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Geography matters: agency, structures and dynamics at the intersection of economics and geography

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Abstract

Contemporary debates in economic geography are characterized by a lack of agreement with respect to both those aspects of the evolving economic landscape that call for explanation and what constitutes an adequate explanation of geographical reality. We articulate a distinctively geographical approach to modeling processes of regional growth and change. The evolving economic landscape is conceptualized as a 'going concern', characterized by complex dynamic interdependencies between the agents and structures that constitute spatial economic systems. At any moment in time, interdependencies between agents are constrained by social and spatial structure, but over time structure and agency are mutually constituted: a socio-spatial dialectic. We contend that the complex interdependence between agents, structures and dynamics increases the likelihood of persistent non-equilibrium space-time trajectories. We conclude that questions of conceptual and epistemological adequacy in economic geography cannot be resolved in favor of any single 'best' approach, and argue that debates should move away from competing monist accounts, towards critically engaged pluralism.

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In recent years, an unfortunate methodological and theoretical polarization has emerged among those who see themselves as engaged in economic geography. Some economists have rediscovered economic geography, employing mathematical techniques and statistical methods to revivify and extend location theory in the neoclassical tradition, a research program that Ottaviano and Thisse (2004) dub geographical economics. In contrast, the majority of geographers have rejected the neoclassical tradition, in their minds associated with spatial analysis and mainstream economics, in favor of neo-Marxian and post-Keynesian political economy—which in turn has diversified into feminist and post-structural approaches. For many geographers engaged in this cultural turn, quantitative approaches have come to be rejected as positivist, pro-market and neoliberal. These tensions have received considerable attention within

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and between geography and economics. Within geography, it has been argued that to dismiss quantitative approaches along with neoclassical theory amounts to throwing the baby out with the bathwater (Plummer and Sheppard, 2001; Sheppard, 2001). In contrast, Amin and Thrift (2000) call for economic geographers to turn away from both quantitative approaches and economics. Similar arguments can be unearthed in economics, where Lawson (2003) argues that an unbridgeable ontological gap exists between neoclassical 'deductivist' and realist economics. Assessing interactions between the disciplines, geographer Scott (2004) and economist Overman (2004) both lament anti-quantitative tendencies in economic geography.

The purpose of this article is to re-examine some of the shared pre-suppositions underlying these assessments, and to suggest one way to transcend this current paralysis dividing geographical economics from economic geography. Unlike Lawson or Amin and Thrift, we argue that a turn away from neoclassical approaches need not entail a turn away from theorization that employs mathematical languages to account for the dynamics of capitalist space economies. Taking this as our starting point, we examine, first, what difference it makes to such theorization, if approached from the ontological perspective prevalent in economic geography rather than that prevalent within geographical economics. Then, we explore the implications of adopting what we will call a social-spatial dialectic for modeling the capitalist space economy as a 'going concern' (Curry, 1998). In particular, we focus on the potential importance of computational and complexity-based modeling methodologies for understanding the dynamics of capitalist space economies. We conjecture that there is a potential value added to exploring the relationship between these modeling methodologies and an ontological perspective that conceptualizes the space economy as a socially constructed socio-spatial dialectic. We argue that such models entail re-focusing mathematical and statistical modeling in economic geography away from micro-foundations, based upon optimizing representative agents and computable equilibria, towards problem-solving 'algorithmic' agents 'groping' for market clearing solutions. The latter can result in the far-from-equilibrium dynamics that characterize complex systems. Finally, we draw out some methodological and philosophical implications. We conclude that our geographic approach leads to quite distinct theoretical conclusions to those reached, to date, within geographical economics. This suggests that geographers have more to contribute than '[g]ood, careful case studies' (Overman, 2004, p. 513), and indeed retain the capacity to develop a 'theoretical re-description of capitalism' (Scott, 2004, p. 492).

1. A tale of two ontologies[1]

Any economic geographic research program entails a particular way of thinking about the social world: what we term here a socio-spatial ontology. Philosophically, an ontology is how we take the world to be. The socio-spatial ontology associated with any

1 It is always hazardous to generalize, as we do here, between geographical economists and economic geographers. It would be inaccurate to claim that all researchers trained or located in geography (economics) programs adhere to the position dubbed economic geography (geographical economics). In addition, we describe the viewpoint of influential theorists within each school, recognizing that many practitioners depart from such views. Nevertheless, we believe that the broad differences here are representative of an important and widely discussed division among scholars who describe their work as economic geography; a division that the *Journal of Economic Geography* seeks to transcend.

research program, then, is how its practitioners take space and society, and their interrelation, to be for the purposes of that program. Within the context of contemporary economic geography there exists a plurality of socio-spatial ontologies, influencing both what aspects of geographical reality call for explanation and what an adequate explanation of what that reality might look like. Unlike logical empiricism, which commits the epistemic fallacy of reducing questions of social ontology to a supposedly idealized foolproof epistemology, we stress the importance of distinguishing between questions of what exists in the geographical world (ontology) from those of how we might justify our explanation claims (epistemology). As we discuss in the final section of this article, this distinction enables us to liberate spatial analysis from its long-standing, unfortunate and inaccurate association with logical empiricism—an association that proponents and opponents alike have used to isolate quantitative from post-positivist economic geography.

