J Econ Interact Coord (2010) 5:111–135
DOI 10.1007/s11403-010-0064-8

REGULAR ARTICLE

Complex agent-based macroeconomics: a manifesto for a new paradigm

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Received: 4 January 2010 / Accepted: 14 May 2010 / Published online: 5 June 2010

Abstract This article discusses some issues and challenges facing modern macroeconomics. We argue for the necessity to replace the reductionist approach at the heart of mainstream DSGE models with an approach rooted on the science of complexity and agent-based modelling. To strengthen and exemplify our position, we show a simple example and introduce several items for a research agenda along these lines.

1 Introduction

The modern history of economic thought proceeds by deep economic crisis, with paradigmatic shifts distanced in time by spans of about forty years. First came the big depression of the 1930s, from which we have inherited the Keynesian revolution and the birth of macroeconomics as an independent body of concepts and theories. Then came the stagflation due to the oil shocks of the 1970s, that gave rise to the neoclassical counter-revolution, rooted in general equilibrium and rational expectations. Now it is the time of the global financial turmoil of 2007–2009, which went almost unpredicted

We would like to thank two anonymous referees, the Editor-in-Chief, Emiliano Santoro and Roberto Tamborini for helpful suggestions and comments on an earlier version. Saul Desiderio provided excellent research assistance.

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and hardly understood by the profession in all its ramifications from originating imbalances to final consequences on unemployment and the real economy.

The need for a meaningful reconstruction of economic theory called on by recent events has become so compelling to have reached the wide audience of laymen. Accounts on the reasons for failures of the currently prevailing conceptual apparatus of economics has left the muffled rooms of academic departments to gain the first page of popular newspapers like the *New York Times*:

> *The economic profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth [...] As memories of the Depression faded, economists fell back in love with the old, idealized vision of an economy in which rational individuals interact in perfect markets [...] Unfortunately, this romanticized and sanitized vision of the economy led most economists to ignore all the things that can go wrong. They turned a blind eye to the limitations of human rationality that often leads to bubbles and burst; to the problem of institutions that run amok; to the imperfection of markets—especially financial markets—that can cause the economy's operating system to undergo sudden, unpredictable crashes; and to the dangers created when regulators don't believe in regulation.* (Paul Krugman, New York Times, 2009-09-02)

and the *Financial Times*:

> *Mainstream models take the view that economic agents are superbly informed and understand the deep complexities of the world. In the jargon, they have "rational expectations". Not only that. Since they all understand the same "truth", they all act the same way. Thus modelling the behaviour of just one agent (the "representative" consumer and the "representative" producer) is all one has to do to fully describe the intricacies of the world. Rarely has such a ludicrous idea been taken so seriously by so many academics.* (Paul De Grauwe, Financial Times, 2009-07-21)

Of course, poor economic models cannot be blamed for poor (as well as for good, of course) economic performances. They did not cause the recent crisis. But those models support the idea that markets—albeit recurrently buffeted by random disturbances—are inherently stable and that all uncertainty is exogenous and additive, two statements which have been treated as principles of faith instead of being rigorously demonstrated. And while no one should expect better models alone to prevent future crises, they may give policymakers better ways to assess market dynamics, detect early signs of trouble and regulate markets more efficiently. The cultural inertia of academic economics should not block any attempt to shed light on phenomena that exert such a powerful influence over our lives. The regulation of markets ought to be based on the very best science we can count on, even at the cost of abandoning some of economists' most cherished dogmas.

In fact, macroeconomics needs a new scientific paradigm, new tools and a new research agenda. The starting points are a full and consistent acknowledgment that any aggregate economic system is more than the sum of the microeconomic decisions of rational agents; that microeconomic decentralized interactions are crucial, as they create collective arrangements that can not be directly traced back to the individual primitive parameters of taste and technology of heterogeneous individuals, left alone to that of a representative agent; that we need new theories and new means of comprehension as we move our attention from low-level to high-level systems (that is, from micro to macroeconomics). In other terms, the core consists in rationalizing market economies as *complex adaptive systems*, and in making use of concepts and tools from the science of complexity.[1]

Fortunately, in this endeavour we do not start from scratch. A lot of work along these lines has already been done by several social scientists engaged in many different projects and fields of specialization,[2] and several pieces of the theoretical architecture we need have been established. Furthermore, various manifestos which move from the patent inadequacy of mainstream theories to explain the 2007–2009 crisis, to forcefully argue for a scientific revolution along the lines above have recently appeared (Buiter 2009; Colander et al. 2009; Stiglitz 2009). Given the lack of permeability to any criticism shown by the mainstream community (Kocherlakota 2009; Lucas 2009), however, we are not worried of being redundant as we make another call to action to revise the methodological credentials of macroeconomics, according to the well-honoured motto *melius abundare quam deficere*.

To paraphrase Kocherlakota (2009), we are indeed perfectly aware that leading mainstream macroeconomists do not ignore frictions, or bounded rationality, or heterogeneity in their models, and that a lot of work has been devoted to the modeling of informational imperfections and bubbles in financial markets during the last three decades. By the same token, we are perfectly aware that prolonged slumps can be easily generated within a dynamic general equilibrium growth model as long as one is willing to exogenously introduce into the picture the right mix of institutional restrictions and rigidities (Kehoe and Prescott 2007). It is not the abstraction of these models which is worrisome, nor is their inability to predict the exact time of the crisis. Theoretical models are abstract by definition and their role is not that of forecasting turning points, but to explain why they happen. Our position is that the ultimate reason to discard modern mainstream macroeconomics lies in the pitfalls hidden in its methodological background, namely *equilibrium microfoundations*, since it does not allow the macroeconomist to recognize the essence of macroeconomics: the emergence of aggregate outcomes and structures as aggregate *unintended and unplanned consequences* of individual human actions and dispersed interactions.

The point is not new. Mainstream models may take into account the divergence of individual intentions and aggregate consequences in terms of externalities, but they merely focus on the properties of the end-state, that is of the equilibrium, a situation in which individual actions are mutually compatible by definition. However, a proof of existence in theory is not enough to scientifically explain how and why a fact happens. On the contrary, we are interested in the processes and causal relationships that can bring about—or, in other terms, that can *generate*—unintended social consequences

[1] References on the notion of complexity in science are too many to be cited here with some pretension of completeness. For a discussion mainly focused on complexity in economics we refer to our forthcoming book, and to the bibliography at the end it (Delli Gatti et al. 2010).

[2] Two of them, Thomas Schelling and Elinor Ostrom, are recipients of the Nobel prize.

as a sort of spontaneous, unplanned social order. Macroeconomic theory must explain how a cluster of interacting agents succeed in coordinating themselves without any central authority, and how they suddenly fail to do so from time to time. Furthermore, as we will discuss in what follows, aggregate phenomena occur and must be explained at a higher level (the macroeconomic system) than that of individual purposive actions (microeconomics). For instance, Fisher's debt deflation or Keynes' saving paradox are instances of collective coordination failures, not of individual preferences and technologies.

In line with Leijonhufvud (2006) and Farmer and Foley (2009), we maintain that the paradigmatic shift descending from an adoption of the complexity view in economics cannot abstract from a wide application of agent-based or multi-agent techniques (Judd and Tesfatsion 2006). In general, in the agent-based approach computational models are built that try to mimic the functioning of one market in isolation, or of an entire multi-market economy, by simulating the autonomous and decentralized behavior of microeconomic units (typically firms, workers, consumers, financial intermediaries and so on). In agent-based models, equilibrium is neither assumed from the outset, nor it is imposed by resorting to a fictitious Walrasian auctioneer. Instead, the modeler lets the market behavior emerge naturally from the local actions of interacting participants. As shown in Delli Gatti et al. (2008), agent-based models can easily outperform traditional ones in explaining a wide range of disparate aggregate phenomena such as fluctuating growth, financial contagion, bankruptcy chains, firms' sizes and growth rates distributions, and much more by means of a unifying framework.

