Endogeneous Macroeconomic Fluctuations from Purely Microeconomic Phenomena Using Large Numbers of Simple Agents

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Conventional macroeconomic models have microeconomic foundations consisting of a few representative agents (workers, firms, consumers) who are assumed to be in general equilibrium[1-4]. As a result, the only sources of dynamics in such model economies are external shocks. These shocks are treated as stochastic, outside the bounds of normal economic processes. However, a wide-range of economic downturns and financial crises appear to have no external cause, but are due, ostensibly, to processes internal to their underlying economies. Here we show that a microeconomic model, written at the level of individual economic agents, can endogenously produce macroeconomic dynamics that closely resemble those of modern macroeconomies: idiosyncratic business cycles, waves of involuntary unemployment, irregular exponential growth, spontaneous firm birth and death, job turnover, skew income distributions, fluctuating prices, power law distributions of firm sizes, heavy-tailed firm growth rates, and a variety of other phenomena. The model is built from millions of software agents and realized computationally. Agents work in team production environments, are paid wages, migrate between firms based on job opportunities, and start new firms when they perceive it advantageous to do so. Prices are local and fluctuate endogenously. Consumers seek utility by purchasing goods from firms, changing the locations they buy from when better prices emerge elsewhere. Firms come and go based on sales and profitability. Microeconomic equilibria exist but are dynamically unstable. No macroeconomic specifications of any kind are employed in the model. Overall, aggregate structure emerges endogenously from the bottom up, through the interactions of the purposive agents. Specifically, the aggregate economy fluctuates about a steady-state while the agent level is out of equilibrium. As the economy gets large, the fluctuations about the steady-state decay in a peculiar way that is consistent with empirical data.

Fluctuations in economic output are a persistent feature of all modern economies. Business cycle-type downturns of a few percent are common, followed by recoveries on a comparable scale, while large declines of 1/3 or more of total output are rare but possible (e.g., Great Depression). Indeed, the recent financial crisis has resulted in the loss of perhaps $20 trillion worldwide. While some recessions are plausibly explained by external events, like the oil embargos of the 1970s, or a country going to war, there are many examples of economic downturns that appear to not have such proximate causes. The Panic of 1907[5], Black Monday (1987), the international crisis of the late 1990s[6], the recent financial crisis[7], and perhaps even the Great Depression[8,9] are all examples of significant financial and economic disruptions for which it is difficult to locate plausible

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external (non-economic) causes[10,11]. Rather, dynamics internal to economic and financial systems seem to be at work in each of these cases.

In this work we do not assume the economic system is in general equilibrium, as is done in so-called *dynamic stochastic general equilibrium* (DSGE) models, the standard modeling approach in macroeconomics today[12] We accept the laudable goal of representing macroeconomic phenomena in terms of microeconomic interactions, but we differ from modern macroeconomics in not requiring the microeconomic level to be in equilibrium.[4] While agent level equilibria are sufficient for macroeconomic equilibrium, we shall clearly demonstrate that they are not necessary: there are broad specifications of agent-level economic dynamics that yield quasi-steady-states when summed over the whole population[13]. Because our models are essentially dynamic at the agent level, but potentially steady-state at the aggregate level, we say that macroeconomic phenomena *emerge* from microeconomic interactions[14]. Most economists will find this philosophical stance unobjectionable—of course the macroeconomy emerges from the actions of individual agents—but know it is mathematically difficult to work with disequilibrium models.[15,16] We have been able to make progress on this problem by utilizing modern computational techniques that permit agent-level adaptation and co-evolution[17,18]. The results reported below are developed using so-called multi-agent systems computer science, also known as *agent-based modeling and simulation* (sometimes *individual-based modeling*).

There are approximately 150 million workers in the U.S., most of whom hold one (primary) job. There are roughly 6 million firms having between 1 and one million employees[19] and another 15 million having no employees (e.g., farms, 'mom-and-pop' operations, and so on). In the past decade comprehensive micro-data have started to become available on the key participants in the U.S. economy—firms, employees, households—primarily through tax and related records. Such data permit the construction of models at the level of individual agents, in dramatic contrast with the 'representative agent' models of analytical macroeconomics[20].

We have created a model at approximately 1-to-1 scale with the U.S. economy. It features 150 million autonomous agents, each pursuing its own ends, earning income by working in a firm, and buying consumption goods. Each agent is locally purposive and perpetually seeks welfare improvements, but no agent attempts to do anything like global utility maximization, both because no agent has systematic knowledge of anything more than a small fraction of the entire economy, and because, even if it were provided a comprehensive snapshot of the economy at some instant, it is incapable of correctly forecasting how such a complex system evolves, even in the near term. It is as if there is a *veil of complexity* that limits every agent's ability to act optimally in the economy.