Much of mainstream geographical economics shares a two-fold socio-spatial ontology.[2] First, is the principle of micro-foundations: the view that aggregate socioeconomic processes and patterns can be reduced to the rational actions of self-interested, autonomous individual economic actors. This is a particular, voluntaristic, version of methodological individualism, constituting 'a special case of rational choice; where individuals broadly speaking are able to achieve their intended aims' (Barnes and Sheppard, 1992, pp. 3–4). A socio-spatial ontology grounded in individual actors, capable of successfully optimizing up to the limits of their information, results in a modeling methodology in which the space economy is defined with respect to spatial equilibria. From the perspective of a 'new' classical economics inspired geographical economist, non-equilibrium dynamics are simply not defined (Hoover, 1988). The question of how agents behave out-of-equilibrium thus does not constitute a meaningful topic within this research program. The possibility of multiple equilibria is central to geographical economics, and path dependency is widely discussed (since initial conditions determine which of the multiple equilibria is predicted to emerge), but what matters is the relation between these conditions and the equilibrium pattern, not the out-of-equilibrium dynamics themselves.

Second, space is taken to be exogenous to the economy, and generally homogeneous, in much the same way that in physics Newton (unlike Leibnitz and Einstein) took space to be an external Cartesian grid. For example, August Lösch (1954 [1940]) pioneered a research program of morphogenesis by showing how central places can emerge on a uniform plain, more recently reinvigorated by Paul Krugman et al.'s demonstrations of economic clustering on a geographically uniform landscape (cf. Fujita et al., 1999). A corollary of this ontology is that these patterns can generally be approximated by one or more stable static (or on occasion dynamical, cf. Walz, 1996) spatial economic equilibria.

Adoption of Paul Samuelson's 'iceberg' formulation for transportation costs exemplifies how space is taken to be exogenous to economic processes in geographical economics. Widely employed in Dixit-Stiglitz models of monopolistic competition in space, this formulation sets transport costs, and thus distance, as an external

2 Lawson does not believe that neoclassical economics qualifies as possessing a social ontology, but we disagree: it is a particular, reductionist, conception of the relationship between individual behavior and social processes.

quasi-freight rate (Fujita et al., 1999; Brakman et al., 2001). The analysis by Jeffrey Sachs and his colleagues of how 'geography' poses a constraint on possibilities of economic development through globalization similarly exogenizes both relative location (distance to a navigable water body) and climate (Gallup et al., 1999; Sachs, 2000). Such assumptions lack realism.[3]

When differences in relative location disappear space is also taken to be homogenous. For Lösch and Krugman, firms of the same type competing in a spatially extensive market are identical not only in their cost structure but in their relative location—they occupy identical positions at opposite ends of a line, or are equally spaced either around a ring or across an unbounded uniform plain. The challenge then is to explain agglomeration. In the absence of differences in relative location, industrial clusters are explained by emergent place-based characteristics; localization or urbanization economies. In most cases, firms maximize total profits, excess profits net of fixed costs are zero (Fujita et al., 1999), and multiple stable equilibria are possible. 'Path dependence' is said to be an attribute of these equilibrium models, because small initial differences, or shifts in exogenous parameters, can determine which equilibrium emerges.

The socio-spatial ontology favored by economic geographers is quite different. First, they eschew any form of methodological individualism. Economic actors are neither fully rational nor autonomous. Their interests and preferences are shaped by their socio-spatial position, their knowledge is imperfect, and they engage in collective action. Their actions shape, but also are shaped by, the social structures and cultural context in which they find themselves. As Marx quipped, they make the world, but not a world of their own choosing.

Second, space is taken to be endogenous to the economy, and uneven. Once we recognize the social nature of distance, i.e. that the closeness of two places is not simply a function of the Euclidean distance separating them but of the intensity and ease of spatial interactions connecting them, the endogeneity of distance becomes evident. We also know, of course, that transportation and communications technologies are endogenous to the space economy, undergoing enormous changes throughout history. Geographers stress the importance of recognizing that spatial structures are produced through socioeconomic processes, if social theory is to avoid spatial fetishism (Sheppard, 1990). Yet it is equally important to recognize that produced spatial structures have their own distinct effects on socioeconomic processes. Ed Soja coined the term socio-spatial dialectic to refer to such reciprocity, whereby 'social and spatial relations are dialectically inter-reactive, interdependent' (Soja, 1980, p. 211). With respect to heterogeneity, for geographers the unevenness of space is a vital starting point for geographical analysis. Notwithstanding morphogenesis, from this ontological perspective empirical analysis must recognize how pre-existing geographical unevenness shapes spatiotemporal change. Despite recent arguments about the death of distance in the face of globalization, differences in relative location remain critical to the possibilities available to economic actors (Sheppard, 2002).

3 Sachs et al. use the incidence of malaria to measure tropicality (Gallup et al., 1999), but it is well known that the spatial incidence of malaria is not simply determined by climate—as illustrated by its eradication from Britain and the United States.

The maximum-and-constraints theorization underpinning general equilibrium models allows geographical economists to tame the complexity of the space economy. However, these theoretical results are obtained at a high price. It is evident from the above comparison that economic geographers are less willing than geographical economists to countenance highly simplified assumptions about social and spatial structure for the sake of analytical tractability. We are, in short, unwilling to accept Milton Friedman's (1953) argument that the evident artificiality of assumptions does not matter as long as an economic theory's empirical predictions seem plausible (Hanson, 1994). We accept that it is always necessary to employ simplifying assumptions in model construction. Nevertheless, it is how those assumptions are employed and why they are adopted that differentiates competing research programs in economic geography. A vital issue, then, is how much difference such simplifications make. Our modeling assumptions shape, and are shaped by, our vision of the dynamics of the capitalitst space economy: our socio-spatial ontology matters. If a theory's core propositions are robust to modifications in its assumptions, then Occam's razor seems a wise strategy. If not, then the plausibility of those propositions is undermined. In short, at issue is whether the simplifications underlying geographical economics' socio-spatial ontology are critical to its theoretical conclusions (Sheppard, 2000).