While complex systems are increasingly studied by many scientists in very different disciplines—from physics to biology, from chemistry to sociology—so far only a tiny fraction of economists have embraced this approach. Instead of exploiting the power of computer simulations to gain insights into the working of a complex economic system, most economists are fascinated just by conceptual frameworks that are based on formal mathematical proofs, so that axioms and fixed-point theorems are still the core-structure of any theoretical paper published in leading journals. Cultural inertia is for sure a major source of hesitation: decades of mainstream dominance have produced a flat horizon which recalls dr. Pangloss' view of the world. Hesitation also comes probably from risk aversion: leaving the old trail for the new one is inherently risky, especially if the former has proved so comfortable until now. We argue that two ingredients are still missing for a widespread adoption of the new approach inside the profession: (1) the appearance of a class of manageable benchmark models one can use and re-use interchangeably to address various research questions—for instance, playing the role that the maximization of discounted utility or the principal-agent frameworks have played for mainstream macroeconomics and political economy; and (2) a clear understanding of how the adaptive complexity approach to economics can be used to design effective policies.

The availability of open-code freeware web-based computerized laboratories will help to address point (1). The normative relevance of complex economics will in turn largely depend on our capacity to pose the right questions. In this paper, we propose a few items for a new research agenda consistent with the paradigmatic shifts we argue for (Sect. 5). In some cases, the relevant research questions have long been raised, just to be quickly abandoned because of a lack of suitable technical tools. In other cases, the cross-fertilization of ideas made possible by contaminations with other scientific fields has allowed the emergence of brand new questions never asked systematically before. Before presenting our personal list of future research topics, however, we pause briefly to discuss what we think is the main methodological weakness of the current mainstream (Sect. 2) and how it can be superseded (Sect. 3). To typify our position, we also briefly discuss an example of agent-based analysis applied to macroeconomic instability (Sect. 4). Some final remarks will close the paper (Sect. 6).

2 Hierarchical reductionism and the lucas critique

An intellectual tension which have pervaded natural sciences for centuries is the search for a unifying theory capable to explain all phenomena—from sub-particle dynamics to the motion of galaxies—by means of fundamental laws. Put differently, along the tree of knowledge which establishes a hierarchy from physics to chemistry, genetics, biology, psychology, ecology and social sciences, the explanatory arrow should always points downward (Weinberg 1992). As the story goes, it could well be that at a certain point some theoretical pieces are still missing, but one day "science *b*" will be eventually founded in "science *a*" which precedes it in the tree of knowledge, since "[…] *nature is one and interrelated*" (Newton 1997, p. 59). In economics this methodological position, let us called it *hierarchical reductionism*,[3] is nowadays the standard, and it is at the heart of the research programme aimed at providing micro-foundations to macroeconomics. The most compelling argument to justify the use of hierarchical reductionism in economics is the critique advanced by Robert Lucas to econometric policy evaluation (Lucas 1976).

The starting point of the *Lucas critique* is that aggregative macroeconometric models—and *a fortiori* the theoretical models from which they are derived—are not *identified*: while they can capture correlations between macroeconomic aggregates, they are not able to capture the causal structure that generates them. The absence of identification makes such models useless for conditional prediction and therefore for policy analysis: since market responses depend upon the expectations of a particular policy regime, demand and supply parameters estimated in one regime do not remain constant as the policy regime changes. In macroeconomics, thus, conditional prediction requires invariance of structure. The solution originally proposed by Lucas, and subsequently warmly embraced by the profession, consisted in building models starting from the primitive parameters of taste and technology of microeconomic units, so that aggregates are just the sum of individual behaviours. In terms of methodological hierarchical reductionism, this implies that there is no higher-level macroeconomics worth preserving as an autonomous field, since all explanations must be reduced to the more fundamental lower level, that is to microeconomics.

[3] In fact, the term reductionism admits a number of alternative definitions and it is not firmly grounded on logical-mathematical basis (Israel 2005). This makes the concept rather slippery from an epistemological viewpoint, and it requires the use of additional qualifications. In a similar search for the particular type of reductionism at the root of the representative agent in economics, Lux and Westerhoff (2009) choose the expression "conceptual reductionism". Their qualification can be used interchangeably with the one we employ here.

If one accepts this position, the next step follows quite naturally. Analytical convenience implies that the modelling strategy almost universally employed to implement the reduction of macroeconomics to microeconomics is that of a *representative agent* (RA), that is a single agent that summarizes the beliefs, expectations and choices of a given type or category of individual units, and that stands for the whole economy. This way to build macroeconomic models—based on a RA that maximizes an intertemporal welfare function subject to some resource or informational constraints, takes or learns to take rational expectations, and is always in equilibrium—is nowadays the only one accepted as scientifically-based by the vast majority of the profession, as it is considered the only one that can pre-emptively remove the Lucas critique. Unfortunately, it is becoming more and more apparent that microfounded macroeconomics as a field of scientific knowledge—exemplified by the class of *dynamic stochastic general equilibrium* (DSGE) models—has been locked into a wrong trajectory, for at least three reasons.

First, as recognized by its very proponent (Lucas and Sargent 1981), the Lucas critique is by itself theoretically empty: the issue of assessing whether a given model is structural or not is empirical, not theoretical.[4] From this viewpoint, it appears that the empirical relevance of the Lucas critique based on super-exogeneity tests is largely questionable (Ericsson and Irons 1995). Furthermore, Estrella and Fuhrer (2003) argue that in some cases the empirically testable counterparts of forward-looking DSGE models are sensibly more unstable than their backward-looking equivalents, a result somehow corroborated by a comparison performed by Rudebusch (2005) between expectational and non-expectational VAR-based models for monetary policy analysis, where the latter are found to be as empirically stable as the former. The conclusion that can be drawn from these exercises is that the empirical relevance of the Lucas critique—that is, what really counts—is at least modest.

Second, the foundation of macroeconomics on microeconomics implied by the Lucas critique requires the existence of first microeconomic principles—i.e., preferences—that are invariant to policy shifts and institutional variations. However, a sizeable literature based on experimental results—as summarized for instance by Bowles (1998)—shows that preferences are largely influenced by policy regimes and economic institutions. In other terms, preferences are endogenous. Once we recognize it, a proper implementation of the Lucas critique entails the need to discern between the effects of incentives and constraints of a policy regime on behaviours given the preferences, and the effect exerted by the policy shift on the preferences themselves. Furthermore, modern mainstream macroeconomics assumes that the reaction of individuals to changed incentives is in accordance with the dictates of the rational-choice theory. From a normative perspective, however, the assumption that people will continue to behave as rationally as before once a new policy is set in place could be seriously misleading, as recently emphasized by Howitt (2009). The main idea behind such a warning is that what appears as the product of a complicated rational deliberation procedure may in fact be the result of a process of natural selection of strategies which successfully adapt to the economic environment. As the policy regime changes, the sluggishness of the

[4] On this point, see also Da Silva (2009).

heuristics guiding the choices of people—extrapolation of patterns, underestimation of small probability events (availability and threshold heuristics), imitation and social learning, and so on—might create a long-lasting misalignment between incentives and choices.