Specifically, agents work in team production environments, characterized by increasing returns to scale[21]. Each agent brings certain endowments to its position and values

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[4] That is, we suggest that neoclassical macroeconomics is guilty of the fallacy of division—attributing to individuals what is true of the economy as a whole—insofar as the quasi-steady-state behavior of the macro-level is claimed to be evidence for equilibrium behavior at the micro-level.

income and leisure in fixed, idiosyncratic proportions while contributing effort to its group. Each group, a proto-firm, organizes production and sells a product to consumer agents at a price set locally and adjusted in a profit-seeking way. Each team has a compensation system for paying wages to worker agents. Agents periodically adjust their effort levels as they 'grope' for welfare improvements. The fortunes of most firms are out of the hands of individual worker agents, but the overall behavior of a firm's workers determines its fate. When an agent can find a better employment option outside its current firm it changes jobs, and when both its current firm and the outside firms it investigates are doing poorly it will consider starting up a new firm. It can be shown that the Nash equilibria of this team formation game with increasing returns and outside options is dynamically unstable.[22] This leads to quasi-stable firms that will eventually go out of business (with probability one), although they can be long-lived and the distribution of firm lifetimes will be studied below. There is constant flux and adaptation at the agent level and the model is calibrated such that agents stay in their jobs an average of about 30 months, in accord with empirical data. The most important structural implication of permitting the agent level to be out of equilibrium—potentially far from equilibrium—is that we gain the ability to model macrodynamics as endogenous, and do not need exogenous shocks to produce credible aggregate dynamics. Exogenous shocks can yet be incorporated into our bottom-up models, but they are *not necessary* in order to produce dynamics.

The model is marched forward with monthly time-steps: firms make and sell goods, pay workers, and secure inputs for next month's production. Workers receive pay and go out into the marketplace to purchase goods. There are three types of goods in the realizations of the model described below, a consumption good that perishes after one month, a durable good that survives for an average of a year but which may fail at any time (exponential probability of failure), and an intermediate good that is used by firms to make either the consumer or durable good. Results will be shown below for realizations over some 300 months, notionally 25 years.[5]

Figure 1 gives typical time series output from a realization of the calibrated model. The first thing to notice, in (a) is that there are endogenous output fluctuations of up to 10%. These occur even though there are no external shocks being applied. Presumably, external shocks would amplify such fluctuations but we have purposely not experimented with such external forcing (yet), so as to better understand the character of endogenous dynamics. The number of firms (b) oscillates with somewhat more variance than the total output time series, while the number of start-ups is yet more volatile with the number of exiting firms being having the most variability of all. The total wages (c) paid each week are somewhat more stable but have evidence of periodic internal shocks from which it typically takes a long time to recover (many years). Finally, even though output and wages are fluctuating significantly, agents are able to 'smooth' these out as the utility time series is the least variable of all (d).

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[5] At this point we do not know how to start the model near a quasi-equilibrium state. From an initial condition involving all the agents working as singletons over ten 'years' of simulaiotn time must go by for transient states to be wiped out.

Figure 2 shows cross-sectional properties of the artificial economy, taken as a snapshot at the end of the model run. We see (a) a heavy-tailed distribution of firm sizes,[19] (b) non-Gaussian growth rates,[23] (c) average firm output that increases linearly with firm size, (d) growth rate variance that declines with firm size,[23] (e) an approximately-exponential distribution of firm ages,[24] and (f) approximately exponentially distributed job tenure

Finally, in Figure 3 we have output data relevant to conventional macroeconomics. Time series (a) is the unemployment rate, which rises precisely when output falls (compare with figure 1a). Plot (b) is the price level and we see downward pressure on prices during recessions. Figure 3c depicts the distributions of unemployment duration, in normal times and during downturns. Clearly aggregate economic distress exacerbates unemployment spells. Part (d) is the resulting distribution of income.[25]

This model, although clearly very simple microeconomically, produces aggregate results that correspond quantitatively to features of real macroeconomies. It is in some ways the polar opposite of the standard neoclassical macro model—in place of optimizing agents we have merely purposive ones, instead of a single representative agent we use 150×10^6 heterogeneous ones, and in lieu of an omniscient social planner seeking to maximize social welfare we take Adam Smith at his word and ask to what extent can agents, each pursuing its own selfish interests, yield high levels of social walfare. In the spirit of bottom up, emergent economic and social phenomena, both the micro- and macro-levels display robust endogenous fluctuations that have much in common with the general features of modern economies.