Our previous research has identified situations in which the differences in socio-spatial ontology described above do make a significant difference to theoretical propositions. Two of these will be briefly reviewed here to illustrate why ontology matters.[4] Consider, first, monopolistic spatial competition between retail firms occupying fixed locations, with identical cost schedules, selling a homogeneous product to spatially dispersed consumers. Consumers, with inelastic demand schedules, choose retailers based on relative price. If consumers are informed about all opportunities and perfectly rational, no stable spatial price equilibrium exists. If consumers only know the prices at locations within their choice set (e.g. within a certain distance of their residence), however, and stochastically choose between retailers in that set on the basis of relative price (using a multinomial choice function), a locally quasi-stable spatial price Nash equilibrium can generally be computed. However, it is questionable whether the profit-seeking actions of retailers, responding to competitors' price setting strategies, enable convergence to this equilibrium (Sheppard et al., 1992). In this case, then, incomplete information matters, and spatial interdependence complicates the possibility that rational individual action results in spatial price equilibrium.

This model treats space as exogenous, but uneven. If space is homogeneous, each retailer charges the identical equilibrium price and excess profits (beyond those necessary to cover fixed costs) disappear. If space is uneven, however, 'differences in the degree of spatial monopoly . . . give rise to permanent differences in profit rates, in a manner analogous to differential rents, and free entry does not imply a long run equilibrium where all firms make minimum profits. Consequently, the traditional argument that profits may be neglected under free entry is inapplicable to the reality of spatially heterogeneous markets'. (Sheppard et al., 1992) In short, uneven space results in excess profits accruing to some sites: with the exception of the geographically

4 Readers are encouraged to consult the published literature for a fuller elaboration.

marginal producer, firms make excess profits reflecting their locational advantage (Curry and Sheppard, 1982). But there are also other differences. For homogeneous space, there are no excess profits and firms maximize total profits in the usual way. When space is uneven, however, excess profits exist and it turns out to be in firms' interest to maximize the rate of profit on capital advanced rather than total profits (Sheppard et al., 1998). Such considerations have empirical implications, as the equilibrium prices associated with profit rate maximization exhibit different spatial patterns from those associated with total profit maximization (Haining et al., 1996; Plummer et al., 1998a). The decision about whether to treat space as homogeneous or uneven thus has substantial theoretical and empirical implications in this case.

The second example examines the implications of conceptualizing space as both uneven and endogenous to the economy (Sheppard and Barnes, 1990). Consider a multiregional, multisectoral capitalist economy, in which one sector in each region is transportation. The transportation sector produces accessibility, which is consumed whenever another commodity or person moves between regions. The price of transportation, endogenously determined like the prices of other commodities, shapes relative location and influences decisions about where to purchase inputs. The economic distance separating regions depends on transportation technologies and the price of transportation in regions, making relative location endogenous to economic processes. In addition, economic actors are divided into two collectivities, or classes: those who own labor and are interested in higher wages, and those who own capital, and are interested in higher profits. Dynamic spatial equilibria can be computed for this inter-regional system: vectors of relative prices and outputs, by sector and region, which enable the economy to reproduce itself along a golden path of accumulation, with profit rates equalized across sectors and regions. This equilibrium is unstable, however, because it is always in the interests of workers and capitalists to increase wage or profit rates, respectively, relative to the wage and profit rate parameters characterizing the equilibrium. In short, there is no distribution of income between wages and profits (and land rent) that is stable in a Nash equilibrium sense.[5]

The endogenous treatment of distance further complicates such theoretical conclusions, originally deduced for a spaceless, single region, version of this theoretical model (Morishima, 1973). For example, with the spaceless version it can be shown that when individual capitalists introduce cost-reducing technological change, the average economy-wide rate of profit increases, contradicting Marx' speculations about a falling rate of profit (Okishio, 1961). For the multiregional model, however, it is possible that individual cost-reducing technical changes may indeed result in a lower economy-wide profit rate. Similar conclusions can be drawn with respect to inter-regional specialization and trade. For a two-region model with exogenous transportation costs, it remains possible to determine the comparative advantage of each region (Steedman, 1979), and whether trade is beneficial for given transportation costs. Once transportation is included as an endogenous sector, however, it is again possible that decisions to specialize and trade that seem profitable to individual capitalists result in a lower economy-wide profit rate (Sheppard and Barnes, 1990). The reason for such

5 This model assumes linear production technologies of the input–output variety and fixed demand schedules, but the instability of equilibrium proposition is robust to replacing this assumption with conventional neoclassical assumptions about production technologies and consumer behavior.

apparently counter-intuitive results lies in the role of transportation in this economy. Changes in technology or in specialization patterns always entail increased transportation requirements for some regional sectors along with decreased requirements for others, altering transportation prices. The effects of these changes on overall profitability seem unpredictable.

In comparing these two socio-spatial ontologies, it is thus possible to identify cases where choice of ontology does matter; i.e. where the simplifying assumptions reflecting the socio-spatial ontology that dominates geographical economics may be critical to the plausibility of some of its theoretical propositions. In contrast, the ontology associated with economic geography is one where profits do not disappear, rational choices can have undesirable unintended consequences, and stable equilibria cannot be guaranteed. This provides a motivation to pursue what it means to model the space economy from a perspective consistent with the socio-spatial dialectic of economic geography. Here, spatial structures shape spatial interdependencies, but in turn are shaped by those same interdependencies. Human agency shapes structure, but broader structural changes may undermine the efficacy of agency. Individuals share interests across class and space lines (not to mention gender, race, etc.) that can result in collective action and social conflict. Markets cannot automatically arbitrate these, and market-based outcomes need not be socially beneficial. Furthermore, we must accept the possibility of, and explore the implications of, the proposition that the geographical space economy may be a complex, non-linear system; one in which space is no longer Newtonian and time is an emergent property of the dynamical system rather than an exogenous coordinate system (Prigogine, 1996, p. 60). While we recognize that the geographical world could be otherwise, we seek to explore what it means to do quantitative economic geography in a context where this proposition cannot be dismissed *a priori*.