Third, mainstream DSGE macroeconomics typically models a RA with preferences that directly mimic the forms that microeconomists have found useful in describing the behaviour of individuals. It is well known, however, that perfect aggregation—a situation in which aggregate quantities behave as scaled-up (average) versions of microeconomic quantities—requires homothetic and identical preferences, both of them prerequisites quite difficult to be justified on the basis of adherence to reality. If preferences are not homothetic and homogeneous there is not any fixed relation between the functional forms that preside over aggregates and those that describe the behaviour of microeconomic units. Moreover, in any RA model the aggregator function is implicitly assumed to be policy-invariant. Unfortunately, as shown by Geweke (1985) this is in general not true. Aggregator functions depend on the policy regime, and hence provide an incorrect evaluation of the effects of a policy change. The problem of ignoring the sensitivity of aggregators to policy changes—a standard practice in modern macroeconomics—is not more compelling than that of ignoring the dependence of expectations on the policy regime.

3 A change of perspective

In fact, a lot of work in hard sciences, statistical physics *in primis*, has shown that one is allowed to use a hierarchical reductionist approach if and only if the interaction between elementary units is linear. In terms of dynamical system theory, this means that the eigenvalues of the whole (high-level system) are linear combinations of the eigenvalues of the parts (low-level systems). This is not the case in many real-world situations with economic contents, especially when information is not uniformly distributed (De Finetti 1974).

If one wants to take the Lucas' critique seriously, therefore, it should be realized that the standard microfoundation methodology, according to which aggregate outcomes are nothing but the choices of a single agent amplified n times, must be discarded, not because of an iconoclastic passion but simply because it is incorrect. From the other side of the spectrum—i.e., post-Keynesian aggregative analysis—a related mistake is also made each time one tries to model the global dynamics of a system by imposing the existence of a relationship between aggregate quantities, according to a top-down methodology.

Interactive non-linearities entail on the contrary a systemic perspective, one that proposes to understand the working of a system by analyzing both its components and their interactions. While this approach has been obscured for centuries by classical mechanics, it is well rooted in the history of scientific thought. As noted by Blaise Pascal:

> *The parts of the universe […] all are connected with each other in such a way that I think it to be impossible to understand any one without the whole […]*

> *I can understand the whole only if I understand its constitutive elements, but I can grasp these elements only if I understand the whole*. (Blaise Pascal, Pensées n. 72)

Accordingly, the main innovation produced by the literature on non-linear interactive systems is its emphasis on the properties of the whole as an emerging result of the non-linear interactions between parts, rather than being properties of the parts themselves. Since these interaction-based properties disappear when the parts are studied in isolation, one needs a new methodological approach capable of studying different hierarchical levels, as well as each single level on its own. If the explanation of an aggregate system cannot be obtained by means of hierarchical reductionism, in fact, macroeconomics as a discipline of scientific investigation faces a basic problem: starting from the micro-equations describing the choices of the economic units, what can we say about the macro-equations? Do they have the same functional form of the micro-equations? If not, how is the macro-theory derived?

The solution we advocate is a bottom-up approach: let us start from the analysis of the behaviour of heterogeneous constitutive elements (defined in terms of simple, observation-based behavioural rules) and their local interactions, and allow for the possibility that interaction nodes and individual rules change over time (adaptation). At the next meso-level, statistical regularities emerge that cannot be inferred from the primitives of individuals (self-emerging regularities). This emergent behaviour feeds back into the individual level (downward causation), but also produces aggregate regularities at the next hierarchical level. High-levels (macroeconomic) systems possess new and different properties than low-level (microeconomic) systems, like water has different properties from the atoms of hydrogen and oxygen that constitute it, as well as from ice and steam, and from the multicellular living organisms containing it. This approach allows each and every proposition to be falsified at micro, meso and macro levels and, de facto, it opposes to the mainstream axiomatic theory of economics, where microeconomic optimization is considered the rule for any rigorous scientific practice.

A paradigmatic example is the well-honoured model of racial segregation in cities proposed by Shelling (1969). He showed that individuals endowed with a relatively small preference for neighbours of one's own type organize themselves into high level of residential segregation through repeated housing decisions. Racial segregation emerges as an unintended aggregate consequence of individual purposive behaviours aimed at finding neighbours with slightly similar characteristics. Segregation is a property of a city as a whole (high-level system), not of the individuals and their primitives (low-level system). Another example which fits well with recent events is discussed by Thurner et al. (2009), who show that a rational attempt to control risk at a local level by individual lenders (for instance, by a bank which adjusts the leverage exposure of collateralized borrowers when the price of the asset used as collateral is dropping) can collectively induce a large instability in prices and involuntarily create more risk, because margin calls cause massive selling at just the wrong time. Fat tails and clustered volatility in price fluctuations emerge at the aggregate level even if all traders are value investors who individually wish to buy when prices fall, and vice-versa. Once again, the properties of the system as a whole can not be deduced from the primitive characteristics of the individuals, an argument we argue has general validity.

Similarly, levels and growth rates of aggregate output and employment, inflation, patterns of international trade, the impact of taxes on savings, the response of investments to interest rates and all other typical macroeconomic occurrences and laws (as, for instance, the ones associated with Phillips, Okun and Beveridge) are social phenomena that must be explained at a different level than microeconomic units.

The approach we endorse has a natural counterpart in the "micro-meso-macro" analytical reasoning recently developed in evolutionary and neo-Schumpeterian economics, as illustrated for instance in Dopfer and Potts (2004), Dopfer et al. (2004) and Foster and Potts (2007). According to this approach, a complex economic system is made of an evolving bundle of generic—or *meso*—rules (relating to behavioural, institutional, technological and organizational domains), each one of them adopted by a population of *micro* carriers. Behavioural heterogeneity stems from the myriad of peculiar ways in which individuals apply meso rules. The meso structures are thus made of lower-level components (micro units), and are constituent parts of a higher-level self-organized *macro* structure.

An important mechanism responsible for the self-organizing macroscopic behaviour of a complex system is *auto-catalyticity*, a property a simple unit possesses whenever the time variations of the quantities characterizing it are proportional (via stochastic factors) to their current values. Take the consequences of any adaptive behavioural rule you can think of for your model economy, and you will realize that you are thinking about auto-catalytic agents. The performance of the whole is then dominated by the micro units which happen to experience the highest auto-catalytic stochastic growth rate, rather than by the behaviour of a typical or *representative* element. In the presence of auto-catalytic processes, therefore, a small amount of individual heterogeneity in initial conditions invalidates any dynamic description of the system in terms of its average:

> *Much of the real world is controlled as much by the "tails" of the distributions as by means or averages: by the exceptional, not the mean; by the catastrophe, not the steady drip; by the very rich, not the "middle class". We need to free ourselves from "average" thinking*. (Anderson 1997, p. 566).

Regulators working in primary organizations have at last recognized that a massive failure in realizing this plain fact is a key determinant of the recent financial turmoil; that a macroeconomic system in general—and the financial system in particular—is in its essence a network, with nodes defined by agents and links defined by contractual obligations among them; that systemic risk in such a network is endogenous, as it depends on the interactive collective behaviour of financial institutions and market operators (Cecchetti et al. 2009; Haldane 2009; Papademos 2009).

This requires a new methodological approach and new tools. Complexity is the new paradigm for building macroeconomic models. Agent-based computational techniques and network analysis are a natural device to analyze the phenomena emerging from the complex gathering of a multitude of interacting purposive agents, whose actions are aimed at satisfying individual needs and attaining individual objectives.

