LABORatorio R. Revelli
Centre for Employment Studies

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"Imagine how hard physics would be if electrons could think"
Murray Gell-Mann

Economics is the science about the intended and unintended consequences of individual actions, in an environment characterised by scarce resources that both requires and forces to interaction. There are other sciences, most notably physics, in which the interaction between a multitude of particles plays a central role. However, there is one fundamental feature of Economics, which distinguishes it from other disciplines. This feature is *intention*. "Imagine how hard physics would be if electrons could think" is a powerful way of express it, attributed to Murray Gell-Mann (Page,1999).

Even if important insights on relevant economic phenomena can be gained by abstracting from individual behaviour and motivations (think for instance of Keynesian macroeconomics) the understanding of the two-ways feedback between the micro- and the macro-structure is of fundamental importance for the possibility of intervening in the system, for instance for policy reasons. But in adopting a micro-approach to economic modelling, the issue of the realism of the assumptions becomes central. These assumptions may regard the way the atomic elements of the model perceive and behave, or the interaction structure itself. The main argument of this paper is that agent-based computational economics (ACE), described as "the computational study of economies modelled as evolving systems of autonomous interacting agents", is a powerful tool for economic analysis, allowing for a more flexible model specification and the inclusion of more tailored assumptions.

As all new methodologies, the use of ACE must be justified, from a methodological point of view. The burden of the proof rests on ACE practitioners. However, instead of definitely establishing the technique the stream of methodological work has ironically confirmed many mathematical economists in their belief that agent-based modelling is inconclusive. In a companion paper (Richiardi, 2003) I have rationalised the main theoretical critiques that can be moved to agent-based computational models, and highlighted the existence of appropriate solutions.

However, non-ACE practitioners sometimes feel that ACE has prompted more methodological discussion than applications. I therefore turn here to the empirical relevance of ACE model as a tool for expanding knowledge about economic systems.

I build on Robert Axtell[1] (Axtell, 2000) identification of three distinct uses of agent-based computation in the social sciences, and rank them according to their auxiliary nature, with respect to analytical modelling.

The first use is *numerical computation of analytical models*. Note with Axtell that «[t]here are a variety of ways in which formal models resist full analysis. Indeed, it is seemingly only in *very* restrictive circumstances that one ever has a model that is completely soluble, in the sense that everything of importance about it can be obtained solely from analytical manipulations». Situations in which resort to numerical computation may prove useful include (a) when a model is not analytically soluble for some relevant variable, (b) when a model is stochastic, and the empirical distribution of some relevant variable needs to be compared with the theoretical one, of which often few moments are known, (c) when a model is solved for the equilibrium, but the out-of-equilibrium dynamics are not known. In particular, with reference to the last point, it

[1] The three categories identified below correspond only partially to Axtell's.

may happen that multiple equilibria exist, that the equilibrium or (at least some of) the equilibria are unstable, that they are realized only in the very long run. Conversely, it may happen that equilibria exist but are not computable. Axtell (2000) provides references and examples for each case. Finally, it may be the case that the equilibrium is less important than the out-of-equilibrium fluctuations or extreme events.

Clearly, agent-based simulations are not the only way to perform numerical computations of a given analytical model. However, they may prove effective and simple to implement, especially for models with micro-foundations.

The second use is *testing the robustness of analytical models* with respect to departures from some of the assumptions. Assumptions may relate to the behaviour of the agents, or to the structure of the model. ACE models can easily include bounded rationality (Sargent, 1993; Leijonhufvud, 1993; Conlisk, 1996) and heterogeneity at an individual level, and investigate variations in the way agents interact with each other or with the institutional setting. One important feature of ACE is that in considering departures from the assumptions of the reference model, a number of different alternatives can be investigated, thus offering intuition towards a generalization of the model itself.

The first two uses of ACE models are *complementary* to mathematical analysis. The third use is a *substitute*, going beyond the existence of an analytical reference model. It provides *stand-alone simulation models* for (a) problems that are analytically intractable, or (b) problems for which an analytical solution bears no advantage. The latter may happen when negative results are involved, for instance. A simulation may be enough to show that some institution or norm is wrong, or does not work in the intended way. Analytical intractability may arise when more complicated assumptions are needed, or when the researcher wants to investigate the overall effect of a number of mechanisms (each possibly already analytically understood in simpler models), at work at the same time.

Finally, one could ask whether the application of agent-based simulations to the analysis of the topics covered in this thesis has any support in the existing literature. More generally, since the models developed here are just examples of the way ACE models can be integrated in the economic analysis, one could be curious to know about the empirical relevance of agent-based computational economics.

Extensive reviews of ACE applications to different fields are provided in Tesfatsion (2001a,b,c) and in Judd and Tesfatsion eds. (forthcoming). Tesfatsion (2003) summarizes the main research areas where agent-based simulations have mostly made their appearance. These are «(i) Learning and the embodied mind; (ii) evolution of behavioral norms; (iii) bottom-up modeling of market processes; (iv) formation of economic networks; (v) modeling of organizations; (vi) design of computational agents for automated markets; (vii) parallel experiments with real and computational agents; and (viii) programming tools for ACE modeling». Her list of references includes 111 papers, selected among the most interesting applications in each area. Models of the labour market are surveyed among the more general topic of the endogenous formation of trade networks. Tesfatsion (1998, 2001d) investigates the relationship between market structure, worker-employer interaction networks, worksite behaviours, and welfare outcomes. Tassier and Menczer (2001) study why socially determined networks (i.e. friends, relatives or other social contacts) perform so well as referral networks, in the U.S. labour market, while they should transmit biased information.

The evolution of firms, as well as industry dynamics and innovation can be grouped under section *v*. Dawid et al. (2001) use a stylised ACE market model to explore how the structure of the market and the internal organization of each participant firm affect the form of the optimal behavioural rules for the participant firms. Among the papers not surveyed by Tesfatsion, Axtell (2003) proposes a dynamical theory of endogenous team formation and evolution, and studies the effects of different compensation schemes. He argues that conventional game theory is ill-suited to studying the kinds of meta-stable structures that emerge and transiently survive in this model. Empirical regularities like the distribution of firm size are recovered. The model has also been extended to the explanation of city size (Axtell and Florida, 2001). Gallegati et al. (2003a,b) develop a model of financial fragility where firms are heterogeneous and interact through the credit market. The model is able to reproduce a number of stylised facts concerning the distributions of firms' size, output changes during business cycles, rates of growth of aggregate and individual production, age of exiting firms, profits, and bad debt.

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