2. Modeling the complexity of a capitalist space economy

Contemporary approaches to modeling the capitalist space economy are dominated by the social ontology and epistemological norms of mainstream economics. Paradigmatically, this involves an ontological commitment to maximum and constraints theory construction that is grounded in methodological individualism. The space economy consists fundamentally of self-interested individuals, with every agent successfully optimizing up to the limits of their information. In principle, unless a theoretical model is grounded in such micro-foundations it is not considered to be an adequate representation of the processes driving the evolution of the economic landscape. As a corollary, the space economy is conceptualized as being in a continuous rational expectations general equilibrium. While mainstream economists may debate the nature, stability and multiplicity of equilibria, it is presumed that equilibrium and steady-state models derived from micro-foundations are adequate for representing reality.

In contrast, our worldview is grounded in the socio-spatial dialectic (Plummer et al., 1998b). We conceptualize the capitalist space economy as a structurally complex evolving dynamical system. Following Punzo and Velupillai (1996b) we identify our methodological core in terms of the *Goodwin code*; a mathematical modeling methodology characterized by three norms. First, models should be formulated using the mathematics of non-linear systems and, subsequently, analyzed in terms of their global behavior. Goodwin pioneered such modeling in post-Keynesian political economy utilizing the mathematical theory of non-linear oscillators. Such oscillators typically are locally unstable but globally stable, endogenously generating irregular propagating macroeconomic growth and fluctuations.

Second, economic structures should be conceptualized in terms of the interactions between the components constituting such systems, a key insight that is consistent with regional political economy. For a given structure of sectoral interdependencies, it is possible to define either (cross) dual price-quantity or wage-employment out-of-equilibrium adjustment mechanisms. For non-spatial systems, the analytical properties of such dynamic systems have been studied extensively by classical and post-Keynesian political economists (Flaschel and Semmler, 1986; Duménil and Lévy, 1987). Third, the integrating concept between the global behavior of non-linear dynamic systems and multisectoral economic structures are the assumptions made about the behavior of either individual economic agents or whole economic systems. In contrast to the rationality assumption underpinning of geographical economics, decision-making in a Goodwin-type model is conceptualized in terms of out-of-equilibrium problem-solving. Typically, this is modeled as a computational algorithm representing a disequilibrium adjustment process 'groping' toward an equilibrium, allowing for the possibility that out-of-equilibrium adjustment mechanisms generate endogenously driven fluctuations around an equilibrium growth path (Goodwin, 1951; Velupillai, 1998). This computational algorithm represents a model of actual adjustment behavior rather than an artificial 'fiction' enabling computation of a solution to a non-linear and interdependent equation system.

2.1. Conceptualizing complexity

Adopting the *Goodwin Code*, we consider what it means to conceptualize the capitalist space economy as a complex spatial system. Complexity theory is the latest in a line of fashionable mathematical modeling tools running from cybernetics in the 1960s, at the core of what was then called general systems theory (Weiner, 1961), through catastrophe theory in the 1970s and chaos theory in the 1980s (cf. Wilson, 1981). Complexity theory has certainly extended the domain of applicability of systems theory, and we recognize the danger of falling into the trap of a new general systems theory (Berlinski, 1976). We are thus agnostic as to whether all of reality can be represented with some combination of simple linear dynamic models, simple non-linear dynamic models, and models characterized by complex spatial and temporal interdependencies.

Mathematically, complex systems are capable of a range of dynamic behavior that transcends both linear and simple non-linear dynamic systems. As is well known, linear systems are characterized by a limited range of dynamics; monotonic or cyclical movements with respect to an equilibrium point. Extension to simple non-linear systems encompasses a wider array of attractors including aperiodic limit cycles and chaotic behavior. Complex systems are characterized by a series of distinctive properties (Prigogine, 1996). They are capable of generating propagating irregular structures that lie somewhere between the domain of periodic attractors and chaotic attractors, at the edge of chaos. Such systems typically have many spatial and/or spatiotemporal equilibria, which may or may not be stable. They may well be far-from-equilibrium at any particular point in time, with spatiotemporal trajectories that can be substantially disrupted by external shocks and show significant dependence on parameter values and initial conditions. Brock (2001) has identified a set of popular terms and ideas that are indicative of complexity-based research:

> Readers can be quite assured that the piece they are reading is 'complexity-based' if they encounter the following terms and ideas: (a) path dependence; (b) self-organized criticality; (c) edge of chaos; (d) power law scaling; (e) renormalization group; (f) fractals and other types of self similarity; (g) genetic algorithms, emergent computation, (h) adaptive neural nets, complex adaptive systems; (i) chaos theory, embedding theorems, correlation integrals; (j) interacting participle systems, statistical mechanics, mean field theory, non-ergodic systems, breakdown of the law of large numbers. (Brock, 2001, p. 302)

We would add to this set of terms and ideas the notion that space is relational (Harvey, 1996). That is, instead of adopting a Newtonian conception of space, as exogenously given coordinates in Euclidean (or Hilbert) space, space is constituted through the persistent non-local interactions connecting system elements (Prigogine, 1996).