4 Granularity and macroeconomic instability

In order to appreciate its potentialities, the narrative exposed so far can be usefully exemplified by means of a simple model aimed at exploring the causal interactions between consumers' choices, industrial dynamics and large aggregate fluctuations. The research question we address is the relationship between the structure of searching costs in the market for consumption goods and the appearance of sudden crashes in aggregate activity. The framework we employ is identical to that of Gaffeo et al. (2008)—to which we refer for technical details—except that here we compare the original baseline version (where households adopt a sort of preferential attachment (PA) mechanism in choosing where to buy) to one in which the PA mechanism is switched off (noPA) (so that households explore randomly the search space).

For the reader's convenience, we briefly overview the basics of the model. A large number of autonomous firms, households (consumers/workers) and banks operate in a fully decentralized manner on the markets for labour, credit and a homogeneous consumption good. Production takes one time period, regardless of the scale of production. Each firm decides the amount of output to produce and the price to charge by taking into account its expected demand. Expectations on the future demand are updated adaptively.

Firms post their vacancies at a certain offered wage, and unemployed workers contact a given number of randomly chosen firms to get a job, starting from the one that offers the highest wage. Firms then have to pay the wage bill in order to start production. Labour contracts expire after a finite number of periods. A worker whose contract has just expired applies also to her last employer, in addition to other arbitrarily chosen firms.

If its internal financial resources (net worth) are in short supply with respect to the wage bill—i.e. if there is a financing gap—a firm can borrow from the banking sector. Borrowing firms contact a given number of randomly chosen banks to get a loan. Each bank sorts the borrowers' applications for loans in descending order according to the financial soundness of firms, and satisfy them until all credit supply has been exhausted. The contractual interest rate is calculated by applying a mark-up (which is itself a function of financial viability) on an exogenously determined baseline interest rate. After the credit market is closed, if financial resources—both internal and external—are not enough to pay for the wage bill of the population of workers, some workers remain unemployed or are fired.

After production has been completed, the market for consumption goods opens. Firms post their offer price, and consumers contact a given number of firms to purchase goods, starting to buy from the one which posts the lowest price. If a firm ends up with excess supply, it gets rid of the unsold goods at zero costs. The good in fact is perishable and cannot be stored to be sold in the future.

Firms collect revenues and calculate gross profits. If gross profits are high enough, they "validate" debt commitments, i.e. firms pay back both the principal and the interest to the bank. If net profits are positive, firms pay some dividends to the owners and invest a fraction of net profits in R&D, in order to increase their productivity. Earnings after interest payments and dividends are retained and are employed to increase net worth. Firms and banks are financially viable—and therefore survive—if their net worth is positive. If, on the contrary, net worth is negative, they go bankrupt, shut down and exit the market. Lenders, therefore, have to register a bad debt (i.e., a non-performing loan). In this case, a string of new firms/banks equal in number to the bankrupt ones enters the market, and their size at entry is smaller than the average size of survivors.

As we said above, here our main interest consists in comparing the aggregate performance generated by two slightly different methods of search households can adopt when buying in the market for the consumption good. In the baseline version of the model, each consumer is allowed to visit a given number Z of firms to assess posted prices. In order to minimize the probability to be rationed, she visits for sure the largest (in terms of production) firm visited during the previous round, while the remaining Z-1 firms are chosen fully at random. In other terms, consumers adopt a sort of PA scheme. Those firms which post lower prices tend to attract a larger fraction of consumers and crowd competitors out, gaining the ability to gain a predominant position also in the future, according to a typical rich-getting-richer mechanism. The alternative treatment of the computational experiment is equal in every other respect to the baseline version, but for the fact that at each time period each household samples randomly all the Z firms to be visited.

Panels (*a*) and (*b*) of Fig. 1 report the time series for the simulated real GDP obtained in the PA and the noPA cases, respectively. Since in the two treatments every other feature of the model is identical, the searching strategy adopted by consumers is for sure the ultimate origin of the different behaviours we observe. While the PA scheme is characterized by punctuated large crashes in aggregate activity—of the type observed for instance during the great depressions of the thirties and the late noughties—the profile of the GDP time series for the noPA case is significantly smoother. To gain some intuition on the underlying mechanisms at work, it seems useful to re-interpret the model in terms of a bipartite producer-consumer network.[5]

Accordingly, the two populations of M producers and N consumers (with $M < N$) are the two kinds of nodes of a bipartite graph, with trading relationships representing edges linking nodes in the first set (households) to nodes in the second one (firms). As consumers switch among firms, at each time period some edges are destroyed and some others are rewired. The set of bilateral relationships on the market for the consumption good is therefore captured by an evolving $M \times N$ adjacency matrix $S = (s_{mn})_{M \times N}$, whose components are $s_{mn} = 1$ if there is at least an edge between firm m and household n, and 0 otherwise. As we let one unit of consumption to define an edge, the total amount of sales registered by the mth firm determines its degree k, that is the total number of edges possessed by that node, while the firms' size distribution measured in terms of sales corresponds to the degree distribution of the set of nodes composed by firms. Finally, since the system is growing due to technological progress, the total number of edges linking nodes of the two groups increase with time.

A rapidly expanding literature has shown that many social and physical networks are characterized by a degree distribution which is noticeably different from the Poisson model predicted by a pure random graph. In particular, several real-world networks

[5] See, for instance, Dahui et al. (2006).