References Cited

1 Sargent, T. J. Macroeconomic Theory. 2nd edn, (Academic Press, 1987).

2 Stokey, N. L. & Lucas, R. E., Jr. Recursive Economic Dynamics. (Harvard University Press, 1989).

3 Woodford, M. Interest and Prices: Foundations of a Theory of Monetary Policy. (Princeton University Press, 2003).

4 Ljungqvist, L. & Sargent, T. J. Recursive Macroeconomic Theory. 2nd edn, (MIT Press, 2004).

5 Bruner, R. F. & Carr, S. D. The Panic of 1907: Lessons Learned from the Market's Perfect Storm. (John Wiley & Sons, Inc., 2007).

6 Lowenstein, R. When Genius Failed: The Rise and Fall of Long-Term Capital Management. (Random House).

7 Gorton, G. B. Slapped by the Invisible Hand: The Panic of 2007. (Oxford University Press, 2010).

8 Friedman, M. & Schwartz, A. J. The Great Contraction, 1929-33. New edn, (Princeton University Press, 2008).

9 Bernanke, B. S. Essays on the Great Depression. (Princeton University Press, 2004).

10 Kindleberger, C. P. Manias, Panics and Crashes: A History of Financial Crises. 4th edn, (John Wiley & Sons, Inc., 2005).

11 Reinhart, C. M. & Rogoff, K. S. This Time is Different: Eight Centuries of Financial Folly. (Princeton University Press, 2009).
12 Smets, F. R. & Wouters, R. Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach. American Economic Review 97, 586-606 (2007).
13 Axtell, R. L. in Proceedings of the Workshop on Agent Simulation: Applications, Models, and Tools (eds Charles M. Macal & David Sallach) 3-24 (Argonne National Laboratory, 2000).
14 Delli Gatti, D., Gaffeo, E., Gallegati, M., Giulioni, G. & Palestrini, A. Emergent Macroeconomics: An Agent-Based Approach to Business Fluctuations. (Springer-Verlag Italia, 2008).
15 Colander, D. C. (ed Colander, D. C.) Beyond Microfoundations: Post Walrasian Macroeconomics. Pages (Cambridge University Press, 1996).
16 Colander, D. C. (ed Colander, D. C.) Post Walrasian Macroeconomics: Beyond the Dynamic Stochastic General Equilibrium Model. Pages (Cambridge University Press, 2006).
17 Holland, J. H. Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence. (University of Michigan Press, 1976).
18 De Jong, K. A. Evolutionary Computation. (MIT Press, 2006).
19 Axtell, R. L. Zipf Distribution of U.S. Firm Sizes. Science 293, 1818-1820 (2001).
20 Blanchard, O. J. & Fischer, S. Lectures on Macroeconomics. (MIT Press, 1989).
21 Holmstrom, B. Moral Hazard in Teams. Bell Journal of Economics 13, 324-340 (1982).
22 Axtell, R. L. in Proceedings of the First International Joint Conference on Autonomous Agents and Multiagent Systems Vol. Part 3 (eds Cristiano Castelfranchi & W. Lewis Johnson) 1082-1089 (ACM Press, 2002).
23 Stanley, M. H. R. *et al.* Scaling Behaviour in the Growth of Companies. Nature 379, 804-806 (1996).
24 Coad, A. The Exponential Age Distribution and the Pareto Firm Size Distribution. Journal of Industrial Competition and Trade 10, 389-395 (2010).
25 Yakovenko, V. M. & Rosser, J., J. Barkley. Statistical mechanics of money, wealth, and income. Reviews of Modern Physics 81, 1703-1725 (2009).