In order to bring some rigor to the numerous and sometimes contradictory definitions and measures of 'complexity' (Rissanen, 2001; Brock, 2001), it has recently been suggested that these definitions and measures can be subsumed under the *Chomsky–Wolfram synthesis* (Casti, 1989; Albin, 1998; Markose, 2005). The Chomsky–Wolfram synthesis establishes a formal correspondence between a complexity hierarchy for formal languages based on Chomsky's linguistic theory, and Wolfram's computational theory of cellular automata. Recently, Albin (1998) has explicitly extended this synthesis to include a hierarchy of dynamical systems based upon their qualitative properties. Elaborating Herbert Simon's work on bounded rationality, he has explored the potential ways in which complex dynamic systems present barriers to both economic rationality in macroeconomic models based upon inter-temporal optimization, as well as game theoretic models of rational decision-making. We conjecture, below, that Albin's interpretation of the Chomsky–Wolfram synthesis, in terms of the decision-making capabilities of economic agents, can be extended to encompass spatially interdependent economic systems.

Essentially, the Chomsky–Wolfram synthesis is a four-step hierarchy of increasing complexity that permits a qualitative classification of dynamic systems. Associated with each level, a computational model can be identified which, if utilized by economic agents, will enable them to replicate the dynamics of that system.

Type 1: Uniform stable behavior. These types of dynamic systems represent a stable equilibrium with all trajectories attracted to a single limit point. Computationally, the system can be replicated by economic agents using only a simple calculator, or a computer without memory.

Type 2: Simple stability or periodicity. These dynamic systems are describable as stable periodic attractors (limit cycles). Computationally, the system can be simulated by agents using a finite memory device of fixed size.

Type 3: Aperiodic behavior. These dynamic systems are qualitatively more complex. In such systems the dynamics can be aperiodic and time irreversible, suggesting chaotic trajectories around strange attractors. Computationally, the memory requirements for a simulating device grow without restrictions. 'Fixed' programs compute with memories that can expand to meet the demands of the computational problem.

Type 4: Irregular and persistent behavior. These are what we denoted as complex dynamic systems. Typically, dynamics can be irregular and 'structure changing' depending on the set of initial conditions and random shocks. Markose (2005) describes these as systems with undecidable dynamics that endogenously generate innovation, much like the creative destruction that Schumpeter associated with capitalism. This type of system may propagate, grow, cycle, contract or die. Computationally, agents must have the computational capacity of a universal Turing machine (a universal computer that can replicate the behaviors of any fixed program), in order to replicate such dynamics.

The *Chomsky–Wolfram synthesis* provides a useful heuristic device with which to classify the qualitative properties of evolving spatially interdependent system, allowing us to address the question of how a complexity-based approach to economic dynamics is possible. From the point of view of the micro-foundations ontology of mainstream economics, Markose argues that competition brings into existence actors with the decision-making capacity of Turing machines. Such actors replicate Type 4 dynamics, with market mechanisms operating as the mediating mechanisms in ways suggested originally by Hayek (1937). From the viewpoint of the socio-spatial ontology of economic geography, however, in dynamical systems characterized by higher levels of complexity, even fully informed and perfectly rational agents will be unable to compute a solution. For dynamic economic systems of Types 1–3 in the Chomsky–Wolfram synthesis, economic decision-making is bounded by the information available to economic agents and the computational processing abilities of those agents. In contrast, the qualitative dynamics that are characteristic of complex dynamic systems (Type 4) suggest the possibility that barriers exist in principle to rational economic decision-making. In the next section, we will argue that exactly this kind of system characterizes the socio-spatial dialectic, with its endogenous spatial interdependencies generating unpredictable dynamics in which intentional action often has undesirable unintended consequences.

2.2. Complexity and spatial analysis

In this section, we establish an epistemological basis for analyzing models of the space economy consistent with the socio-spatial dialectic. To establish such conditions, consider the example of regional competitiveness in capitalist economies. In line with our socio-spatial ontology, we initially assume a high dimensional spatiotemporal process governing the dynamics of economic agents interacting both within and between regionally disaggregated economies. Let there be a finite set of economic agents possessing different resource endowments and potentially following different decision-making rules. These individuals are assumed to be operating over a large, but finite and discrete number of time periods ($t = 1, \ldots, T$). For simplicity of exposition, these agents are aggregated into a finite and discrete set of heterogeneous regional economies ($i = 1, \ldots, N$). We restrict analysis to discrete time and space for two reasons. First, any dataset used for explanatory spatial analysis is collected for discrete spatial and temporal units, whose temporal and spatial resolution constrain empirical spatial analysis. Second, Newtonian calculus should not be seen as the holy grail for spatial analysis. In economics and physics, for example, calculus has been recently argued to be a limiting rather than an enabling mathematical technology (cf. Mirowski, 1984; Smolin, 1997).

Consider, then, the following general specification of multiregional dynamics. Let $Z_t = [Z_{1t}, \ldots, Z_{Nt}]$be a vector of observations hypothesized to be relevant to explaining regional economic competitiveness. This set of variables defines the state space at any given time, t.[6] Making the simplifying assumption that the process is a first order dynamical system, the potential set of spatiotemporal trajectories can be represented by a model of the system, consisting of a vector-valued function $F_\beta(\cdot)$ mapping the vector of variables Z_t onto itself:

$$Z_t = F_\beta(Z_{t-1}) = A_{t-1}Z_{t-1} \tag{1}$$

The vector function, parameterized by the set of potentially changeable parameters, β, thus defines the inter-regional economic interdependencies in terms of the $N \times N$ matrix A. The degree and complexity of inter-regional interaction depends on the responsiveness of these spatial interdependencies to changes in the state space.

