Introduction

One of the main problems that economics has faced—one could say right from the very beginning—is how billions of agents, with different tastes and abilities, coordinate with each other without any central control. The dominant economic theory has covered several paths, which model agents who interact indirectly. On the one hand, the approach in Walras's Elements Walras (1874)—and in the version of Arrow (1951), Debreu (1951), Arrow and Debreu (1954)—where a market auctioneer is provided with all the information—the single agents only know their own payoff and utility functions—and coordinates the market through the vector of prices. On the other, the equilibrium context without any coordinating figure, where information is distributed among the agents as in Dynamic Stochastic General Equilibrium (DSGE) approach. Both can be thought of as models for interacting agents, but only the second can aspire to become a paradigm for methodological individualism because, in the first it is crucial to model at the micro level in order to have an exact aggregation at the macro one (see the discussion in Chap. 1).

A model of such "interactions" among economic agents is nothing else but a "map" of the world. In microeconomic models, the agents meet in various markets and follow rules of behaviour, based on axioms or on empirical evidence (from which the modeller can obtain simple rules of the thumb). Agents and markets are the fundamental constituents also of every micro-founded macro model. If this is true, it seems to us that micro models are all agent-based and that their differentiation occurs at a following level, when considering information about the world for which the map is built. In traditional models it is assumed that one has a complete characterization of individual preferences. Or plainly speaking, one knows exactly what economic agents want. Payoff and utility function existence theorems were extracted from this hypothesis Debreu (1954), Debreu (1960), Diamond (1965), making it possible to represent the preference scheme of economic agents with scalar objective functions for which the maximum value exists.[1]

[1]Unfortunately, those same assumptions give rise to the Sonnenschein–Mantel–Debreu theorem Sonnenschein (1972), Debreu (1974), Mantel (1974) that demonstrates how many properties at the

From here follows the whole traditional approach to macroeconomics and micro-founded finance. An argument in Muth (1961) further elaborated by Lucas (1972), Lucas (1976) affirms, in fact, that if the economist assumes to be able to represent the preferences of individuals then, in the model, it must be assumed that the same individuals know their preferences and behave so as to get the best they can (optimization) given the information they have at their disposal about the world. In other words, in traditional models the fact that agents optimize is a mere consequence of the initial hypothesis, made by the scholar, of knowing the preference scheme of the agents who are the object of the analysis.

Agent-based literature, on the other hand, aims to study economic phenomena in their complexity; taking into account joint distributions of individual characteristics, the direct and not only indirect interactions and therefore the way in which economic networks are made and changed. Hence, it cannot assume to be able to perfectly represent the preferences and therefore to have an exact knowledge of the objective functions. The starting point of each agent-based analysis is a description of the rules of behaviour, that is, the map between the actions and the information set available to them in which a partial knowledge of the objective functions is included. These rules can be derived from empirical work, from economic experiments, from studies carried out in disciplines other than economics (psychology, sociology, etc.) or from a purely normative analysis. In other words, what would the aggregated relations be if the agents followed certain kinds of rules, which have had important results in auction models (Tesfatsion and Judd 2006).

From the beginning, the agent-based literature had to face the Lucas critique (Lucas 1976). When one wants to assess the effect of an economic policy one has to take into account that the latter will enter the information set of agents, changing their behaviour. This could result in a neutralization of the economic policy or its much lesser effect than expected ex ante. Agent-based models, to respond to the Lucas critique, have often resorted to the use of learning algorithms and switching mechanisms between different rules to take account of the effects of economic changes in the environment on the behaviour of agents. On the other hand the solution proposed by Lucas, based on the use of rational expectations, runs into a potentially worse problem than what had motivated it, since in order to work it has to assume that agents have perfect knowledge, perfect rationality, and almost infinite computing capabilities. "Satisfactory" adaptivity, bounded rationality and behaviour (instead of optimizing) are thus a typical feature of agent-based models: the agents can change their mind during the simulation and often change the rule. Given the only partial knowledge, ex ante, of the objective function there can only be an update, ex-post, on the basis of the results. A rule resists so long as it "works", that is produces good results. Otherwise it will be changed. Let's give a simple example. Suppose we want to divert a stream of ants marching straight towards our

(Footnote 1 continued)
micro level disappears at the macro one, when aggregating. An important consequence is that many properties of an aggregate variable may be generated both by optimizing agents and non-optimizing agents.

house. The Lucas critique would tell us that we cannot simply put an obstacle in their path, or at least it might not be sufficient. The ants could go round it and continue undeterred towards our house. In an agent-based perspective we should study the ways ants bypass obstacles—and thus change the "local" rule of movement when they encounter an obstacle—depending on the size and shape of the latter: a macrofoundation of microeconomics.

