] Therefore, the formula-agent approach is relatively *weak* as opposed to an alternative approach to the co-evolution test, and Lensberg's agent-based model of investment is an illustration of this alternative.

Lensberg's model tested *Bayesian rational investment behavior*. However, unlike Chen and Hwang' setting, Lensberg did not initialize the market with

[*5] Path dependence is ubiquitous in ABM. For example, in Herbert Dawid's agent-based model of double auctions, the distribution of competitive prices is sensitively dependent on the distribution of initial bids and asks.

any *Bayesian rational investor*. In other words, all agents' investment rules were generated from scratch (by GP). It was then shown that, in later periods of evolution, what dominated the populations (the surviving firms) were the behavioral rules as if they were expected utility maximizers with Bayesian learning rules. Therefore, the Bayesian rational investment rule was validated as a behavior emerging from the bottom.

However, not all cases have lent support to what economic theory predicts. Black LeBaron's version of the SFI (Santa Fe Institute) artificial stock market is a case in point. *Stationarity* associated with the *asymptotic theory* plays an important role in current developments in econometrics. In the mainstream rational-expectations econometrics, agents are assumed to be able to learn from this stationary environment by using the so-called *Kolmogorov-Wiener filter*. The use of this filter can make sense only if agents believe that the entire time series is stationary, and never doubt that things may have changed in the recent past. Agents with this belief are called *long-horizon agents* in LeBaron's ABM. In a similar way to Lensberg, LeBaron questioned whether these long-horizon agents can eventually emerge from the evolution of a population of short-horizon agents, given that the true dividends-generation process is indeed stationary. He interestingly found that, while long-horizon agents are able to replicate usual efficient market results, evolving a population of short-horizon agents into long-horizon agents is *difficult*. This study, therefore, presents a typical coordination failure problem frequently addressed in macroeconomics.

Within this co-evolution test framework, the maximizing-expected-utility (MEU) behavior of investors, known as the *principle of maximizing certainty equivalence*, was also rejected by Martin Lettau, George Szpiro, Oscar Cacho and Phil Simmons. In their agent-based models of *investment under uncertainty*, they all came up with the same conclusion: *those who survive were not the most efficient in a normative sense*, i.e. the MEU agents were not able to survive. Hence, in a sense, the equivalence between *efficiency* and *survival* broke down. What happened instead was that the surviving investors either took too much risk (in Lettau's case) or were too cautious (in Szpiro's and Cacho and Simmons' cases).

3.3 Novelties

As mentioned earlier, in ABM, what may come with a co-evolutionary process is a novelties-generation process. This feature is similar to Hayek's evolutionary concept of "*competition as a discovery procedure.*" The neoclassical economic models are completely silent on the novelties-generation process, from their general characteristics to their formation process. One basically cannot anticipate anything unanticipated from the neoclassical model. All types of economic behavior are determined exogenously and can only be renewed manually by the model designers in a top-down manner. This makes it very hard for neoclassical economics to give a constructive notion of preferences, commodities, technology, human capital, and organization, concepts that are fundamentally related to the *theory of economic change*.

Back in the late 1980s, John Holland and Brian Arthur already had sketched a research idea, known as "*growing artificial economy*", which was basically to simulate the evolution of an economy from its primitive state to the advanced state. This big plan, however, was never carried out. Instead, what was actually implemented was found in Joshua Epstein and Robert Axtell's famous book, "*growing artificial societies.*" In a model of cellular automata, they evolved many interesting kinds of economic and social behavior, including trade, migration, disease, distribution of wealth, social networks, sexual reproduction, cultural processes, and combat. In addition to this major piece of work, Thomas Sargent studied how money as a medium of exchange can emerge from a bartering economy, Arifovic, Bullard and Duffy also simulated the appearance of an economic take-off (the industrial revolution), and Chen and Yeh showed how firms adapted to structural changes, etc.

Despite these studies, one has to say that the novelties-generation process has not been well exploited given the current state of ABM. There should be more left for the researchers to do. In their research project, the *functional-modularity foundation of economics*, Chen and Bin-Tzong Chie proposed an agent-based model of preference changes and technology formation to *grow* both technology and preferences. [4] In their model, consumers' current preferences will determine the direction of technology advancement. However, the technology developed will in turn evolve the preferences as well. GP is applied here to give size-free and shape-free representation of technology and preferences.

§4 Concluding Remarks

Research trends in the agent-based modeling of macroeconomics are presented in this article. We review developments in agent engineering and the interesting features coming out of them. The efforts made over the last decade shown that ABM provides a promising true micro-foundation for macroeconomics. The use of computational intelligence tools not only enhances the economic modeling of adaptive agents, but also motivates the conversations among economists, sociologists, and psychologists in the cognitive foundations of agents.

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