This dynamic system describes a disequilibrium adjustment mechanism that produces a set of possible space-time trajectories, contingent upon the set of initial conditions and range of parameter values defining the nature and degree of spatial competition operating within and between regional economies. Mathematically, the global behavior of the interacting parts of such a system corresponds to the iterative steps of an algorithmic procedure that computes a solution to the system of interdependent equations. Employing the methodological norms of the Goodwin code, this dynamic system corresponds with a problem-solving model of behavior in which economic agents (or economic systems) apply the algorithm to compute an equilibrium solution (Goodwin, 1951; Smale, 1981). In equilibrium:

$$Z^* = F_\beta(Z^*) = A^*Z^* \tag{2a}$$

equivalently,

$$[I - A^*]Z^* = 0 \tag{2b}$$

This equilibrium corresponds to the fixed point of the recursive algorithm defined by Equation (1). As a corollary, this method of solution defines the model of decision-making driving the dynamic competitive interdependencies between regional economies. Assuming that such a dynamic system converges to a fixed point, the solution defined in Equation (2) describes the properties of the expected or equilibrium spatial configuration of prices, outputs and profits and the flow of commodities, capital and labor between regions.

Different specifications of A correspond to different levels in the Chomsky–Wolfram hierarchy. Lower levels can be examined using standard spatiotemporal analytical techniques, but higher levels exceed the capabilities of these methods. If A is linear, then the dynamics described by Equation (1) fall within levels one and two of the Chomsky–Wolfram scheme. The assumption of linear dependence between regional economies $(\partial A_t/\partial Z_t = 0)$has been quite general in spatiotemporal analysis in human geography. Whether in mathematical models of the space economy (cf. Elhorst, 2001), or in spatiotemporal statistical analysis (cf. Bennett, 1979), this implies constant or 'exogenous' spatial interdependencies. It is then possible to compute a solution to the dynamic system defined in Equation (1), and to establish its equilibrium properties.

6 Here, the very large set of variables potentially characterizing the state space has been partitioned into relevant and non-relevant variables. This partitioning depends on which aspects of the geographical world call for explanation, which in turn is contingent on the socio-spatial ontology of the investigator.

This case of exogenous spatial interdependencies describes a situation where the spatiality of the inter-regional economy is given *a priori*. A constant matrix A implies a Newtonian view of space (Sheppard, 2000) in which relative location is exogenous and unchanging.

In this linear case, analysis of the existence and stability of equilibria is straightforward. Stability conditions depend on well-known mathematical properties of A (Gandolfo, 1980). Generically, in order to examine possible disequilibrium dynamics, it is conventional to linearize around the equilibrium point using a Taylor's series expansion:

$$Z_t = \frac{\partial F_\beta(0)}{\partial Z_{t-1}} Z_{t-1} + \frac{1}{2} Z_{t-1}^T \frac{\partial^2 F_\beta(0)}{\partial Z_{t-1}^2} Z_{t-1} + \cdots + \tag{3a}$$

$$Z_t = \frac{\partial (A_{t-1} Z_{t-1})}{\partial Z_{t-1}} Z_{t-1} + \frac{1}{2} Z_{t-1}^T \frac{\partial^2 (A_{t-1} Z_{t-1})}{\partial Z_{t-1}^2} Z_{t-1} + \cdots + \tag{3b}$$

For exogenous spatial interdependencies, the first term in this expansion is a constant (A) and higher order terms are zero. Thus, local stability conditions can be used to explore the global evolution of the model in state space. If the equilibrium is determined to be locally stable, and if model parameters imply rapid convergence to equilibrium relative to the time interval between observations, then it is plausible to empirically test for the presence of this equilibrium using conventional spatial analysis. Under these conditions, therefore, a powerful suite of mathematical and statistical tools is already available to analyze the spatial characteristics of an observed sequence of map patterns.

If, in addition, A is block diagonal with no inter-regional interdependencies ($a_{ij,t} = 0, \forall i \neq j$), then spatial analysis can be dispensed with altogether. Each region can be analyzed in isolation, using time series analysis. If the equilibrium is stable and the speed of adjustment is 'fast' relative to changes in system parameters, the spatial equilibrium pattern is predicted by the set of intra-regional equilibria.

If A is block diagonal but non-linear ($\partial a_{ii,t}/\partial z_{it} \neq 0$), space can be dispensed with but time series analysis becomes far more complex. The state space can display out-of-equilibrium dynamics ranging from convergence to a unique equilibrium through to limit cycles and chaotic attractors. Levels one through four of the Chomsky–Wolfram hierarchy are possible, depending on the specification. In the absence of knowledge of the range of parameter values that are empirically plausible for such a system it is no longer justifiable to proceed 'as if' the system is either at equilibrium or will move rapidly towards it. For level four, time is an emergent property of the dynamical system rather than an exogenous coordinate system (Prigogine, 1996, p. 60). Spatial analysis adds nothing, as regions can be examined in isolation, and the empirical question is whether observed intra-regional dynamics are consistent with those predicted by the theoretical model specified as A.

Finally, consider cases where the theoretical model specifies non-linear spatial interdependence between regional economies ($\partial A_t/\partial Z_t \neq 0, \forall i \neq j$). In this case, space is no longer Newtonian, as the socio-spatial dialectic applies. There are variable or 'endogenous' spatial interdependencies. As a consequence, relative location as measured by the intensity of spatial interdependence (given by the off-diagonal elements of A) changes over time as a result of the dependence of A_t on Z_t. We cannot rely on local information to explore the global behavior of the system because the laws of motion change as the system moves in state space. That is, higher order terms in the Taylor series expansion are likely to be non-zero. As a consequence, using spatial analysis to examine an equilibrium point or its local neighborhood is not sufficient, but neither is time series analysis. Integrated spatiotemporal analysis becomes essential. This poses considerable challenges for empirical evaluation. Methods for spatial analysis presume that the system is at or near spatial equilibrium, and the vast majority of techniques for spatiotemporal analysis presume that spatial and temporal relationships are linear. Methods of coded dynamics may be adaptable for this case, but their feasibility remains to be investigated (Day and Pavlov, 2001; Brida et al., 2003; Plummer and Sheppard, 2007).