This book guides the reader in the world of such agent-based models (ABM) and of the technicalities that need to be solved to evaluate the effect of different rules and their switching. One thing must immediately be made clear. The current agent-based literature is vast and is not just about economics. Our review of the techniques will inevitably be biased towards the work and the problems that our research group has had to face and resolve in more than 20 years of analysis, producing numerous scientific publications. When we refer to agent-based models, the reader must always keep in mind this explanatory bias.

That said an ABM, then, is a computational model, populated by many heterogeneous agents interacting with each other from the bottom—bottom up—that is, without a central coordinator. These interactions produce emergent results in which the aggregate result is different from what it would be if each agent were isolated from the others, that is, without feedback or externalities (see the review on aggregation made in Chap. 1). In ABM economic results can be aggregated, and in particular added together to calculate the GDP, consumption and investment, and in general also the distributions (see the analysis of distributions made in Chap. 4) and economic networks can be studied. These economic statistics are difficult to obtain using traditional approaches and analysis of economic networks is virtually absent.

For a macroeconomist that the GDP is the sum of individual activities is something perfectly familiar: as shown in Chap. 1, even though the approaches are different, a DSGE model could give similar results to an ABM in terms of aggregate dynamics. After all, even a DSGE model is populated by many agents who interact and the results of these interactions produce economic results, and if we add up these results we obtain the GDP and so on. Our argument is that by giving up the assumption of perfect knowledge of the objective function (except for exogenous disturbances), one can describe a much richer set of phenomena than with the DSGE models. Obviously there are important differences between ABM and DSGE, even in the pre-analytical vision. It is however possible, in principle, to pass from an ABM to a DSGE through successive simplifications that identify, unless there are stochastic disturbances, the objective functions. One only has to impose the demand–supply equilibrium, that there are one or more representative agents (or that the distribution of individuals in the period $t + 1$ can be computed), that the agents maximize an objective function bound to some balance sheet, that from an agent-based model it is possible to theoretically obtain a DSGE. In other words, an important difference between the two approaches is the information and computational capabilities of the agents.

If the information is incomplete the future becomes uncertain while asymmetry leads to interaction. This, however, is not harmless, since economic agents are strategic agents and with their actions change the structure (and the laws: not by chance does one speak of empirical regularities). Moreover, with heterogeneity one interacts locally and the "system" becomes endogenous.

In an ABM, the interactions are governed by rules of behaviour that the modeller codifies directly in the individuals who populate the environment. In an ABM, the behaviour is the point in which a modeller begins to make hypothesis. The DSGE modellers make assumptions about what an optimizing agent wants, compatibly with budget and resource constraints, and represent these wishes with concave real-valued functions defined over convex sets. Based on the combination of objectives and constraints, the behaviour is derived by solving the first-order conditions and when necessary also the second-order conditions. The reason why economists set their theories in this way—making assumptions about the goals and then drawing conclusions about the behaviour—is that they assume that the allocations, decisions and choices are guided by individual interests. Decisions and actions are carried out with the aim of reaching a max-min goal. For consumers, this usually regards utility maximization; a purely subjective assessment of well-being. For businesses, the goal is typically to maximize profits. This is exactly where rationality, for DSGE, is manifested in economics. In a nutshell, in DSGE models the modeller sets the objective function and the consequent maximization generates the rules. In the ABM the modeller sets directly the behavioral rules given empirical evidence and experiments that should control the degrees of freedom. The introduction of information problems in the Walrasian model is only apparently harmless for the externalities and non-convexity deriving from it. The issue of asymmetric information assumes that the agents are different from each other (Greenwald and Stiglitz 1993). According to Leijonhufvud (1981) this distinction is a condition sufficient to generate failures in coordination. In particular, whether information is complete or not, if it is evenly distributed, banks and businesses would become a single aggregate where every debt–credit ratio is cancelled and money has no role to play. The game theory has also shown that rational behaviour can generate multiple equilibria. Along the same lines, it can be argued that if there is asymmetric information the problems of adverse selection prevent a decentralized system from reaching Pareto-optimal positions (Akerlof (1970), Stiglitz and Weiss (1981)), thus giving rise to market failures.

The Arrow–Debreu works established conditions to have a Pareto optimum: the information need not be perfect; it can be incomplete provided it is exogenous, that is, the beliefs must not change as a result of the agents' actions. In short, there must be no direct interaction. The case in question is represented by a central actor (the auctioneer) and the connections going from him to all agents. Instead, when information is imperfect the single agents will come into direct contact, that is, there will be links between agent and agent.