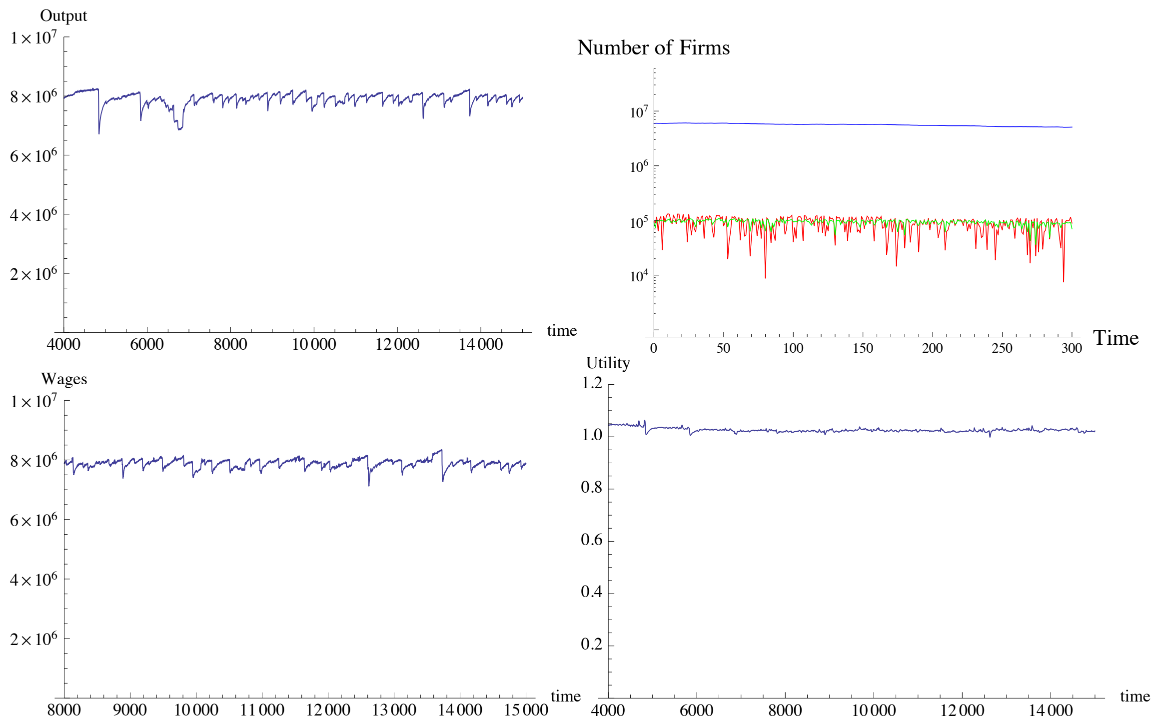

Figure 1: Typical time series produced by the MASs Macro model, (a) output, (b) number of firms (total) as well as entering and exiting firms, (c) total wages, and (d) total utility; time in days (a, b, d) or months (c) with the populations of agents and firms updating their behavior once each period