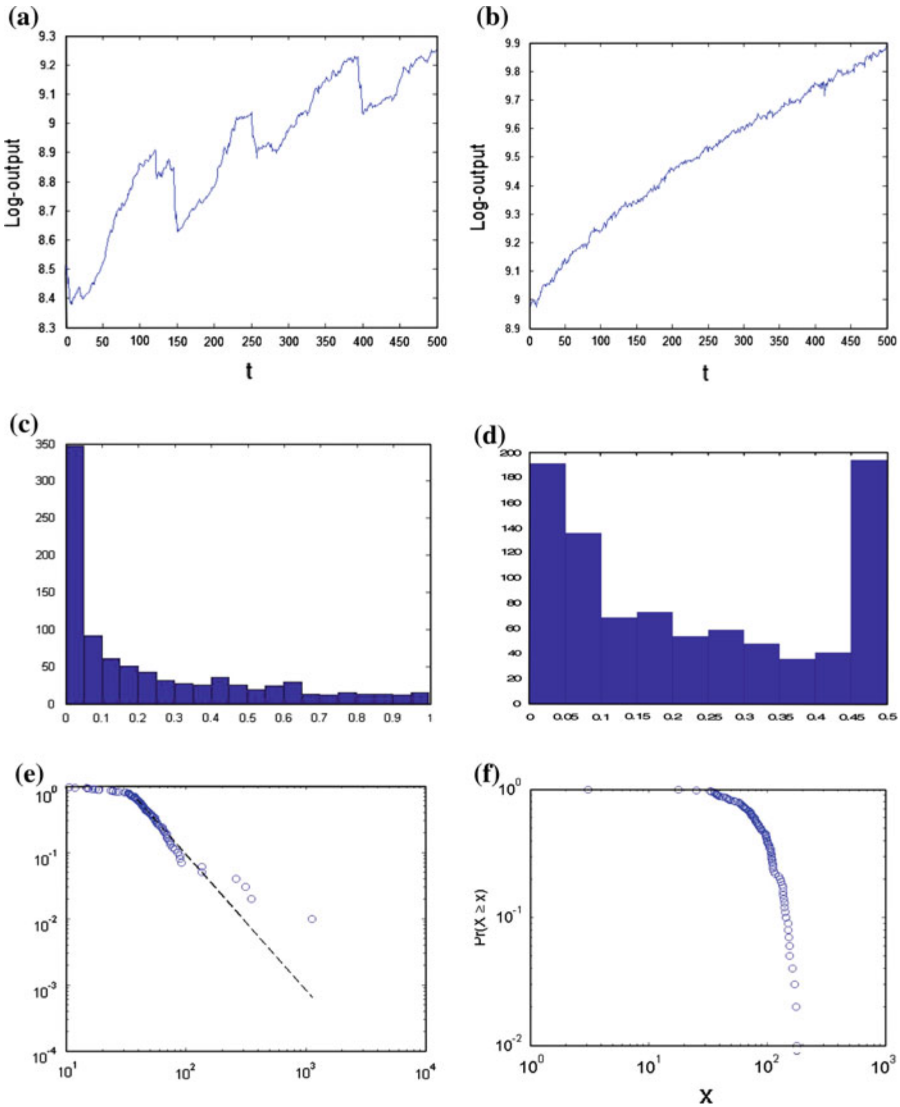

Fig. 1 **a** GDP for the baseline model; **b** GDP for the model without preferential attachment (noPA); **c** distribution of p-values obtained from 1000 K-S tests performed on cross-sectional sales, comparing the baseline simulation and a power law distribution; **d** distribution of p-values obtained from 1000 K-S tests performed on cross-sectional sales, comparing the noPA simulation and a Gaussian distribution (p-values censored at 0.5); **e** typical sales distribution for the baseline case (dashed line: power law fitting of the right tail); **f** typical sales distribution for the noPA case

are found to be scale-free, whose key attribute is a degree distribution which is heavily right-skewed and possesses a power-law tail. Moving from these premises, we performed a comparison between two typical simulation runs, one for each treatment. In both cases the number of simulated time periods was set to 1,000, M to 100 and N

to 1,000. We focused in particular on some statistical hypothesis testing and distributional fitting exercises aimed at assessing commonalities and differences between the firms' degree distributions emerging, in every single time step, as the treatment is varied.

The initial result we found is that the PA and noPA mechanisms return degree distributions which belong to different distribution functions (DFs). A series of 2-sample Kolgomorov-Smirnov (KS) tests reject (at the 5% significance level) the null hypothesis that the pairs of independent random samples belong to a common underlying DF in 969 cases out of 1,000. Furthermore, all the 31 time steps for which the null was not rejected were confined into the first 100 periods, which are usually considered as transients. Thus, the searching strategy employed by households in the consumption goods market plays in fact an effective role in qualitatively affecting the structure of supply.

As we moved to the following question, that is the proposal of a statistical model for the degree distributions associated with the two searching mechanisms, we decided to exploit the main findings of the empirical literature on social networks,[6] and limit ourselves to four relevant candidates, namely the Poisson, the exponential, the Guassian and the power-law distributions. First, making use of a K-S testing strategy, we were allowed to reject the Poisson model at a standard significance level in both cases for almost each period (around 99%). This result should not come as a surprise, not only for the PA treatment—it is well known that the PA mechanism can in principle generate scale-free networks—but also for the noPA one. In this latter case, in fact, while the choice of potential transaction's partners made by consumers is fully random, the real appearance of an edge—and thus the degree k of each firm—depends on the relative convenience of the posted prices, which are determined autonomously according to a set of adaptive rules. From a theoretical viewpoint, nothing ensures that this mechanism is consistent with the predictions of an ordinary random graph.

While for both treatments we were allowed to reject also the hypothesis that the simulated data were drawn from an exponential DF, an interesting dichotomy emerged from the last two candidate models. As shown in Panels (*c*) and (*d*) of Fig. 1, respectively, for the PA scheme we were able to accept (at the 5% significance level) a power-law model in the 65.4% of the simulation periods, while for the noPA treatment the rate of acceptance of the Guassian model we found was 80.7%. Panels (*e*) and (*f*) of Fig. 1 show the degree distribution (in a log-log plot) for a typical period in the PA and noPA cases, respectively. It turns out that the degree distribution in the PA case generally possesses a very fat tail, with a small number of firms which are even larger than predicted by a power-law fit (dashed line).

In Gabaix (2009), the very existence of large firms is at the root of the so-called "granular" theory of aggregate fluctuations. Briefly stated, this theory affirms that a great part of the observed macroeconomic volatility can be due to idiosyncratic shocks to a small number of very big players. The only sufficient condition for this to happen is that the firms' size distribution is power-law distributed with a characteristic exponent α lower than 2 (in absolute value). When this holds true, as the total number of firms M

[6] See for instance Ohkubo et al. (2005), and the references therein.

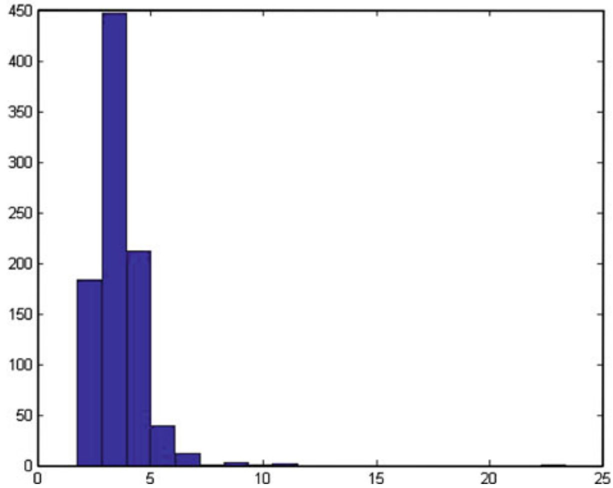

Fig. 2 Histogram reporting the values of the characteristic exponent α calculated on simulated firms' degree distributions for the PA case

increases the volatility of the GDP decays much more slowly than $\sqrt{M}$. Therefore, it seems interesting to test whether the period-by-period characteristic exponents of the power-law degree distributions calculated for the PA treatment obey this requirement.

Our calculations are summarized in the histogram reported in Fig. 2. It turns out that the bulk of the distribution for the estimated values of characteristic exponent α is comprised between 2 and 5, a range which is fully consistent with the empirical estimates obtained for other large-scale social networks (Albert and Barabási 2002). Admittedly, these values are significantly higher than those usually observed for the size distribution of firms, which are found at around 1 also when the latter is measured by total sales (Axtell 2001). Such a disagreement between the empirical and the simulated values will be taken as a guiding principle in directing future research.

What we argue is the most interesting point of our analysis, however, is that the prerequisite set by Gabaix (2009) for idiosyncratic shocks having significant macroeconomic consequences—a power-law firms' size distribution with characteristic exponent $\alpha < 2$—could be relaxed as soon as one admits the possibility that negative idiosyncratic shocks can force large firms to go bankrupt.

In this case, in addition to an aggregate volatility in line with that measured on real-world data, the system incurs sporadic crashes caused by a sort of contagion mechanism. Even though the number of financially fragile firms is moderately stable over simulations, average fragility increases as the economy expands simply because the financial position of a small number of very large firms eventually starts to become more and more unsafe. Even a small liquidity breakdown can now force one of those large firms to fail, and the idiosyncratic disturbance will then trickle down across the whole distribution of agents because of negative aggregate demand spillovers on the one hand, and credit restrictions as banks register net losses on bad loans on the other one. If composition effects are large enough, the response of the system to an identical stream of microeconomic shocks changes over time, as it depends on the actual distribution of firms in terms of the balance between their internal and external finance.