It must be recognized that if there is information asymmetry, the agents interact directly with each other outside the market, stimulated by profits. In that case, however, the Walrasian star type of network presents serious difficulties. And of course the idea of a representative agent has to be abandoned. Which is not only a problem of fallacy of composition, or of aggregation: it is that with interaction aggregate behaviour is no longer a linear summation, but a nonlinear process that emerges from the individual one and as such is endowed with properties that are different from that of the single constituent parts. The ABM approach aims precisely to describe, in a reduced scale, the behaviour of single individuals and bring out the aggregate properties.

Chapter 1 will analyze in detail the ABM approach compared to the traditional one mentioned above. The idea of this chapter is to give a set of tools necessary to understand the construction of two economic models developed in Chaps. 2 and 3. The chapter opens with a discussion on the problems of aggregation of macroeconomic models. To be honest, such a discussion would not be strictly essential in the ABM models which implement a bottom-up approach that takes into account the distribution of the agents in each period. Aggregation is performed at the end of each period by simply adding or calculating the per capita values. It is, however, important to be aware of this problem which must, instead, be solved in the construction of traditional models. The chapter continues with a comparison between the traditional models and the ABM approach showing the advantages of the latter in the analysis of distribution evolution regarding the features and choices of agents and in the analysis of economic networks. The second session of the chapter analyzes in detail the "box of tools" necessary to the ABM economist. In particular, it illustrates the choices of consumption and production, the expectations, the matching between demand and supply of credit and the entry–exit of companies from a market.

Chapter 2, using the tools of Chap. 1, describes step by step the construction of an educational version of the agent-based model published in Riccetti et al. (2013). The model analyzes the interaction between the distribution of the companies that produce a homogeneous good with external sources of funding and the banking system which is also heterogeneous. Although this is a "toy model", its description proposes a twofold goal: (1) on the one hand it allows us to show how the tools described in the first chapter can be used to build an existing model in the literature and (2) shows the basics of computer programming.

A few words must be spent about the use of programming languages. When two of the editors of this book were young, virtually every economic model had to be analyzed analytically. Certainly it could be simulated and this was a possible strategy of analysis: simulation was performed in order to understand the properties which later were analytically demonstrated. Today many models, both standard and agent-based, are impossible to be analyzed analytically. The attack strategy to the economic problem has been completely reversed. Maybe one can analytically analyze a very simplified version in order to understand the basic properties, but the one and true model can only be studied numerically. Therefore, it is necessary to strongly invest in one or more programming languages (MATLAB/Octave, R, Fortran, C, C++, Python, etc.). The choice of the second chapter fell on R because it is open-source, with a good learning curve (the language is similar to MATLAB even though Octave is closer) and rich in statistical functions with which to analyze the results of an economic model; functions like those also described in Chap. 4. The chapter is packed with exercises in R that provide a thorough knowledge on programming techniques and on the construction of an economic model which is, of course, the ultimate goal of this book.

In Chap. 3, instead, we chose to use the most classic and fastest programming language, C. This is because we believe that for the most complex economic models the choice of fast programming languages (as well as Fortran and C++) is hardly avoidable. Investing in one or more of these compiled languages is a choice, perhaps not necessary, but which we strongly recommend to students, graduate students, young researchers who are interested in the subjects of this book. Chapter 3 presents the construction of a simplified agent-based model drawn from the publications of Tedeschi et al. (2009), Tedeschi et al. (2012b). The model represents, in a stylized form, the operation of a financial market in order to reproduce the most important statistical regularities we observe in financial time series. The main mechanism of the model is the endogenous mechanism of imitation, via a preferential attachment rule (Barabási and Albert 1999) in which the agents are more likely to imitate the choices of others who have generated higher profits in the past. The aims of this chapter are (1) to show how using the classic and fast programming language C it is possible to build an agent-based model for financial markets; (2) how agent-based modelling allows to analyze direct interaction phenomena that generate financial networks and make them evolve.

The book ends with Chap. 4, a valuable chapter for those who study agent-based economic models, but not only. This chapter describes density and probability functions which are useful to represent empirical distributions of individuals and businesses depending on their characteristics. Also illustrated, and implemented in R, is their estimation procedure. They are all "heavy-tail" distributions in the sense of having heavier tails than normal and than their derivatives. This is one of the most robust stylized economic facts that agent-based models must and can explain. In reality the probability of extreme events is higher, and often much higher, than that implied by Gaussian distributions.

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