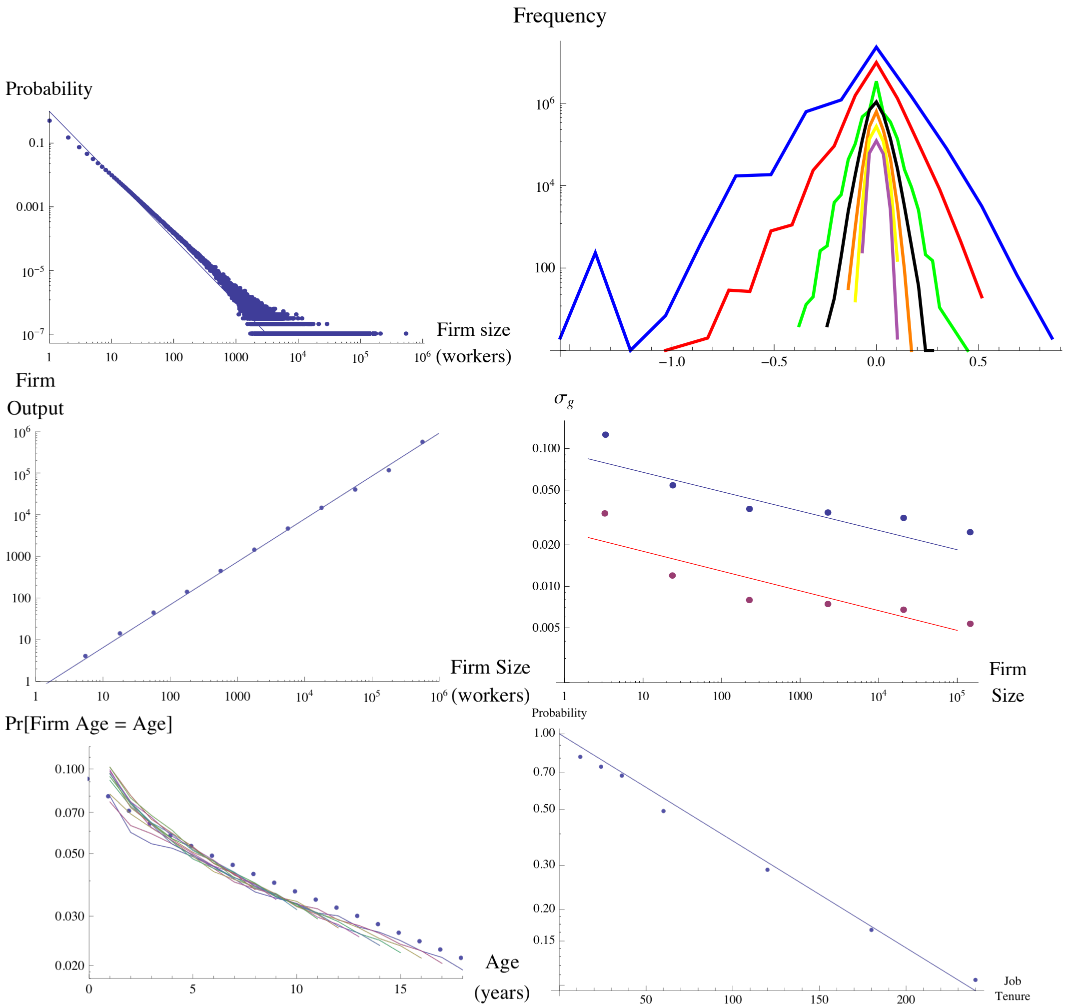

Figure 2: Typical quasi-stationary cross-sections of produced by the artificial economy after a long time, (a) firm sizes, (b) firm growth rates by firm size, (c) firm output as a function of firm size, (d) firm growth rate variance as a function of firm size, (e) firm age distribution, and (f) job tenure distribution

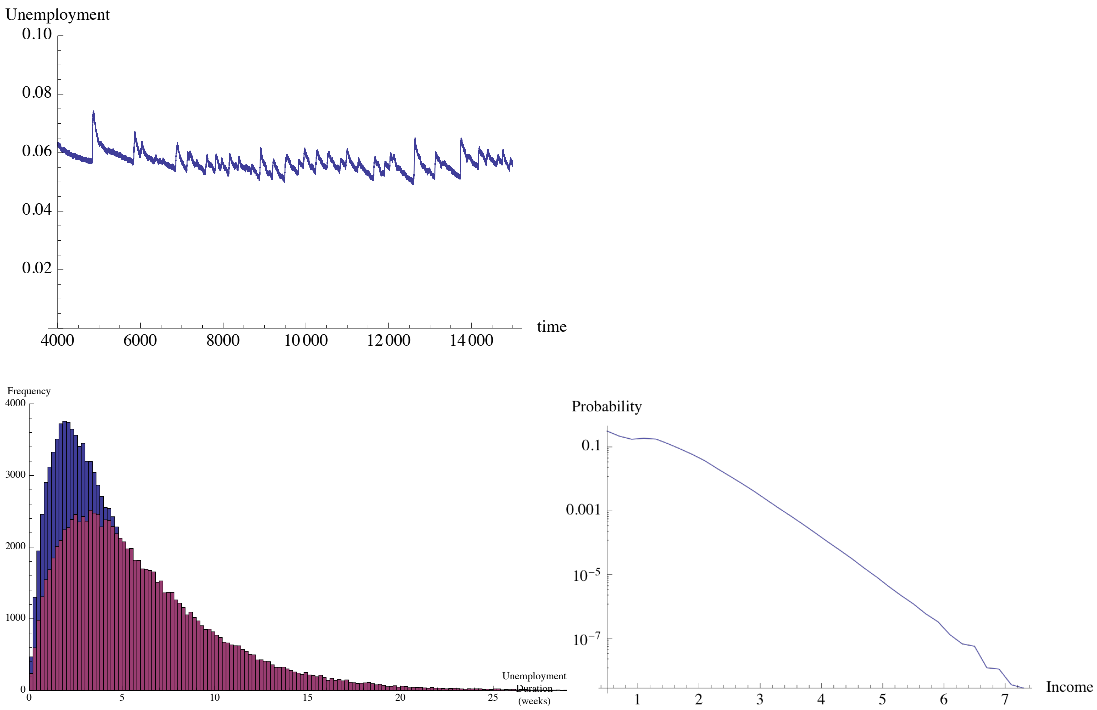

Figure 3: Typical macroeconomic-type output from model, including (a) unemployment time series, (b) price level, (c) distribution of unemployment duration, and (d) distribution of income