5 A research agenda for the new paradigm

In a complex economy, since the consequences of individual choices depend on what all the others are autonomously doing, people take actions into an environment characterized by radical or endogenous uncertainty. The aggregate outcomes emerging from their continuous and asynchronous localized interactions are almost incomprehensible at an individual level. In spite of this, modern market economies display a reasonably coordinated state of affairs most of the time—say, within few percentage points from full-employment, and without persistent pathological shortages or surpluses of goods—unexpectedly punctuated by deep crisis, just like in the model discussed above. Borrowing a concept developed by Axel Leijonhufvud (1981, 2009) , it is as if the system normally operates inside a *corridor* of stability—where even large shocks are absorbed without excessive casualties—to be sometimes pushed outside it along a ruinous path by apparently insignificant flips.[7] In other terms, the macroeconomy is characterized both by a substantial resilience and a deep fragility.

This opens the way to some fundamental theoretical and policy questions that future research must seriously address, regarding how built-in feedback mechanisms operates in a complex economy, and how government interventions should interact with them to prevent future departures from the corridor. In the remaining of this section we discuss three of them.

5.1 Coordination in asynchronous markets

In a modern system of manufacturing, production firms are interrelated by a nexus of contractual and delivering arrangements, since each firm uses specialized goods and services that are produced by other firms in the system. Even if at an individual level production functions are convex, in the aggregate the economy can display *parallel scale economies* (Leijonhufvud 1986) as soon as the system is sufficiently coordinated. Delays or failures in the delivering of just one input or obligation, however, can easily cascade through the whole interrelated system, potentially triggering coordination failures on a grand scale.

In such a world, agents face endogenous uncertainty, that is uncertainty generated by their own actions. As shown by Chichilnisky (1999), in the presence of endogenous uncertainty markets are incomplete by definition, and no matter how many state-contingent securities are added into an Arrow-Debreu general equilibrium framework, Pareto efficient allocations cannot be reached. Markets cannot simultaneously hedge one another, given that even a Walrasian auctioneer cannot simultaneously

[7] In the U.S., the burst of the dot.com bubble on Wall Street in 2000 caused a loss in real GDP of around 1%. Contrast it with the currently estimated 6% loss associated to defaults in sub-prime mortgages, a tiny fraction of the market for loans.

determine the market-clearing contingent prices for a commodity and for the options aimed at hedging positions on that commodity. To understand why, suppose the auctioneer announces simultaneously market-clearing prices for all states and time periods. Futures contracts are in that case useless in allocating risk, as there is no price uncertainty left to hedge. In order to solve the problem, markets must be instead organized according to a sequenced order, so that the uncertainty on the states belonging to different logical classes—or *layers*—can be solved sequentially. Briefly, markets must clear according to a time hierarchy, with low-frequency markets receiving price and quantity signals from high-frequency ones.

In fact, this is the way markets are normally organized:

> *Consider the simple case of bread. The wheat market clears annually. The inventory is drawn monthly. It can be hedged with three month futures contracts. Bakers rent their shops on five years contracts. Rental contracts are adjusted yearly, contingent on the price level. Bakers own their equipment in perpetuity, but borrow on three year notes to buy it. The commercial note markets clear hourly. Equipment orders take six months to produce. The used equipment market is thin; its transactions are episodic and few. Bakery employees are hired weekly. Bread is baked and consumed daily.* (Arthur De Vany 1996, p. 325)

Each market possesses its own frequency, which is dictated by the technological characteristics of the good or service exchanged (production period, durability, and so on), the bids and asks arrival rates, liquidity and the depth of the demand and supply processes. The aggregate activity thus emerges from the combination of markets operating at different frequencies and from their interrelations. When the rhythms in consumption and production in hierarchical organized markets gain systemic coherence, the economy can grow along a coordinated balanced path. The banking sector plays a crucial role in the process, as it provides liquidity means and maturity transformation services which allow firms and households to hold in their balance sheets credit assets and liabilities expiring at different settlement dates in different markets.

Of course, systemic coordination failures may occur if, for whatever reason, frequencies stop to support one another, and if displacements in one market propagate through the economy. The chronicle of the 2007–2009 crisis is a case in point. An increase of subprime mortgage defaults (a market where contracts last ten to thirty years, and payments are made monthly) which started in February 2007 caused a prolonged decline in asset-backed securities (ABS) and credit default swaps (CDS) indices (whose market clears hourly); the decrease in ABS and CDS indices caused in turn a series of write-downs in commercial and investment banks' balance sheets (an information market which opens every three months); uncertainties on the consistency of potential losses in intermediaries' books triggered by the default of a primary investment bank dried-up liquidity on the inter-bank market (which clears daily); the generalized deleveraging process provoked a substantial restriction of lending to the private sector, which generated a displacement in the trade-credit market (on which payments occurs on 3-month notes). In general, the propagation process depends on which market is initially affected: shocks to high-frequency markets will be immediately transmitted but slowly propagated through the hierarchically organized multi-market structure, while shocks to low-frequency markets can remain for long cornered into a small portion of the aggregate economy before the transmission mechanism gains momentum, and their effects become systemic.

This modelling approach entails both positive and normative interesting research questions. Some of them can be borrowed from a small but inspiring literature devoted by economic geographers to the study of the spatial and temporal synchronization of periodic markets in rural areas (Hill and Smith 1972; Symanski and Webber 1974), that can be suitably adapted to proper macroeconomic analysis.

From a positive viewpoint, the key point is that of generating and assessing the properties of macro systems characterized by asynchronous interrelated markets. Several distinct topics worth exploring can be suggested. How does the right frequency of each market depends on the distribution and evolution of preferences and technologies of the agents operating in it, as well as on the market institutions organizing their transactions? How is information created and transmitted among markets operating at different frequencies? How can coordination be achieved by the emergence of an array of contractual arrangements forcing coherence among settlement dates in different markets? How are aggregate and idiosyncratic shocks propagated through the system? Is there a trade-off between resilience and fragility of the whole system in correspondence with alternative hierarchical market organizations?

Moving from this ground, the availability of a computational agent-based laboratory would allow to address additional normative questions. What sort of institutional arrangements—for instance, in terms of market microstructures, or imposed periodization—should be devised to coordinate decentralized actions in this interrelated system? In order to let the system maintain the coherence of market frequencies when serious displacements threaten to trigger a systemic crisis, should the supply of liquidity and market depth by public intervention be generalized or limited to selected markets? Can new contractual arrangements or new markets be designed and implemented, so that aggregate coordination is guaranteed?

5.2 Networks

Networks are the main subject of a rapidly growing literature which applies the conceptual and analytical tools already developed in sociology, computer science and physics to economics and/or provides new notions and methods to be applied specifically to economic phenomena.[8] Among them, the complex pattern of credit relationships is a natural research issue to be dealt with by means of network analysis, as it is straightforward to think of agents as nodes and of debt contracts as links in a credit network.

There are indeed influential examples of network analysis applied to credit networks. The most famous one is probably the model of financial contagion developed by Allen and Gale (2001) to explore the spreading of financial distress in the network of interbank relations. In this case, however, the networks considered are too simple

[8] Recent books by Jackson (2008), Vega-Redondo (2007) and Goyal (2007) describe the frontier of research on economic networks. Caldarelli (2007) analyzes networks from the physicist's point of view. His book presents plenty of applications to different fields, economics being only one of them.

and unrealistic as they consist of few nodes organized in canonical forms.[9] A related line of research (Boissay 2006; Battiston et al. 2007) focuses on the network of trade-credit relationships within the corporate sector, i.e. among suppliers of intermediate goods and producers of final goods along a "supply chain". While these two strands of literature analyze specific credit relationships (among banks on the interbank market, and among firms along the supply chain), in our view there is a long way to go before reaching a comprehensive and satisfactory network model of credit relationships, since at least three features of a credit network must be reproduced in a model.

First and foremost, credit and credit networks are pervasive, so that a general and "encompassing" framework is needed. Agents are linked by *inside* credit—i.e. credit relationships connecting agents belonging to different layers of the same class of agents—and *outside* credit—i.e. credit relationships connecting agents belonging to different classes. Typical instances of inside credit are the interbank lending/borrowing relationships (within the banking industry) and the links between suppliers of intermediate goods and producers of final goods (within the corporate sector). As said above, in modern manufacturing firms are connected by a nexus of contractual arrangements, since each firm uses goods and services that are produced by other firms. The supplier (upstream firm), however, is not only the starting point of the supply chain but also the lender in a trade-credit relationship. The producer (downstream firm), correspondingly, is not only the ending point of the supply chain but also the borrower in a trade credit relationship. The most straightforward example of outside credit, on the other hand, is the lending/borrowing relationship between a bank and a firm (or a household) on the market for bank loans (mortages).[10]

Second, networks are continuously changing. Their topological structure, in fact, is evolving over time due to the disruption of previous relationships and the formation of new ones. This is the consequence, in turn, of the choice of the partner in a relationship: old partners are abandoned and new ones are embraced. Jackson (2005) distinguishes between a random graph approach to network evolution, borrowed from physics, and the game theoretic approach specifically designed to deal with economic networks. The former is, in a sense, "mechanical": network formation is purely stochastic or the product of an ad hoc algorithm. The latter focuses on "equilibrium" networks, where links are formed as a consequence of cost-benefit analysis on the part of self-interested agents.

As a useful approximation to real world network evolution, we argue for an approach which is in a sense half-way between the two: the choice of the preferred partner allocates links to nodes as a consequence of the search for the "best bargain" within the limits of an environment characterized by fundamental uncertainty. In every period, an agent in search of a partner in a transaction—a customer in search of a supplier, a firm in search of a bank—chooses the partner who offers the best terms, for instance who posts the minimum price/interest rate, in a randomly selected subset of agents. Transaction costs in fact limit the search for a new partner to a neighbourhood of

[9] A remarkable body of literature has developed from these premises (Freixas et al. 2000; Furfine 2003; Boss et al. 2004; Iori et al. 2006; Nier et al. 2007).

[10] Battiston et al. (2007) and Delli Gatti et al. (2009) are examples of the type of analysis of credit network we have in mind.

available partners. If the minimum price is lower than the price the agent paid to the old partner, she will switch to the new partner, otherwise she will stick to the old one. The number of links connecting the nodes, therefore, changes over time so that the topology of the network is also in a process of continuous evolution.

The execution of standard economic tasks—production, consumption, lending and borrowing—by each agent on each market occurs at a different time scale with respect to the choice of the partner. In other words, routine economic activity and the choice of the partner are organized according to a sequenced order, or time hierarchy. The choice of the partner is a low-frequency phenomenon while price and quantity determination is a high-frequency one. Of course the two are intertwined. Economic incentives are crucial—albeit not unique—in the choice of the partner and therefore in network formation.

Third, credit networks are fragile and vulnerable. In a financing hierarchy perspective, the scale of activity of each agent is constrained by a measure of her financial robustness, for instance her net worth. Changes in net worth of an agent, say borrower A, brings about changes in the same direction of agents, say lenders B and C, linked to A in a credit relationship. An unexpected shock to A's net worth, if large enough, may impair the ability of the borrower to fulfil debt commitments and may lead to bankruptcy.

The bankruptcy of a borrower would be irrelevant if, so to speak, the agent were an "island" or the network were fragmented in many relatively small and independent sub-networks. In a dense network, on the contrary, bankruptcy will not be an isolated and therefore insignificant phenomenon. The bankruptcy of a producer of final goods may bring about the default of the suppliers whom the producer interacts with along the supply chain. Moreover non-performing loans affect the net worth of banks, which can also go bankrupt. If they manage to survive, they will react to the deterioration of borrowers' financial conditions increasing the interest rate. The interest rate hike leads to more bankruptcies and eventually to a bankruptcy chain.

Establishing several credit relationships allows an agent to diversify the risk of a loss if the agent is hit by a negative shock, but it also entails the propagation of financial distress to connected agents, i.e. financial contagion in the wording of Allen and Gale. In this context, in principle one cannot rule out the risk of a systemic crisis, i.e. the diffusion and amplification of financial distress until the collapse of the financial system. In other words, as connectivity increases, a trade off emerges between individual risk—which decreases because of risk sharing—and systemic risk—which increases due to the amplification of financial distress. Therefore the relationship between connectivity and systemic risk is not monotonically decreasing as in Allen and Gale, but—at least under certain circumstances—it may be non monotonic (Battiston et al. 2010).

Risk sharing, distress propagation and bankruptcy cascade can be conceived of in the most general terms as externalities. In case of a negative shock to an agent, these effects impose additional costs to the other nodes in the neighbourhood. Risk sharing however by itself is a benign externality. In the absence of the other effects, it will gently lead the probability of individual bankruptcy and of a systemic crisis to zero as the connectivity increases. On the contrary distress propagation and the bankruptcy cascade effect are malign externalities. They may amplify the effect of the initial shock and lead to a full fledged systemic crisis if they more than offset risk sharing.

The policy implications of this approach are obvious and far reaching. First of all, once the structure of the network has been analyzed and measured empirically (in terms of distance between nodes, diameter and average path length, presence of clusters and subgroups and so on), one could devise early warnings of a systemic crisis. Second, policy measures could be adopted to steer the structure of the network in a safer direction in case financial fragility and vulnerability become "excessive". For example, the heated discussion on the fact that some financial institutions are —or have become—"too big" and/or "too interconnected" to fail can be interpreted in network terms. A policy proposal to break up financial conglomerates may be grounded on the notion that clusters or "hubs" in the credit network carry a higher risk of contagion. The rationale behind a proposal to reintroduce barriers among different segments of the financing industry (for instance, by means of an updated version of the Glass-Steagall act) may be the need to reduce the connectivity of the network in order to attenuate the financial amplification mechanism described above.

5.3 Monetary policy

As a natural extension of the arguments raised so far, the third item of the research agenda for complex macroeconomics we propose focuses on monetary policy. According to the general consensus, a central bank must perform three different tasks: (1) it must provide a "nominal anchor" to the monetary unit used to sign contracts, to quote prices and keep accounts, with the aim to control inflation and inflation expectations; (2) it must ensure that such an obligation is managed at the minimum cost in terms of output fluctuations; (3) it must promote a secure and efficient payment system to prevent financial collapses and sudden shortages of means of payments. Standard macroeconomic monetary models insert tasks (1)–(2) into a rational-expectation general-equilibrium framework to obtain optimally designed policies (Clarida et al. 1999), while task (3) is simply ignored on the presumption of efficient markets and perfect arbitrage. The recent global financial crisis has dramatically proved how wrong and misleading these assumptions could be.

In the complex adaptive macroeconomic system we are depicting here, endogenous uncertainty affects both the public *and* policy-makers, and the very notions of rational expectations and rational learning are meaningless. In the absence of a Walrasian auctioneer, individual agents can fail to coordinate their choices, and macro-financial instability materializes as a marker of such failures. Traditional monetary policy (tasks i–ii) and the promotion of stability in the financial system (task iii) —including the general provision of liquidity to financial institutions and other unconventional policies in the wake of a financial crisis—are thus interlinked and must be devised within a unitary framework. Several interesting research questions arise from this approach.

A promising approach is the one rooted into the long tradition that goes back to the idea of a *natural rate of interest* elaborated by Knut Wicksell (1898) and the notion of *forced saving* developed by the Austrian school in the 1930s. Simply stated, the point is as follows. Suppose the economy possesses a real interest rate consistent with full employment and stable prices (and consistent private expectations thereof), and call it *natural*. In a world of radical uncertainty, a central bank which aims to peg the interest rate cannot know for sure where the natural rate is at any particular point in time,[11] and a discrepancy between the natural and the market rates can easily occur and be maintained for quite long. When the market rate is lower than its natural counterpart, entrepreneurs are encouraged to borrow from banks to undertake investments that will add to the supply of consumption goods in the future. However, that same discrepancy implies that consumers are not willing to sacrifice current consumption for future consumption (that is to save) at the rate expected by entrepreneurs to make their investments profitable. As a result, an intertemporal coordination failure between saving and investment emerges due to a wrong market signal: the economy builds up a stock of capital in excess to what is needed. Notice also that such a process can continue without overall price inflation if the economy is growing, and the rate of growth of available nominal money does not exceed that of the demand for real balances. The recent history of the U.S. and other industrialized economies—marked by exceptionally low interest rates, massive capital inflows from China and oil-producing countries, decreasing households' saving rates and a spectacular accumulation of office buildings, houses and excess productive capacity—can be interpreted along these lines. Mostly valuable for the issue we are dealing with, the grouping of large cumulating financial imbalances and of missing (CPI) inflation has shown that the practice of *inflation targeting* followed by many central banks around the world not only has failed to engineer financial stability as a by-product,[12] but in fact it has actively contributed to create asset-price bubbles (Leijonhufvud 2007).

Once again, the crucial point is that saving-investment imbalances are emerging properties of a macroeconomic system composed of heterogeneous interacting units, and cannot be deduced from the primitive characteristics of a representative agent. As we abandon rational expectations, one must ask how monetary policy must be conducted to prevent an economy from sliding along a cumulative destabilizing path characterized by increasing financial instability. The lessons for monetary policy marvellously summarized by Howitt (2006) are a natural starting point for new research along a new paradigm. In particular, agent-based explorations of how adaptive heterogeneous mechanisms of expectation formation interact with different assumptions on how prices and quantities adjust in real time can shed additional light on the viability of alternative interest rate rules in anchoring inflation expectations, or solving intertemporal coordination failures.[13]

A second strand of issues arises naturally as soon as one starts to think how monetary policies aimed at addressing tasks i) to iii) should be designed and implemented

[11] Not to talk of the possibility, suggested by Keynes in his *General Theory*, that the economy possesses multiple natural rates, many of which compatible with involuntary unemployment.

[12] In a previous life, Governor Bernanke made use of a New-Keynesian DSGE framework to ask himself whether central bankers should respond to movements in asset prices, and the answer he gave is negative: "*Changes in asset prices should affect monetary policy only to the extent that they affect the central bank's forecast of inflation. To a first approximation, once the predictive content of asset prices for inflation has been accounted for, there should be no additional response of monetary policy to asset-price fluctuations*" (Bernanke and Gertler 2001, p. 253). Notice, incidentally, that the same conclusion is still sustained by recent research (conducted, needless to say, by means of a structural DSGE model) at the IMF (International Monetary Fund 2009).

[13] On these points, see also Anufriev et al. (2009).

in the presence of endogenous waves of optimism and pessimism, that is what Keynes called *animal spirits*. For a couple of examples to be interpreted as a starting point for additional explorations, see De Grauwe (2009), who discusses a simple New-Keynesian model in which reinforcement learning mechanisms can generate correlations in beliefs, with interesting implications on the role of monetary policy in stabilizing output fluctuations; and Canzian et al. (2009), who insert a social contagion mechanism inside a dynamic IS-LM model to provide an agent-based description of the behavioural traits contained in Keynes' original description of the business cycle (Chapter 22 of the *General Theory*).

Finally, it could be interesting to extend the analysis put forth in Delli Gatti et al. (2005), where some issues on the *rules-vs-discretion* debate are discussed in a fully decentralized macroeconomic agent-based model, where the learning processes of the central bank is mimicked by means of a genetic algorithm. In particular, such a framework could be usefully employed in evaluating alternative proposals on new macroprudential arrangements, or innovative feedback adaptive rules as the "Taylor rule for capital adequacy" recently proposed by Ingves (2009).

6 Conclusions

Assuming that a property is true for the whole when it is true for its constitutive parts is logically wrong. For example, assuming that the observed aggregate labor supply or the observed aggregate demand behave as they do (say, positively sloping and negatively sloping, respectively) because they inherit by necessity their properties from the balance of income and substitution effects characterizing the preferences of a representative agent is logically wrong. Epistemologists call it a *fallacy of composition*: it is certainly true that aggregate entities' *laws* depend somehow on the individual behavior of constituents, but the properties of a high-level system cannot be deduced solely from primitive parameters of technology and tastes. Each level of analysis has its own fundamental laws, so that different aggregation levels possess new and different properties with respect to those of individual elements. According to this approach, a complex system is organized hierarchically and it must be explained from the bottom-up, so that collective behaviors can materialize as we move from a low hierarchical level to a higher one. This is largely recognized to be true for all the (hard and soft) sciences, except for mainstream macroeconomics, whose practice remains entrapped into the reductionist microfoundation program commanded by the Lucas critique.

It is time for this state of affairs to radically change, and for a new research paradigm to enter the scene. Admittedly, complexity and agent-based modeling—the approach we advocate in this paper—are not brand new fields of scientific investigation by themselves. A lot has been written on these subjects, and several important results are already available in the literature. However, a broad acknowledgment by the profession of their usefulness for the economic discourse has yet to come. The failures of the received DSGE doctrine in interpreting the "how and why" of the 2007–2009 financial and economic turmoil is an unrepeatable opportunity to change this situation. Still, the probability of success will also largely depend on our capacity to pose the right research questions. That is why here we have advanced three of them.

We conclude with two quotations. The first one summarizes the key point raised in this paper:

> *In conclusion: there are no absolute fundamental laws which, starting from the smallest scale permit the derivation of all the other properties at all the other scales. There are different levels and fundamental laws for each of them which permit the step to the next level*. (Pietronero 2008, p. 27)

The second one aims at being an encouragement to unrepentant traditionalists to join us in the (small) paradigmatic revolution we argued for in this paper:

> *Scientific development depends in part on a process of non-incremental or revolutionary change. Some revolutions are large, like those associated with the names of Copernicus, Newton, or Darwin, but most are much smaller, like the discovery of oxygen or the planet Uranus. The usual prelude to changes of this sort is, I believed, the awareness of anomaly, of an occurrence or set of occurrences that does not fit existing ways of ordering phenomena. The changes that result therefore require 'putting on a different kind of thinking-cap', one that renders the anomalous lawlike but that, in the process, also transforms the order exhibited by some other phenomena, previously unproblematic.* (Kuhn 1977, p. xvii)

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