Integrated spatiotemporal analysis with an endogenous conceptualization of space and time is consistent with Leslie Curry's (1998) conception of the evolving space economy as a 'going concern'. The evolving economic landscape is characterized by dynamic interdependencies between agents and structures that also constitute those spatial economic systems. At any moment in time, these interdependencies are constrained by social and spatial structures. However, over time, structure and agency are mutually constitutive. We conjecture that the existence of such complex non-linear interdependencies, in which agency and structure are mediated by dynamics, increases the likelihood of persistent non-equilibrium space-time trajectories (Plummer, 1999). Furthermore, according to our interpretation of the Chomsky–Wolfram synthesis, this implies that problems exist which no economic agent can solve, even in principle. That is, the iterative procedures that define the disequilibrium adjustment mechanism in regionally interdependent economies can constitute absolutely undecidable and uncomputable problems (Punzo and Velupillai, 1996a). It can be concluded, therefore, that the existence of endogenous spatial interdependencies makes it much less likely that agents can utilize a decision-making algorithm, designed to model out-of-equilibrium rational economic decision-making, to compute a spatial equilibrium configuration. In short, the existence of endogenous inter-regional interactions, or the presence of the socio-spatial dialectic, calls into question approaches that prioritize equilibrium analysis to the neglect of out-of-equilibrium dynamics.

3. Method in geography and economics: from plurality to pluralism

In its early days, spatial economic analysis seemed fairly straightforward. Theories, borrowed from economics, were used to predict equilibrium locations or spatial interactions. Data were collected, and statistical analysis used to determine goodness of fit. The major challenge was developing statistical methods to incorporate spatial interdependence, where significant progress was made. The procedure was justified by a positivist, logical empiricist epistemology, and was precise. Predictions were deduced from theory, goodness of fit estimates made, and accurate predictions were taken as equivalent to adequate explanations.

We have argued above that the socio-spatial ontology characterizing contemporary economic geography calls into question the sufficiency of this quantitative methodology. Unless we have *a priori* reason or evidence to accept the proposition that space and time are Newtonian, or that the system is in spatial equilibrium, economic geographers should undertake integrated spatiotemporal analysis. This requires an explicit theorization of the dynamics of spatial interdependencies, and thereby the socio-spatial dialectic. To date, however, the overwhelming tendency is to treat spatial interdependencies, if at all, as exogenous. It is common in spatial statistical analysis, for example, to approximate A either with a binary matrix, based on nearest neighbor or distance relations between spatial units, or with the Euclidean distance between spatial units. Recent research in geographical economics takes the same tack, with all the limitations sketched in Section 2 (cf. Fingleton, 2000).

3.1. From analytical to computational thinking

Acknowledgement of the possibility that the capitalist space economy is a complex dynamical system, a socio-spatial dialectic, creates considerable difficulties for analysis. One response is to take these difficulties as insuperable; an impossibility theorem that would justify resorting to tractable models with all their overly simplistic assumptions. We contend that the opportunity costs of this strategy are too high; that these difficulties, and the philosophical as well as methodological challenges they pose, need to be faced head-on to avoid slipping into idealism (in empiricist clothing). Fortunately, across the social and natural sciences, an alternative research program has begun to emerge. It is now broadly understood that this requires a shift in the philosophical underpinnings of quantitative analysis. Complex systems cannot be reduced to general mathematical theorems, meaning that computational rather than logico-deductive approaches become necessary. As a consequence, computational intensive simulations are receiving considerable attention as a research tool. The same is increasingly the case for statistical analysis: computational methods such as bootstrapping and Monte Carlo Markov chain (MCMC) have allowed for distribution-free approaches to be developed for model estimation and testing.

We fully endorse the utility of such computational approaches, since restricting ourselves to cases where general mathematical or statistical theorems can be utilized is highly constraining, requiring heroic assumptions and axioms about the economy, and spatiotemporal relations, that undermine the plausibility of analysis. Restriction to analytically tractable models also runs the danger of reifying assumptions, initially adopted for heuristic convenience, as characteristics of the actual geographical world. However, quantitative geographers, and economists, have limited familiarity with statistical and mathematical techniques that could be used for integrated spatiotemporal analysis. Time and spatial interdependencies remain minority interests in cartography and geographical information science, and as yet there exists no sustained research program on spatiotemporal modeling and estimation in geography that extends beyond the fixed spatiotemporal relationships characterizing ARIMA and related forecasting models. Spatiotemporal analysis also poses some distinctive problems, such as categorizing spatiotemporal trajectories, which have received little attention anywhere. Yet promising avenues exist for economic geographers to explore, such as the mathematics of coded dynamics and related methods of ‘qualitative econometrics’ noted above.

3.2. Incorporating prior beliefs

Any plausible perspective on spatial analysis involves a combination of theory, observation and rules of inference to establish the degree of support for a theoretical model relative to competing ones. In practice, the degree of support for a theoretical model always depends on both the evidence in favor of it and our prior degree of belief in it. Given that the intersection between geography and economics includes research programs with distinct social ontologies and epistemologies, with passionate and widely differing support for the various alternatives, prior belief in one or the other ontology should be incorporated into our epistemological procedures. One approach that, at least in principle, explicitly incorporates the researcher's prior ontological commitment is Bayesian epistemology. Based upon the assumption that our uncertainty can be represented using the calculus of probabilities, Bayes' theorem takes into account how the prior degree of belief that investigators have in a particular ontology and theoretical model influences their *ex post* degree of belief in its performance. As a generalization, applying Bayes' theorem in this way makes it possible to get around the relativist claim that every model is just *ex post* story telling. Bayesian inference allows us to evaluate the degree of support that is provided for a theory by (theory-laden) empirical evidence, in conjunction with our subjective belief. In a sequential testing scenario, we can update our degree of belief as new information becomes available. From the opposite end of the philosophical spectrum, this approach also enables empirical researchers to steer away from the problematic empiricist claim that observation is a necessary and sufficient condition for knowledge.

