

Scale, causality, complexity and emergence: rethinking scale's ontological significance

Mitch Chapura

Scale remains a pivotal yet highly contentious concept in geography. I survey the lively discussions engaged in recently by many critical/radical geographers regarding the theoretical status of scale. While these discussions have been intellectually fruitful, I argue that much more needs to be said. Drawing from complex systems theory, I argue that scale should be understood as an ontological category essential to understanding causality. Revalorising Aristotle's four categories of cause – formal, final, material and efficient – from two centuries of positivist thinking facilitates this endeavour. Research on the relationship between university-based poultry scientists and the poultry industry illustrates the explanatory potential of poly-scalar analysis.

key words scale causality ontology Aristotle complex systems theory poultry industry

Department of Geography, University of Georgia, Athens, GA 30602, USA
email: mchapura@uga.edu

revised manuscript received 14 June 2009

Introduction

In the same river we both step and do not step, we are and are not. (Heraclitus; Fragment 14; quoted in Kaufmann and Baird 1994, 16)

Being has no coming-into-being and no destruction, for it is whole of limb, without motion, and without end. (Parmenides; Fragment 8; quoted in Kaufmann and Baird 1994, 22)

Reality is that which, when you stop believing in it, it doesn't go away. (Dick, 1995)

Throughout the ages, humans have grappled with the paradoxical characteristics of the beings, themselves included, populating and comprising the world. The coherence, yet ultimate impermanence, of 'things', as well as their simultaneous individuation and interconnectedness, have confounded and inspired minds seeking sense and wisdom. Two and a half millennia before the intellectual pretensions of 20th-century European philosophy, the doctrine of *shunyata*, the emptiness or incompleteness of all beings abstracted from the totality with which they inter-are, formed a centrepiece of Buddhist ontology

and ethics.¹ Even Plato's much maligned doctrine of the Forms² was, in part, an attempt (unsuccessful though it was) at reconciling the Eleatics' arguments, particularly those of Parmenides, that all of Being is perfect, complete, undifferentiated and unchanging,³ with Heraclitus viewing Being as constant creation and destruction. This paradox, contained within each and every 'thing' in our world, I believe it is fair to say, remains very much with us today, confounding our attempts at understanding the 'reality' (which, let us recall, derives from the Latin word for 'thing', *res*) in which we participate. Wittgenstein's (1949) (in)famous opening line to his *Tractatus Logico-Philosophicus* reminds us of this: 'The world is the totality of facts, not of things.' And while he largely rejected the logical positivism of this work in his later thought, the 'thing' remained deeply problematic to him. Far from adding clarity to the issue, the remarkable investigations of 20th-century physicists have replaced the ultimate 'solidity' of matter with a murky quantum realm that, in many respects, appears to have rediscovered sub-atomically the paradoxes intuited at the human scale by so many mystics and philosophers.

I will make no pretence here of attempting to resolve such issues. On the contrary, my hope is that by recognising the queerness, the 'emptiness' of all beings, especially those that seem the most ordinary, theories describing reality that may at first seem strange and counterintuitive might, ultimately, be seen as rather ordinary, after all. Specifically, I will address an issue from the discipline of geography that I feel has yet to be resolved satisfactorily: the ontological status of scale. Rethinking scale's ontology, in turn, will lead to significant implications for how we understand causality and agency.⁴ To aid in this task I will draw from an area of interdisciplinary scholarship commonly referred to as complex systems theory. Such scholarship provides a sophisticated way of thinking about scale, causality, ontology, and the relationship between the three. While some social theory has been informed by the concepts of complex systems theory (e.g. Foley 2003; Lansing 2003; Rihani 2002; Saperstein 1995; Simpson 2000; Smith and Stevens 1996), it appears that little explicit engagement with these ideas has been made by geographers, though Nathan Sayre's superb (2005) essay offers a promising start.

I find this absence ironic, given the centrality of scale to both complex systems theory and to geography. Nonetheless, recent discussions by critical geographers have provided thought-provoking analyses concerning the manner in which the ontology of scale should be understood (e.g. Brenner 2001; Marston 2000; Marston *et al.* 2005, Marston and Smith 2001; Purcell 2003; Sayre 2005; Swyngedouw 1997). The eloquence of such scholarship notwithstanding, I remain sympathetic to Sayre's observation that discussion of scale within critical geography 'has foundered on basic conceptual and methodological questions' (2005, 277). Indeed, the outright rejection of scale as an ontological category, proposed by Marston *et al.*, derives, at least in part, from the absence of 'agreement on what is meant by the term or how it should be operationalized' (Marston *et al.* 2005, 416). The need remains for a detailed and coherent theoretical framework for thinking about scale ontologically.⁵ On the following pages I offer what I hope will prove a useful contribution to the development of just such a framework. This project will demand a critical examination of causality, with a little help from Aristotle. Rethinking causality, in turn, will have significant implications for the manner in which we understand social processes and behaviours.

Scale

If we are to integrate successfully the pursuit of theory and the performance of empirical research, a more sophisticated theory of scale will alert us against exploring a number of wasteful cul-de-sacs. (Smith 1989, 169)

In recent years, the issue of scale in social theory has received much insightful and productive discussion by critical geographers (e.g. Brenner 2001; Marston 2000; Marston and Smith 2001; Purcell 2003; Sayre 2005; Smith 1992; Swyngedouw 1997). From this discussion, tentative agreement among many geographers seemed to have emerged, at least temporarily, regarding several interrelated ideas about the ontological nature of scale:

- 1 Scales (at least those most obviously relevant to social theorists) are socially produced and contested.⁶
- 2 Consequently, scales are not known *a priori*, but must instead be understood according to the processes producing them.
- 3 Because many causal processes operate across multiple scales, comprehending most social phenomena will demand a poly-scalar approach.

Neil Smith has argued,

There is nothing ontologically given about the traditional division between home and locality, urban and regional, national and global scales ... The differentiation of geographical scales establishes and is established through the geographical structure of social interactions. (1992, 73)

Eric Swyngedouw further develops this line of reasoning:

The ontological priority for a process-based view ... refuses to tackle global-local interplays in terms of a dialectic, an interaction or other mode of relating a priori defined things ... a typically reified way of grappling with scale, assigning motive, force, and action to pre-given geographical configurations and their interaction rather than to the struggles between individuals and social groups through whose actions scales and their *nested articulations* become produced as temporary standoffs in a perpetual transformative sociospatial power struggle ... The sociospatial structuring of the everyday does not in itself offer the local, the global, or any other scale as the preeminent site for analysis ... *The role of particular geographical scales, their articulation and interpenetration, has to be theorized.* (1997, 141, 143; emphasis added)

Neil Brenner summarises this process-driven, *a posteriori* view of scale well:

Traditional Euclidian, Cartesian and Westphalian notions of geographical scale as a fixed, bounded, self-enclosed and pre-given container are currently being superseded – at least within the parameters of critical geographical theory and research – by a highly productive emphasis on process, evolution, dynamism and sociopolitical contestation ... Each geographical scale is constituted through its historically evolving positionality within a larger relational grid of vertically ‘stretched’ and horizontally ‘dispersed’ sociospatial processes, relations and interdependencies. Consequently, the very intelligibility of each scalar articulation of a social process hinges crucially upon its embeddedness within dense webs of relations to other scales and spaces. (2001, 592, 606)

However, the recent exchanges between Marston *et al.* (2005), Jonas (2006), Collinge (2006), Hoefle (2006), Leitner and Miller (2007), Escobar (2007), and Jones *et al.* (2007), in which the ontological reality of scale is variously challenged and defended, reveals the problematic and contested status of scale’s ontology within contemporary geography. Of course, there is nothing inherently wrong with such a situation, as intellectual progress (assuming one believes in such a thing) so often emerges from challenges to established thought. It is in this spirit that I will attempt to provide a conceptually rigorous and empirically applicable theory of scale that might facilitate our ability to comprehend socio-spatial reality.

Sayre (2005) finds in the discipline of ecology a plethora of sophisticated thinking about scale from which geographers might productively draw. Among the insights he gleans from ecology is the idea that cross-scalar processes may prove ontologically non-reductive:

What happens at a small scale cannot necessarily be extrapolated up, and vice versa, because results are nonlinear across scales ... This poses a fundamental challenge to reductionist science and its faith in quantitative methods ... Expressed in Hegelian language, thresholds are where quantitative change becomes qualitative change. (2005, 280)

Though the phrase does not appear in his essay, Sayre is invoking the idea of ‘emergent properties’.⁷ This idea will prove critical in thinking about scale and, consequently, applying scalar thinking to understanding social processes. Before exploring this line of thought, however, a brief discussion of complex systems theory, sometimes

referred to as ‘complexity theory’, will serve to clarify the broader intellectual context within which ‘emergent properties’ become theoretically relevant.

Complexity

To speak of ‘non-linear’ science is like calling zoology the study of ‘non-elephant’ animals. (Stanislaw Ulam quoted in Campbell *et al.* 1985, 374)

The diversity of ideas, methods and empirical applications comprising complex systems theory make a thorough and detailed treatment of the subject beyond the scope of this essay.⁸ Instead, I will provide a brief conceptual overview and then proceed to focus upon the issues most relevant to my treatment of scale and causality. More of a meta-theory than a theory *per se*, ‘complex systems theory’ provides a schema and vocabulary for analysing processes that are both non-linear and non-chaotic. One may gain an intuitive sense of the difference between a linear system, a chaotic system and a complex system through prototypical examples of each.

The parabolic trajectory of a cannon ball in flight may be predicted from initial conditions (e.g. mass of ball, angle of cannon, force of explosion etc.) using relatively simple mathematical equations (simple, that is, for those of us living after the development of Newtonian mechanics). More generally, linear systems are those in which

all variables are uniquely and precisely defined and ... given values for all required parameters, the values of the variables at each instant in time are uniquely related to their values at an immediately previous instant. A rule connects successive values of any of the variables. (Saperstein 1995, 549)

The intellectual limitations of neoclassical economic theory and ‘social physics’ (e.g. Stewart 1956) demonstrate paradigmatically the problems encountered when trying to model social behaviours in a linear fashion. Brownian motion, the random movement of particles in a gaseous state, exemplifies a chaotic system. Predicting the movement of any given particle proves impossible and no discernible patterns of organisation emerge. For their part, while not chaotic in nature, complex systems nevertheless behave in a nonlinear and ‘path-dependent’ fashion. Perhaps the most obvious example of complexity is organic life itself (Saperstein 1995).

The nonlinearity of complex systems facilitates the transmission of information in a manner impossible in either linear or chaotic systems. This capacity, in turn, enables such systems to behave adaptively:

For food webs in rainforests to sustain biodiversity, innumerable specific flows of nutrients ... must persist in the absence of any form of centralized control. Similarly, an immune system also lacks centralized control and cannot settle into a permanent, fixed structure; instead it must be able to adapt to unknown invaders. Yet despite its protean nature, a person's immune system is coherent enough to distinguish oneself from anyone else. (Lansing 2003, 183)

Increasing awareness of the ubiquity of complex systems has inspired applications of complexity theory in such diverse fields as economics (e.g. Arthur 1999; Foley Duncan 2003; Rihani 2002; Simpson 2000), sociology (e.g. Smith and Stevens 1996), climatology (e.g. Rind 1999), neuroscience (e.g. Koch and Laurent 1999), biology (e.g. Weng *et al.* 1999), physical geography (e.g. Werner 1999), chemistry (e.g. Whitesides and Ismagilov 1999) and ecology (e.g. Gunderson and Holling 2002; Zimmer 1999). 'Common to all studies on complexity', observes Brian Arthur 'are systems with multiple elements adapting or reacting to the patterns these elements create' (1999, 107). Among the characteristics of complex systems most relevant for rethinking the relationships between causality and scale is the emergence of systemic properties irreducible to the system's individual components. To this we will now turn.

Emergence

Then the venerable Nagasena addressed the King.

'Your Majesty, how did you come here – on foot, or in a vehicle?'

'In a chariot.'

'Then tell me what is the chariot? Is the pole the chariot?'

'No, your Reverence.'

'Or the axle, wheels, frame, reins, yoke, spokes, or goad?'

'None of these things is the chariot.'

'Then all these separate parts taken together are the chariot?'

'No, your Reverence.'

'Then is the chariot something other than the separate parts?'

'No, your Reverence.'

'Then for all my asking, your Majesty, I can find no chariot? The chariot is a mere sound. What then is the chariot? Surely what your Majesty has said is false! There is no chariot!...' (From *Milindapanha*; quoted in Embree 1988, 105)⁹

Complex non-linear interactions may coalesce via processes of feedback into relatively autonomous structures displaying characteristics irreducible to the mere agglomeration of their constituents. It is this characteristic of complex systems that endows scale with ontological, as opposed to purely epistemological, significance: 'If we shift our attention from the causal forces at work on individual elements to the behavior of the system as a whole, global patterns of behavior may become apparent' (Lansing 2003, 185). As one's scale of observation (episteme) changes, provided the 'objects' in question are complex systems, one is not merely seeing the linear aggregation of constituent components, but, rather, emergent properties with unique ontological qualities. A biological cell, for example, is not simply an agglomeration of its constituent molecules, but exists only when specific configurations and processes occur. To be sure, the cell 'appears' to the observer at a particular scale resolution, but the cell itself 'emerges' ontologically at this scale of organisation as well. Mitochondria, a few ribosomes, and a nucleus etc. do not make a cell, any more than a random gathering of humans makes a business, a class, a state or a family. The organisational structure of the constituents proves just as critical, in some instances even more so, than the nature of the constituents themselves.

Of course, one may trace the emergence of novel properties in both scalar directions. The organelles comprising the aforementioned cell are themselves examples of complex systems, in this case comprised primarily of amino acids. As scale increases, cells may combine to form tissues,¹⁰ which in turn make up organs, which, as part of organ systems, constitute organisms, which interact with each other to form ecological communities. While the examples I have thus far employed to illustrate the phenomenon of emergence may strike the reader as quite intuitive, particularly if they have some background in ecology or biology,¹¹ it is worth emphasising that particular instances of ontological emergence

cannot be assumed *a priori*, but must instead be theorised and ultimately validated empirically.

Complex systems theory provides social theorists with a framework for comprehending the multi-scalar processes at work in human behaviour and organisation, for

understanding how cooperation, coalitions and networks of interaction emerge from individual behaviors and feed back to influence those behaviours. (Levin 2003, 3)

Human economic behaviour serves as a case in point. Unlike the reductionism of orthodox neoclassical theory, economics approached from a complex systems perspective may appreciate the often counterintuitive causal dynamics relating systems to their components.

Complex systems paradoxically tend to exhibit features that are in many respects the opposite of the tendencies of their components. The resolute pursuit of profit by individual capitalists, for example, may lead to a falling average rate of profit in the system as a whole. (Foley 2003, 8)

Emerging from such complex interactions will be both formal and informal social institutions that, though historically contingent, are nevertheless real. Economic class, for instance, may be understood not only as a theoretical construct, but as an emergent property of capitalist relations of production.¹²

Lansing's work on Balinese water management systems underscores the fact that 'seeing' many important systems of human organisation will require relaxing preconceptions of the forms such organisations might take:

[An] important development is the revelation, foreshadowed by theoretical work on complex adaptive systems, that social systems can emerge from the bottom up as a result of feedback processes linking social actors to their environment. Such institutions might look very different from those that social scientists normally study; they might even be invisible ... In the Balinese case, global control of terrace ecology emerges as local actors strike a balance between two opposing constraints: water stress from inadequate irrigation flow and damage from rice pests such as rats and insects. (Lansing 2003, 198–99)

Among the more theoretically significant implications of complex systems theory is the existence of causal relations operating bi-directionally between different scales of organisation.

[E]mergent properties are thought to be autonomous to some degree of their smaller-scale composite

processes and even to have the capability of influencing events at lower levels of the organic hierarchy. (Ulanowicz 1990)

Given the rhetorical baggage associated with the term 'hierarchy', such as its historical association with patriarchy and its connotation of a system of rigidly ordered ranks in which higher ranks control lesser ranks (e.g. Gibson-Graham 1996), I prefer Gunderson and Holling's (2002) term 'panarchy'. Greek for 'rule of all', the term 'panarchy' underscores the notion that causal or explanatory priority cannot be assumed *a priori* for different panarchical levels of organisation. In other words, one should not assume that one scale is necessarily more important than another.

Returning to economics for an illustration of panarchical systems, we may recognise that the behaviour of capitalist firms will be constrained by the political-economic milieu in which they operate. Kauffmann argues,

the modern corporation is a collectively self-sustaining structure of roles and obligations that 'lives' in an economic world, exchanges signals and stuffs, and survives or dies in ways at least loosely analogous to those of *E. coli* ... Both *E. coli* and IBM coevolve in their respective worlds. (1995, 300)

In addition to the sheer rhetorical appeal of comparing modern corporations to a strain of faecal bacteria complicit in countless cases of deadly food poisoning, Kauffmann's description captures the panarchical nature of economic processes. A corporation is comprised of numerous human actors whose roles and behaviour are conditioned by the company's structure and goals, which, in turn, are constrained by the economic system in which it participates.

From scale to causality: revalorising Aristotle

It seems quite fair, at this point, to consider more critically a number of terms that have been employed thus far to describe the cross-scalar relationships between different panarchical levels. 'Constraining', 'conditioning', 'influencing' etc. imply some form of causality, yet may leave one to wonder just what sort of causality this might be. Such an inter-scalar causality seems quite different (at least to this author) from that which occurs, for example, when one billiard ball strikes another,

or when a rocket is launched into space. As Ulanowicz (1990) argues compellingly, comprehending the differences between linear and complex systems requires the expansion of causal models beyond those employed so successfully in the scientific study of linear systems. Fortunately, Ulanowicz reminds us, we need not begin this project from scratch. Aristotle has already done much of the work for us.

In his *Physics*, Aristotle describes four types of causality which may be at play in any given event: material, efficient, formal and final. These are distinguished as follows.

In the familiar example of the building of a house the material cause exists in the mortar, lumber and other supplies going into the structure. The labourers and craftsman constitute the efficient cause, while the blueprints, or *bauplan*, is cited as the formal cause. Finally, the need for housing on the part of eventual occupants is usually taken as the final cause of building the house (Ulanowicz 1990, 43).

Ulanowicz argues that the success of Newtonian physics and the consequent adoption of mechanism as a model for all of science have left us with 'a symbiosis of reductionism and positivism' in which 'mechanical causes are considered efficient in nature, and the notions of formal and final causalities have been left to atrophy' (Ulanowicz 1990, 43). Formal and final cause, however, provide means of understanding the cross-scalar relationships between levels of a panarchy.

Systemic structures – 'loops' in Ulanowicz's cybernetic terminology – may emerge ontologically from the behaviours of their components which possess the ability to influence the behaviour and constitution of those very same components. As such an 'autocatalytic feedback loop' emerges, 'what might have begun as a chance configuration of composite mechanisms now possesses attributes proper only to the whole structure' (1990, 43). Eventually, a situation may arise in which the 'structure of the system endures beyond the replacement of all its constituents, and where the overall configuration has exerted an active influence upon what those eventual replacements could be' (1990, 45). The causal effects of such a system upon its constituents, then, may be understood to be formal in nature.

Most readers, I suspect, will find this description of formal cause to be relatively intuitive and easy to comprehend. But what of final cause? Ulanowicz's rethinking of teleology in terms of the

dynamic interplay between scales in a hierarchy (panarchy) proves the most ingenious aspect of his thesis:

When a feedback loop is apparent at the focal level of the hierarchy, one perceives it as a formal cause. When the autocatalytic loop is acting at a fine scale, it will appear to the observer, along with manifold other agents, in the guise of an efficient cause. Conversely, when the focal system is but part of at least one larger cybernetic loop, that unseen autocatalytic behavior will impress itself on the object system via the boundary conditions. That is, its influence will be perceived at the focal level as *final* in nature. (Ulanowicz 1990, 45; emphasis in original)

Teleological behaviour is thus understood to emerge in a panarchy from the influence of one system (playing the role of formal cause) upon its components.

In this cross-scalar interplay of formal and final cause, agency, too, appears as a poly-scalar, relational phenomenon. Deriving from the Latin *agere* (to do), agency should be distinguished from sentience or intentionality.¹³ Instead, agency may more broadly be understood as 'acting as cause', as a recent headline in the *San Francisco Chronicle* illustrates, 'AIDS as an Agent of Reform?' (Kilduff 2004). If causality can operate across multiple scales, agency can as well. As with causality, we should expect our perception of agency to be inextricably tied to the resolution at which we observe a panarchic system.

The immune system illustrates this point well. A variety of specialised cells exist to find and destroy or neutralise pathogens that have entered the body. Observed at the cellular scale, the behaviour of macrophages, neutrophils, and eosinophils etc. appears quite purposeful. They 'discriminate' between different pathogens and 'seek out' those which they may 'attack' and will even alter their 'attack strategy' so as to most effectively neutralise the pathogen. Such behaviour suggests agency, yet I suspect I am not alone in having misgivings (due to my lingering anthropocentric bias?) about attributing agency to individual immune cells.

Changing the scale of observation will improve our understanding of the mechanisms involved in this behaviour, but will not resolve the search for agency (so long as we seek to locate agency at only one scale). At a more refined scale we may see the roles of molecular signals and markers. A coarser resolution allows us to see individual cellular

behaviour as but part of a highly organised and coherent total immune response. Still, the scale at which we are witnessing agency remains unclear. We might expand our scale once again to the level of the organism. For the sake of argument, let us assume that 'I' am the organism in question.

Without the proper functioning of my immune system I could not exist. Yet I am not consciously aware of its actions, nor do I control the billions of cells constantly at work. In all honesty, I am quite thankful that I am not responsible for directing my immune system, as I would hardly know the details of what it should do. Countless viruses, bacteria and other pathogens are constantly entering my body, yet I remain blissfully unaware of this 'trespass' thanks to the 'awareness' of my immune system. On the occasions that I do become aware of such pathogens, this awareness is only indirect, via the symptoms of illness.

Of course 'I' can influence my immune system, for better or for worse, by eating a healthy diet, taking medications etc. Still, my ability to causally influence my immune system, i.e. my agency, remains incomplete and indirect. Acting to influence my immune system as a whole is not equivalent to directing the complex operations of its components' seemingly purposeful behaviours. Moreover, my actions cannot be understood in isolation from my semiotic and material milieux. Let us imagine, for example, that, experiencing symptoms of illness, I consume an antibiotic. The very possibility of this action results from my participation in socio-material systems larger than 'me'. Perhaps most saliently, without the narratives, practices and technologies of contemporary biomedicine, including the 'germ theory of illness' and the consequent creation of ingestible antibacterial substances, the dissemination of knowledge through medical educational institutions, and the production and sale of my specific antibiotic by a pharmaceutical corporation, my actions would be both unintelligible and impossible.

Where, then, does my immune system's agency reside?¹⁴ If we attempt to answer this question with an *a priori* presumption of 'ontological flatness', what might our answer look like? I expect that we would either fixate on one scale, thereby producing a reductionist narrative, or arbitrarily jump from one scale to another, misidentifying causal relations and ultimately producing a kind of 'chaotic conception' (Sayer 1984). In both cases our analyses would only recognise material and efficient causality. Inter-

scalar causal relationships would remain unrecognised. In contrast, a poly-scalar analysis may potentially prove both more complete and more coherent. Insofar as my immune system is both composite and component, the agency in question is itself a poly-scalar phenomenon.

Despite the inevitable anthropocentric perspective permeating most of our lives, social scientists should avoid the facile temptation of treating humans as the *a-toms*¹⁵ of social theory. This is not to suggest that we should embrace reductionistic anti-humanist structuralisms, be they of the socio-biological, economic or semiotic varieties. Causality and agency should, instead, be recognised as poly-scalar phenomena.¹⁶ Not all systems (or actor-networks), however, will necessarily give rise to emergent properties. Discerning which do and which do not will require empirical inquiry. For those which do, scalar relationships will be relevant concerns. As a way of exploring the practical applications of such a poly-scalar approach, I now turn to a brief case study.

An illustration

Elsewhere (Chapura 2007) I argue that a poly-scalar mode of analysis facilitates our understanding of the functional relationship between university-based poultry science researchers and the US poultry industry, observed by numerous scholars (e.g. Boyd 2001; Heffernan 1998; Lewontin 1998; McMichael 1998; Watts 2000), whereby the academic practices and discourses of scientists are 'translated'¹⁷ by agribusiness into means of maximising exchange value. Because it is not *prima facie* obvious why the interests of corporate executives and shareholders should necessarily be the same as those of research scientists, a causal explanation for this neat articulation is called for. Following the work of Ulanowicz (1990), who applied a complex systems approach to ecosystem development, I focus upon the impact of *selection* on a system's components. I expect that some readers will be uncomfortable with the language and reasoning I employ in the analysis to follow. I am not asserting that competitive selection will prove a salient feature of all social systems. I also wish to stress that my approach should not be conflated with sociobiology, nor do I intend to imply that the process of selection in a social system is identical to that of a biological system. Ecosystem development involves the selection of genetic patterns based upon the

reproductive/survival fitness of the phenotypic expressions of these patterns, within specific biophysical contexts. In contrast, selection in social systems does not, in most instances, impact genes (obvious exceptions include eugenics and genocide). Instead, the selection that is most common in human social systems involves the selection of practices and narratives.

Given the system of academic promotion in the US university system, often referred to as 'publish or perish', the acquisition of research funding by faculty (and aspiring faculty) is critical to career advancement. Much of the money available to researchers in the field of poultry science comes from sources with interests other than 'the general pursuit of scientific knowledge'. Specifically, such interests prove to be financial.¹⁸ Consequently, poultry research with certain aims (e.g. increasing the economic efficiency of production) are more likely to receive funding than others (e.g. minimising the suffering of the chickens or mitigating ecological externalities associated with production and processing that are not specifically prohibited by law). Thereby, certain actors (private companies associated with the poultry industry) are able to employ indirect, but nevertheless real, financial pressure to influence the research projects pursued by university-based scientists towards goals perceived to be in their own financial interest. Interviews with faculty members at the University of Georgia Department of Poultry Science confirmed that one's record of acquiring extramural funding is an important criterion, second only to peer reviewed publication success, in the determination of professional promotion, including tenure. Furthermore, because novel research greatly facilitates the potential for journal publication, success in obtaining grants will indirectly contribute to publication success, which is the most important promotion criterion.¹⁹

In the language of systems theory, aspiring faculty who are unable to obtain sufficient research funding will not be 'selected' for continued participation in the system, that is, the department. Insofar as there exist more aspirants than tenured faculty positions, competition for research funding will ensue.²⁰ Given a greater demand for research funds than are available, those unable to successfully compete for funding will not 'survive'. Those who design research projects that appeal to the priorities of funders will be selected for continued participation within the system. Those who do not will be selected out of the system.

An important point I wish to emphasise is that this selection pressure is largely independent of the individual researcher's priorities themselves. By this I mean that aspiring faculty with research priorities that are inconsistent with those of funders will tend to be 'selected out', unless they are willing and able to change their own priorities. The corollary to this is that those aspiring faculty whose research priorities are consistent with those of funders will be more likely to be 'selected in'. Those who 'survive' without having to alter their research priorities or those who did so unconsciously, might not even be aware that such a selection dynamic exists. This is because the selection dynamic is a characteristic of the system, and is not apparent if one were to take an atomistic approach, focusing exclusively on aspiring faculty as independent individuals. A shifting of scale is required.

This explication is analogous to Marx's (1976) analysis of overproduction in a capitalist economy. No individual capitalist intends to overproduce, nor does she even necessarily perceive that systemic overproduction is occurring, at least until prices fall. Overproduction results from the systemic competition exerted on all capitalists within an industry to maximise their appropriation of surplus value. A capitalist who recognises the systemic overproduction and attempts to change her individual behaviour by, for example, raising wages in order to create more effective demand, will be 'selected out of existence'. The atomistic approach of orthodox neoclassical theory, by way of contrast, has a difficult time accounting for such 'market failures', because it acknowledges only one scale of economic reality, that of individual human agents.

It is almost impossible, I would argue, to even discuss intelligibly the activities of poultry scientists without at least implicitly referencing multiple scales of organisation. The genetic researcher seeking to improve growth rate or to increase the ratio of white to dark meat manipulates poultry genes, yet gene selection by the researcher is ultimately dependent upon the genes' phenotypic expression at the scale of the individual chicken. Furthermore, because the process does not (as of yet) involve techniques of directly manipulating genetic information at the molecular level, such as those used to produce GMO and transgenic plants, breeding of individual chickens must still occur in order for selection of favoured traits to occur.

Frequently the poultry scientist does not decide independently which phenotypic traits to develop. This decision can be traced to the source of funding enabling the scientist to engage in the research. Of course, businesses that provide research funding, whether directly or indirectly, do not exist in a vacuum either. They, too, are subject to the selective pressures of the economic markets in which they participate. I am not arguing that the dynamic I have described is the *only* reason for the neat articulation between research and capital. This dynamic is worthy of focus, however, both because it is not intuitively obvious and because it has not received attention in the geographic literature. In addition to the significance of hegemonic narratives, which I discuss elsewhere (Chapura 2007), there remains the history of crony relations between politicians and capital, resulting in the subversion of public tax-dollars for the benefit of private interests. One faculty member pointed out in the course of our interview that ultimately the public is the largest financier of poultry science research, funding the material infrastructure (buildings, laboratories, etc.) and the faculty salaries. Private companies are thus able to 'piggy back' on this indirect corporate welfare, paying only for the cost of the research itself.

From analysis to transformation

As I hope that the example of poultry science research has illustrated, in order to understand human social systems we must recognise that agency is not the sovereign realm of human subjectivity. Instead, agency is dispersed, in some cases, dispersed across scales. In the example provided, the 'downward' causality exerted by the *systemic* competitive grant-seeking behaviour of the network of researchers ('formal cause' in Aristotelian terms) is particularly powerful, influencing its constituents, i.e. the researchers, by influencing the *telos* ('final cause' in Aristotelian terms) of their research. An explanation for the faculty members' research agendas based solely upon their individual agency proves incomplete. One simply cannot locate the research *telos* by looking exclusively at the individual researcher, any more than one can understand this *telos* by considering only the needs of capital.

In a recent essay, James McCarthy poses the question, 'If scale is produced or constructed, then

the questions immediately arise: who produces scale, how, and for what purposes?' (2005, 733). The problem with this question is that it retains an implicit assumption of intentionality. Sometimes scale is produced intentionally. Sometimes, however, scale is produced by everyone and no one, without intention or even awareness. In the context of university-based poultry science research, the highly competitive grant-seeking behaviour of researchers emerges from the significant undersupply of (non-industry) research funding and the importance of acquiring funding for promotion. This emergent dynamic enables capital to influence research objectives. Researchers' agency to determine the goals of the research projects in which they engage is constrained by the macroscopic context in which the individual faculty members operate, and which they co-create. And while private companies may be effectively exploiting this situation, they did not create it.

Recognising the causal dynamics of the complex systems emerging from social interactions not only allows us to better understand the social world, but also provides insight into how to *transform* the social world. The success of the 'animal rights' group People for the Ethical Treatment of Animals (PETA) in prompting a focus by the poultry industry on issues of animal welfare during the last several years illustrates this potential. During the course of my interviews, several faculty members stated that within approximately the last five years the poultry industry has become increasingly interested in funding research related to issues of animal welfare. At first, this seemed to contradict my assumptions. Why would industry be interested in funding such research? A bit of subsequent investigation revealed an explanation that illustrates how contesting narratives may reverberate across articulating poly-scalar systems and ultimately translate into changing practices.

In 1997, PETA began an aggressive public campaign designed to pressure the world's largest 'fast-food' chain, McDonald's, into improving the welfare of the animals who would become its 'Happy Meals', 'McNuggets' and 'Big Macs'. Daniel Zwerdling describes the ultimately successful strategy:

PETA protesters were passing out brightly colored cardboard boxes to customers heading for McDonald's. If you glanced quickly, the boxes looked like a McDonald's Happy Meal promotion: big cheerful letters, a drawing of the grinning clown; but then you looked

closely, it read 'Unhappy meal' and Ronald McDonald was swinging an ax. When you opened the box, you didn't find a hamburger, there were plastic animals painted with fake blood....

The way PETA saw it, McDonald's was vulnerable. Consumers over in Europe were all fired up about animal welfare; they were getting their governments to pass laws that told food companies exactly how to raise their animals. Industry officials back in this country warned that the movement was heading here. So PETA figured that McDonald's executives had a choice: They could seem to drag their feet on animal welfare, PETA would keep harassing them, and eventually lawmakers might order industry to change. Or McDonald's could lead the campaign for animal welfare and they'd impress consumers as 'The Company that cares,' and maybe they'd head off legislation. Around three years after PETA launched its protests, McDonald's became the first major food company to tell farmers, 'You have to treat animals more humanely.' (2002, np)

McDonald's developed a set of welfare guidelines for layers (hens) prohibiting previously standard industry practices such as debeaking and forced molting, a practice of withholding food from hens for up to 2 weeks in order to temporarily stress their bodies into increased egg production. Effective from 1 January 2002, McDonald's refused to purchase eggs from suppliers who failed to follow these guidelines (Zwerdling 2002). The issuance of these guidelines marked a major paradigm shift for poultry producers. Because poultry are exempt from the federal Animal Welfare Act and Humane Methods of Slaughter Act, poultry welfare had never before been a concern of industry. And because McDonald's is the largest single purchaser of eggs in the US, its decision reverberated throughout the industry.

While the poultry industry itself has never shown any interest in trying to satisfy 'animal rights' groups, McDonald's, with its extraordinary purchasing power, commands attention. PETA succeeded in creating the perception among enough of McDonald's corporate management that *de facto* conditions had changed in the US 'fast-food' market, in this case, that consumers were increasingly concerned with the (mis)treatment of food animals, as well as instilling a fear that *de jure* conditions might change if no preemptive actions were taken by the corporation to reassure US legislators that no governmental regulation of poultry welfare was needed. Once those McDonald's executives with power to alter the behaviour of the corporation's

supply chains were convinced that changes would prove beneficial to their corporation's long-term success, changes were made.

McDonald's changing behaviour significantly altered the behaviour of the egg-supplying companies contracted by them. 'Ripple effects' occurred throughout the entire US 'fast-food' economy, as Wendy's and Burger King responded by implementing (and publicising) similar animal-welfare regulations. Poultry companies, recognising a changing economic landscape, one in which optimising product price and quality were no longer the market's only relevant criteria, had to rethink their production practices if they were to avoid being 'selected out' of the poultry industry. In Aristotelian language, their *telos* changed, however slightly. This ultimately translated into an increasing willingness to fund academic research on poultry welfare issues. Most poultry companies and industry trade organisations remain hostile to animal welfare organisations, but the campaigners at PETA recognised that they did not need to sway individual companies directly in order to change their behaviour. Instead, PETA succeeded by altering the economic context in which poultry companies operated. The efficacy of PETA's strategy illustrates the importance of choosing the appropriate scale at which to focus one's actions in order to most effectively and efficiently induce social change.

James Glassman has argued,

structure is merely the agency of large collectivities of people ... The only issues are whether, where and how some subset of a larger collectivity can gain enough support in its actions to substantially alter relatively long-standing features of the social relations that constitute 'the structure'. (2003, 266)

I hope that my discussion has convinced the reader that this is not, in fact, the case. Instead, structures emerge from the complex interactions of multiple actors and may reciprocally influence the behaviours of these actors. Structures are poly-scalar phenomena, not reducible merely to the summation of their constituent parts. I do not doubt that Glassman's idea of collective agency is indeed relevant to many important aspects of social existence. In fact, I would argue that it may facilitate our understanding of the fast-food consumers PETA sought to influence and McDonald's sought to assuage. It is not sufficient, however, to comprehend many of the causal forces at play in human social existence. The poly-scalar approach I have proposed and illustrated will surely add to this endeavour.

Notes

- 1 An excerpt from Buddhist monk Thich Nhat Hanh's essay, *The Heart of Understanding*, illustrates this idea: 'If you are a poet, you will see clearly that there is a cloud floating in this sheet of paper. Without a cloud, there will be no rain; without trees, we cannot make paper ... So we can say that the cloud and the paper inter-are ... If we look into this sheet of paper even more deeply, we can see the sunshine in it. If the sunshine is not there, the forest cannot grow ... And if we continue to look, we can see the logger who cut the tree and brought it to the mill to be transformed into paper. And we see the wheat ... and the logger's mother and father ... Looking even more deeply, we can see we are in it too ... Everything co-exists with the sheet of paper' (1988, 3, 4).
- 2 'Plato was convinced by Heraclitus that in this sensible world all things are in flux and, if this sensible world is all there is, no rational discourse is possible. This led Plato to the conclusion that there must be another world beyond the world of sense experience – a realm utterly free from change, motion, and time' (Kaufmann and Baird 1994, 15).
- 3 Zeno of Elea, another of the Eleatics, constructed a series of paradoxes designed to prove that all motion and change was illusory. Perhaps the most famous of these paradoxes, 'Zeno's Arrow' purports to demonstrate the logical impossibility of an arrow in flight ever actually moving.
- 4 My focus upon causality in this discussion of ontology reflects my affirmation of 'critical realism' (e.g. Sayer 1984). Readers committed to 'non-realist' epistemologies/ontologies may find this focus to be misguided or irrelevant. Regrettably, a defence of 'critical realism' is far beyond the scope of this essay.
- 5 One might reasonably ask why we should worry about scalar ontology at all. Why not adopt the 'flat ontology' advocated by Marston *et al.* (2005)? The most compelling reason, for this geographer, is that if scale is, in fact, ontologically real, analyses that reject, *a priori*, the existence of inter-scalar dynamics, i.e. analyses that are ontologically flat, risk missing many of the most relevant processes and relationships at play in the reality they seek to describe and understand. This may take the form of arbitrarily privileging one scale to the exclusion of others, or uncritically (and unconsciously) jumping from one scale to another. I am *not* arguing that scale will necessarily always be ontologically relevant, but rather, that it often will be. We should, therefore, neither assume nor reject the ontological relevance of scale *a priori*. Secondly, a consensus as to the meaning of 'scale', regardless of whether or not there is agreement about its ontological existence or explanatory salience, would eliminate a tremendous amount of unproductive equivocation among geographers.
- 6 This can be interpreted as a statement about both ontology and epistemology. While my focus in this essay will be on scalar ontology, this should not be interpreted as an attempt to subordinate research on scalar epistemologies (in practice, of course, the two can never be completely separated). Scholarship on the uses and effects of scalar narratives (e.g. Kurtz 2002) remains as important as scholarship on scalar ontologies.
- 7 Corning (2002) provides a superb overview of this idea's history.
- 8 The diversity of views among complex systems theorists is such that I suspect many would disagree with aspects of my analysis and application. Conversely, I consider much complex systems research, ironically, to be attached to reductionist ontology and epistemology (e.g. Wolfram 2002). Attempting to explain reality with computer programs instead of equations does not necessarily make a scientific paradigm any less reductionistic, no matter how powerful the computer! Moreover, applications of complexity theory to human social systems have often suffered from a tendency to fetishise computer models at the expense of empirical observations and an inadequate attention to and appreciation of the roles played by discourse in shaping both social structures and humans themselves. Thus, while this essay focuses on potential ways in which complex systems theory can contribute to the ideas and research efforts of geographers, this does not mean that the reverse is not also true.
- 9 The Theravadan Buddhist text, *Milindapanha*, relates a dialogue between the monk Nagasena and the Greek king, Milinda, who ruled portions of Northwest India during the 2nd century BCE. One might imagine a contemporary dialogue, more immediately related to economic geography, as follows:
Then the heretical Geographer addressed the CEO.
'Mr. Walton, what is this trans-national corporation that you founded?'
'Wal-Mart,' replied the CEO.
'Then tell me, what is Wal-Mart? Are you Wal-Mart?'
'No, your Irreverence.'
'Or the shareholders, or the board of directors, or the check-out clerks?'
'No your Irreverence, none of these is Wal-Mart.'
'Then the children in the Chinese factories, or the objects they produce, or the retail stores themselves, or the customers who patronize them?'
'No, your Irreverence.'
'Then all these separate parts taken together are Wal-Mart?'
'No, your Irreverence.'
'Then is Wal-Mart something other than the separate parts?'

'No, your Irreverence.'

'Then for all my asking, your Highness, I can find no Wal-Mart....'

- 10 Heart tissues grown in the lab from stem cells illustrate this quite vividly by pulsing rhythmically in unison as if 'beating'.
- 11 Some readers may consider the use of biological examples to illustrate a concept I will apply to human social relations to be problematic. Given the reductionistic functionalism of sociobiology (e.g. Wilson 1975), this is understandable. I hope that as my arguments unfold it will become abundantly clear that I am *not* offering a new version of sociobiology and that my approach is fundamentally opposed to both reductionism and functionalism.
- 12 Although he does not engage explicitly with complex systems theory or relate his discussion directly to scalar ontology, Sayer makes similar points in his lucid discussion of 'stratification and emergent powers' (1984, 108–11).
- 13 Readers familiar with Bruno Latour's Actor-Network-Theory may appreciate the similarities between the definition of agency I am proposing and Latour's notion of 'actancy' (e.g. Latour 2005). I have argued elsewhere (Chapura 2007) that Actor-Network-Theory's primary weakness derives from its rejection of scale as an explanatorily relevant concept, and can, therefore, benefit by acknowledging the ontological reality of scale and inter-scalar processes.
- 14 Hofstadter and Dennett (1981) creatively demonstrate that the best answer to such a search for agency (at only one scale) is 'mu' (the sound an infant makes), which in the Zen tradition implies that the question needs to be 'unasked' because its present formulation precludes the possibility of any satisfactory answer.
- 15 'A-tom' is Greek for 'not-divisible'.
- 16 Smith and Stevens (1996) demonstrate the explanatory potential of just such an expansive multi-scalar analysis. By integrating cognitive science, developmental psychology and sociology, this fascinating work explores the causal linkages between neuro-chemical pathways, the formation of infant-parent bonds and community-level processes of socialisation, without arbitrarily privileging one organisational scale over another.
- 17 'Translation refers to the processes of negotiation, representation and displacement which establish relations between actors, entities and places' (Murdock 1998, 362).
- 18 By focusing upon economic forces I do not intend to imply any sort of economic determinism, whether the 'cultural materialism' of anthropologist Marvin Harris (1979) or the 'base-structure-superstructure' model proffered in some of Marx's own writings (e.g. 1904, 11).
- 19 I have no reason to believe that the situation is different in other agricultural science departments across the US, especially those for which corporations and industry trade associations provide a substantial share of extramural research funding. I have employed the example of university-based poultry science research to illustrate my theoretical arguments concerning the relevance of scale to understanding social phenomena because the poultry industry has been an area of my empirical research. I would expect that academic disciplines/departments with negligible industry funding, or those in which obtaining extramural funding carries little weight in promotion decisions, would display different dynamics guiding the selection of research topics.
- 20 Of course, the same criteria apply for obtaining a tenure-track professorship in the first place.

References

- Arthur B W 1999 Complexity and the economy *Science* 284 107–9
- Boyd W 2001 Making meat: science, technology, and American poultry production *Technology and Culture* 42 631–64
- Brenner N 2001 The limits to scale? Methodological reflections on scalar structuration *Progress in Human Geography* 25 591–614
- Campbell D, Crutchfield J, Farmer J and Jen E 1985 Experimental mathematics: the role of computation in nonlinear science *Communications of the Association for Computing Machinery* 28 374–84
- Chapura M 2007 Actor-networks, economic imperatives, and the heterogeneous geography of the contemporary poultry industry M A Thesis University of Georgia
- Collinge C 2006 Flat ontology and the deconstruction of scale: a response to Marston, Jones and Woodward *Transactions of the Institute of British Geographers* 31 244–51
- Corning P A 2002 The re-emergence of 'emergence': a venerable concept in search of a theory *Complexity* 7 18–30
- