Sonnenschein-Mantel-Debreu theorem (Sonnenschein (1973), Mantel (1974), Debreu (1974)) indicates that under a set of the standard assumptions under which general equilibrium theory has been developed, there exist essentially no restrictions on the behavior of data aggregates, either within a cross-section or intertemporally. By implication, there are essentially no restrictions placed by the theory on aggregated data.[13] This absence of empirical restrictions on aggregate data in no way challenges the importance of general equilibrium theory as an overarching organizing framework for economics. Rather, the absence of aggregate empirical restrictions in general equilibrium theory suggests that the theory, at least as classically conceived, is incomplete as a way of understanding economic phenomena.

This incompleteness is evident when one tries to account for the presence of common types of aggregate behavior which emerge across different economic environments. A list of such common aggregate behaviors (and associated interactions-based explanations would include: 1) Zipf's law, which states that within a country, the natural logarithm of a city's population is proportional to its population ranking (Krugman (1990)), 2) large cross-community differences in socioeconomic outcomes despite similar microeconomic characteristics (Glaeser, Sacerdote, and Scheinkman (1993), Brock and Durlauf (1999a)), 3) stratification of communities by income and ethnicity, (Bénabou (1993,1996), Durlauf (1996a,b)) and 4) spatial agglomeration of economic activity (Arthur (1987)).

What makes these aggregate features interesting is their presence in many different contexts despite the presence of substantial heterogeneity across or within the groupings in which they occur. This heterogeneity

[13]It is worth noting that the Debreu-Mantel-Sonnenschein theorem has not been extended to infinite horizon economies, where equilibrium existence proofs typically employ more restrictive assumptions than other cases. Also, Boldrin and Montruccio (1986) have found a similar result which says that a representative agent model can be constructed which replicates any set of aggregate time series on investment and consumption.

suggests that a number of features of economic behavior exist whose aggregate properties are robust with respect to at least some features of the microeconomic specifications of individual actors. In other words, a number of phenomena such as racial segregation, the ratios of population among the largest cities of a country, and substantial persistence in business cycles, characterize a range of very different socioeconomic environments. Interactions-based systems embody the mathematics of such robust properties, and in this regard commend themselves as tools in economic modelling.

Of course, recognizing that general equilibrium theory (as opposed to particular general equilibrium models) fails to generate aggregate data restrictions, any of the common features which one might identify are perfectly compatible with the theory. The relevant point is that this compatibility does not mean that general equilibrium theory provides an understanding of these features.[14]

To see why compatibility is not equivalent to understanding, consider the relation between the neo-Darwinian synthesis and speciation. Modern evolutionary theory provides a framework in which to study patterns of speciation. However, without a successful theory of developmental biology to explain how genetic information expresses itself in phenotypes, evolutionary theory is not capable of explaining why some speciation patterns emerge and not others. By analogy, we are interested in asking how the application of interactions modelling to economics can provide a deeper understanding of common aggregate features beyond the formal compatibility of these features

[14]The meaning of "understanding" in the context of scientific theories is controversial among philosophers of science; see Little (1991) for a discussion. For our purposes, we say that a theory provides understanding of a phenomenon when it provides a causal explanation of how and why the phenomenon occurs in a way which permits a researcher to extrapolate to related contexts. We proceed on the basis that the argument in favor of theories which produce understanding is robust to whatever ambiguities exist at the borders of the concept.

with general equilibrium theory.

The interactions approach can contribute to the development of such an understanding by identifying how certain aggregate behaviors emerge from particular classes of individual characteristics and particular specifications of how individuals interact. One does not, however, get something for nothing by employing this approach in order to generate aggregate dynamics. Particular emergent phenomena depend upon particular sets of individual-level specifications; these methods can only be valuable to the extent that these individual specifications are plausible descriptions of actual economic environments. In the absence of any restrictions on the distribution of individual characteristics, the Sonnenschein-Mantel-Debreu theorem implies that general equilibrium theory imposes only extremely limited restrictions on aggregate data. What interactions methods bring is the possibility that common types of aggregate behavior emerge for widely varying collections of individual characteristics.

The strategy of identifying classes of individual interactions which produce common data implications is paralleled by some recent work on aggregation in economics. Grandmont (1989), Caplin and Leahy (1991), Hildebrand (1994), and Caballero and Engel (1995) have studied economic environments in which restrictions on the distribution of initial conditions and/or individual characteristics allow inferences about aggregate behavior. However, they have not emphasized the collective and emergent features of aggregate behavior which are the hallmark of the interactions approach.

Finally, we would note that for many of the aggregate phenomena in which we are interested, externalities or other types of market failures typically exist. Such features do not, in general, fall under the purview of general equilibrium theory. (General equilibrium theory with incomplete markets, see Magill and Quinzii (1996) is an important exception to this.) In this sense, interactions-based models again complement general equilibrium theory, this time by characterizing alternative microeconomic foundations.

5. Interactions-based models and reductionism in economics

The application of interactions-based analysis to economics illustrates a context in which economic analysis is and ought to be nonreductionist. We argue this in two senses.

First, in many economic environments, there does not exist a unique mapping between specific microeconomic characteristics to aggregate properties, at least when these characteristics are restricted to individual preferences and technologies. As discussed in Blume (1997), this indeterminacy can be attributed to the absence of an explicit characterization of the interaction structure between individual actors. The mathematics of interactions provide tools which can resolve the problem of multiple equilibria (in the sense of explaining how a particular equilibrium is selected) which is necessary to bridge microeconomic structures and macroeconomic outcomes.

Second, the linkage between classes of interaction structures and aggregate outcomes is necessary if the goal of economic modelling is to understand aggregate behavior. While knowledge of the characteristics of each economic agent can, in principle, allow one to characterize a particular aggregate environment, in such environments this knowledge does not provide much insight as to why the environment emerges. As Anderson (1972) puts it, such environments are not "constructivist" in that it is impossible to reason from the properties of the individual objects by themselves to the property of aggregates. It is the nature of collective interactions that is critical in understanding aggregate economic behavior.

Here, some standard examples taken from science are helpful. The statement that a group of water molecules have formed into ice is not reducible in an explanatory sense to information about each water molecule in isolation. Similarly, knowledge of the DNA structure of all species would not lead to an understanding of the collective properties of the biosphere, a point emphasized by Lewontin, Rose, and Kamin (1985). The property of ice or biosphere diversity is emergent in the sense that it occurs at a more aggregated level of measurement than the level at which the individual elements of the system are described. Crutchfield (1994) defines an emergent property in essentially this way.[15]

To see how this applies to economics, again consider our model of binary choice with social interactions under the assumptions of global interactions and rational expectations. When $\beta J > 1$ and $h = 0$, all individuals are identically specified and each has an ex ante 50% chance of using either 1 or -1, yet their behavior is compatible with two average choice levels with nonzero mean. This asymmetric outcome from a symmetric underlying structure, referred to in physics as broken symmetry, is a canonical example of an emergent phenomenon (Anderson and Stein (1984)).

Notice that this example is not consistent with Crutchfield's definition, since each agent in the global case reacts to the expected average choice, while the realization of the average choice is the object under analysis. However, similar properties hold for the local interactions case. For example, if $h = 0$, and agents are arrayed on a two-dimensional lattice, then there exists a critical J_c such that if $J > J_c$, the model exhibits multiple average choice levels in the large economy limit, whereas if $J < J_c$ then the average will always converge to zero in the limit.

In our view, socioeconomic phenomena such as patterns of out-of-wedlock births, racial residential segregation, and technology diffusion, have a

[15] It can be a far from a simple matter to determine whether a system exhibits emergence. In one prominent case, philosophers and cognitive scientists are actively debating whether consciousness is an emergent property of the brain; see Searle (1993) and Churchland (1986) for expositions of opposing sides in this debate.

similar interpretation. This claim is at least partially justified by the success of theoretical models of these phenomena in demonstrating how they can emerge from the combination of well-specified individual decision rules and relatively simple interaction structures. In short, while we accept the central role of microfoundations in macroeconomics as articulated by the modern Chicago school of macroeconomics, we also believe that macroeconomics is a distinct discipline from microeconomics (and by implication neoclassical general equilibrium theory) due to the presence of these emergent properties. This argument in favor of a nonreductive explanation of socioeconomic phenomena appeared earlier when we discussed the relationship between interactions models and general equilibrium theory.

While we emphasize the nonreductionist aspect of interacting economic models, one should recognize that neoclassical economic analysis often focuses on emergent properties.[16] Perhaps the clearest case is the First Welfare Theorem of Economics, which states that (under a well specified set of conditions) every competitive equilibrium is Pareto efficient, i.e. that it is impossible to make anyone better off without making someone else worse off. This aggregate-level efficiency is an emergent property of a system in which individual agents are pursuing their own ends. Other types of emergent properties abound within the context of specific economic environments. Becker (1962) provides a set of cases in which aggregate implications of neoclassical economics survive as emergent properties in environments which deviate from neoclassical assumptions. Thus, we regard our emphasis on the nonreductionist aspects of interactions-driven economic environments to be consistent with the spirit of much existing analysis.

At the same time, interactions-based models are fully consistent with methodological individualism, which we define as the requirement that the

[16]General invisible hand arguments of the type discussed by Nozick (1974) pp. 18-22 implicitly rely on the existence of particular (and conjectured) emergent properties of social systems.

individual agents within an economic system follow well-defined decision rules and that the analysis of the system proceed from the specification of these rules. This requirement simply means that any higher order properties of the system emerge either directly or indirectly from the rules which determine the behavior of individuals. These higher order properties would occur, for example, if one were to find scaling laws in residential segregation patterns, in which the scaling laws exist with reference to communities, whose compositions are endogenously determined by individual decisions.

While the general ideas of methodological individualism are fully compatible with interactions, this approach is important in extending methodological individualism to richer environments than those which are conventionally studied in economics. As discussed in Blume (1997) a powerful critique of the particular instantiation of methodological individualism found in most modern economic theory may be based on the failure of many theories to account for the relationships between individual decisionmaking and different levels of aggregation of the environment in which they interact. This failure lies at the heart of some of the most severe criticism made by social scientists who are not economists as well as by some heterodox economists; Granovetter (1985) summarizes this position well:

> "Classical and neoclassical economics operates, in contrast, with an atomized and *under*socialized conception of human action...The theoretical arguments disallow by hypothesis any impact of social structure and social relations on production, distribution, or consumption." (pg. 55)

It is precisely this ability to provide socially mediated connections between individual behavior and larger socioeconomic aggregates that makes the interactions approach useful in breaking what we regard as obviously artificial disciplinary barriers between economics and sociology when studying complicated problems such as social pathologies.

6. New applications of interactions-based modelling

As should be clear from this discussion, there is nothing about conventional economic problems which makes interactions-based modelling especially appropriate. Indeed our view is that there are a wide range of range of social and political phenomena where interactions-based approaches can be fruitful.

i. Language

Sociolinguistic studies have made clear that there exists a deep relationship between socioeconomic status and language use. For example, it is well documented that the use of nonstandard grammar or pronunciation by a given individual is more probable when someone is poor and male, controlling for other factors – see Chambers (1995) chapter 2 and Wardhaugh (1995) chapter 7 for surveys of evidence on this. What the sociolinguistics and psychology literatures makes clear is that language is closely tied to individual identity and that both are in turn influenced by one's reference groups; see Akerlof and Kranton (1999) for a provocative discussion of how identity shapes socioeconomic outcomes; their discussion places sociolinguistics findings in a broad context. Further, there is some recognition that dialectic choice, defined in terms of adherence of standard grammar or pronunciation, can have important economic consequences. For example, Jupp, Roberts, Cook-Gumperz (1982) and Akinasou and Ajirotutu (1982) argue that ethnic minorities are at a relative disadvantage in job interviews due to differences in language structure and style.

While sociolinguistic studies seem to have made clear that linguistic behavior is determined by one's economic and social status, there has been, little formal modelling of the processes by which language and socioeconomic communities jointly evolve across time.[17] This would appear to be an ideal case for understanding the interplay of private and social incentives. The use of Black English, for example, is a choice which is conditioned both by social interactions (the language choices of one's social network) as well as the incentives set by the economy as a whole.[18] In turn, use of Black English influences socioeconomic opportunities. Formal modelling using interactions could both make rigorous many standard ideas in sociolinguistic theory as well as provide a nice test case for the assessment of statistical tools designed to uncover interactions.

Beyond the issue of dialect choice, one can also imagine using interactions-based models to study regional patterns in pronunciation.[19] Labov (1996) is a recent example of empirical work on this issue, documenting the evolution and persistence (despite homogenizing factors such as mass media) of such differences. These spatial patterns would intuitively seem to be a prime candidate for a social interactions explanation, since it hard to imagine any purely private incentives for such choices. Put differently, since pronunciation does nothing more than facilitate communication with others, the choices of others are naturally the object that determines these choices; pronunciation choices may even be thought of as examples of network externalities of the type that apply to choice of computer operating systems.

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[17] Among economists, a notable exception is Lazear (1995). Lang (1986) discusses the effects of language barriers on wages. Akerlof (1997) discusses the importance of understanding the interdependence of language and economic status.

[18] Notice that this type of choice need not be conscious. What we mean is that the choice-based framework we employ can be used to understand how individuals take up behaviors, such as belief in God, tendency towards liberal versus conservative political views, etc. in which the private and social incentives are not employed in a conscious calculus, but rather simply represent factors which influence individual outcomes.

[19] We thank William Brock for this suggestion.

ii. **Security issues**

Interactions models have had little application in security issues.[20] However, it is clear that many of the ideas and metaphors which motivate socioeconomic contexts are also relevant in this case. One possible question is the probability of a nuclear weapons accident. As made clear in Sagan (1993), understanding the probability of an accidental launch requires understanding the behavioral outcomes of an organization (military of course) comprised of many decentralized, yet highly interdependent decisionmakers. Indeed, a major argument in defense of so-called "normal accidents" theory (so dubbed by Sagan), at least as developed by Perrow (1984), is that there exist sufficiently many nonlinear interactions between elements of large organizations that mistakes will invariably arise which cannot be accommodated by safety features which can only accommodate foreseeable contingencies. Rochlin (1997) has further argued that the extremely high degree of computerization of defense capabilities has produced an extremely high degree of interdependence within various defense organizations, so this general concern about organizations seems especially applicable to defense.

Could interactions-based methods help clarify the probability of a nuclear weapons-related accident? It is certainly plausible to believe that the answer is yes. Formal modelling of command and control systems could be achieved with a great deal of accurate detail about microstructures. We are willing to conjecture two features of such an exercise. First, it will be possible to produce scenarios under which accidents occur at unacceptably high frequencies. One message of interactions-based studies of stock price

[20]This is not to say that security and defense issues have not been subject to formal modelling – see Epstein (1997) for a nice introduction to successful examples of the applications of mathematics to issues in this area.

movements generated by interdependent traders (Arthur, Holland, LeBaron, Palmer, and Tayler (1997)) or the distribution of rates of social pathologies (Glaeser, Sacerdote and Scheinkman (1995)) is that extreme outcomes in the sense of highly correlated behavior in a population have a nontrivial probability of occurring due to positive feedback effects; hence a similar result in the context of nuclear accidents seems reasonable. Second, it may nevertheless be possible to design redundancies and safety mechanisms within the system to render this probability negligible. Why? Because the same interdependence which may make accidents seem relatively likely can also mean that small but common influences on individual decisions can have large aggregate effects. By making each actor in the system slightly more cautious, the feedback effects may render the system as a whole much more cautious. How this can be done naturally requires expertise in the details of the organization of interest (and indicates why interactions models complement rather than substitute for institutional knowledge), but the capacity for large heterogeneous systems to experience collective order due to positive interactions suggests that this goal can in principle be accomplished.

One might argue that normal accidents theories are based on the claims that certain contingencies cannot be foreseen rather than on claims about the complexity of organizations per se. However, if the concern about interactive environments is that there are contingencies whose nature we cannot characterize, let alone whose probabilities we cannot evaluate, then it is incoherent to talk about the probability of accidents being high or low. Also, the issue for system performance is not the identifiability of the range of possible shocks to the system, but rather the identification of the range of responses and interconnections. If the argument that complex interdependent organizations are likely to produce errors is to make sense, it is presumably a statement about how the interactions in such systems evolve, which is why interactions-based modelling seems a natural approach.

7. Conclusions

Interactions-based models provides a powerful set of structures that are conducive to modelling a wide range of socioeconomic environments. These models are capable of incorporating individual heterogeneity and cross-individual dependencies which have proven difficult to model in the past and are able to do so in ways with interesting empirical implications, in particular with respect to aggregate patterns.

Although we are confident that interactions-based analysis has much to offer economics, we recognize that our views are still fairly speculative. While this approach has provided numerous theoretical insights, there has yet to be a decisive empirical demonstration either of the interactions which underlie the microstructure of the approach or of the presence of the sorts of emergent phenomena which are the hallmark of aggregate implications of these theories. Even Zipf's Law, which is often taken as the most evident scaling law in economics, has yet (at least in our opinion) to be subjected to sufficiently rigorous econometric examination. Further, as made clear in Manski (1993,1997) and Brock and Durlauf (1999b), the econometric identification of interaction effects is complicated, with identifiability depending sensitively on details of the modelling context.

At this same time, it should be recognized that there have been a number of interesting developments on the empirics of interactions. One problem in the empirical analysis of interactions is that one is interested in inferences about these effects for heterogeneous populations in just the same way as one wishes to theorize in the presence of heterogeneity. Such populations are, for cases such as neighborhoods and schools, endogenously sorted into relevant groups. Manski (1995) provides many insights into how one can obtain bounds on various effects in the presence of self-selection and heterogeneity; Brock and Durlauf (1999b) show how to adapt these ideas to identify interactions effects. Additionally, Brock and Durlauf (1999b) provide conditions under which self-selection, if properly modelled, can facilitate identification. Both these approaches seem very promising, although much remains to be done. Beyond the development of new econometric methods, it will likely be necessary to construct new data sets in order to accurately characterize the microstructure of particular types of interactions. See Rauch (1996) for an interesting exercise along these lines.

Despite these interesting developments, the long run success of the interactions-based approach in economics depends on a clear demonstration of its empirical salience over a range of contexts. This of course will require that more empiricists and econometricians participate in the analysis in order to complement the economic theorists whose work launched the field. The interactions between these groups should themselves prove to be two-sided. Just as empirical research is needed to characterize the nature of interactions in actual socioeconomic phenomena, which should then inform the ways theories are constructed, theoretical research can help to identify new ways of thinking about data.

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