3.3. Debating ontologies

Obviously, the higher an investigator's prior belief in a particular social ontology, the less likely it is that her belief can be challenged by empirical evidence. Thus, advancement of understanding requires that debate occur between different world-views. Within mainstream (including geographical) economics, diverse approaches receive some attention, with occasional prominent calls for methodological pluralism (Caldwell, 1982; Boylan and O'Gorman, 1995; Salanti and Screpanti, 1997), although the playing field where mainstream and heterodox approaches meet is profoundly uneven. Within Geography, a tendency toward a live-and-let live approach to the discipline's profound methodological diversity is more widespread, notwithstanding occasional calls for purism. We argue, however, that it is necessary to go beyond appreciation of a plurality of approaches, towards a critically engaged pluralism. To avoid the tendency for economic geographers and geographical economists to circle their respective wagons rather than engage in debate, it is necessary to find a forum for academic debate that allows distinct approaches to engage with one another without presuming either that one must eventually 'win' by dominating the other, or that anything goes. Helen Longino (2002) offers a vision that we would all benefit from pondering. She argues that a 'plurality of adequate and epistemically acceptable explanations or theories can be generated by a variety of different factors in any situation of inquiry' (p. 184). She dubs these 'local epistemologies', each of which is a situated understanding of the subject at hand, grounded in a set of methodological and substantive assumptions with respect to which the account is persuasive. She argues, in principle, that this plurality of explanations need not be reducible to a single, monistic account of the world. Indeed she expresses skepticism of the monistic accounts that have come to dominate disciplines and subdisciplines, arguing that they often do so by pushing aside competing explanations rather than persuading others of the validity of their arguments, a common practice in both geographical economics and economic geography.

To exemplify the possibility of a critically engaged pluralism, consider our example of accounting for regional macroeconomic dynamics (Plummer and Sheppard, 2006). In this case, there is a common explanandum, whereby some variables of interest may matter for both geographical economics and regional political economy, such as GRDP, regional employment, transport and communications costs, production technologies, sectoral mix, and regional income inequality. At the same time, each approach might well ask very different questions about these dynamics, stemming from their distinct socio-spatial ontologies. Geographical economists tend to be more interested in their dynamic variation relative to long-term and stable regional economic equilibria predicted by theory, on the basis of empirically observed transport costs and technologies, under assumptions of minimal profits net of fixed costs. Regional political economists may seek to model the political and economic mechanisms shaping economic growth, regional capital accumulation and profitability as an out-of-equilibrium process, in which capitalists' and workers' strategies (including investments in the transportation sector and infrastructure, relocation of investments, changes in production methods, wage bargaining strategies, and attempts to influence state intervention) have unpredictable and possible counter-productive effects.

Notwithstanding such differences in what aspects of regional dynamics call for explanation, it is possible to develop a methodology to estimate the relative probability that observed trajectories of these variables are consistent with one or the other theory (Plummer and Sheppard, 2006). This probability is Bayesian, depending on both the likelihood that the observed trajectory is consistent with predictions drawn from a theoretical model derived from each theory, and on the investigator's prior belief in each theory. Clearly this estimate would rarely result in consensus, as geographical economists and economic geographers are likely to begin with very different prior beliefs. Yet as long as participants are open-minded enough and willing to engage seriously with one another's beliefs, Bayesian epistemology can provide common ground for a debate over differing interpretations of regional economic dynamics, forcing us to recognize the degree to which theoretical beliefs and empirical performance matter in assessing the relative merits of the competing theories. Longino argues that knowledge production governed by critically engaged pluralism can lead to ongoing debate that never converges on a consensus understanding. The result, she argues, can be constantly changing knowledge, as an emergent attribute of ceaseless debate between different local epistemologies.[7] Yet such debate may provide more credible knowledge about the world than any artificial resolution into a single monist viewpoint.

We have argued against the current dualism between a quantitative, logical empiricist geographical economics, and a qualitative, post-positivist economic geography. Serious attention to the socio-spatial dialectic requires recognizing the possibility that the space economy is a complex non-linear dynamical system, for which conventional economic principles of micro-foundations, equilibrium-based methods, and associated tools of spatial analysis, are insufficient. At the same time, notwithstanding the richness of qualitative economic geography, it remains possible to productively pursue a quantitative approach to analyzing such systems. Such an approach is fraught with difficulties,

7 In this sense the evolution of knowledge is itself an example of a self-organizing complex dynamical system, capable of producing locally stable, but globally unstable knowledge structures.

since pertinent methods of integrated spatiotemporal mathematical and statistical analysis remain to be developed, but for us the opportunity costs of the alternative, i.e. resorting to one or another pole of the dualism, are too high. We do not suggest that our approach can eliminate debates between competing social-spatial ontologies and methodologies. Indeed we feel that the key to better science is more, constructive and reflexive, debate. Knowledge about the world is more credible when the various 'local epistemologies' are placed in rigorous engagement with one another. Clearly, geographical economists and economic geographers have some way to go before they can be seen as engaging in this kind of open-minded and equal exchange. Indeed such normative schemes are always difficult to realize. Yet, we remain committed to the proposition that quite different social ontologies at the intersection of economics and geography can communicate with one another across the intellectual divide. If there is merit to the arguments of this article, then the dream of a foolproof explanation of reality must be abandoned, and such intellectual debate must become a priority.

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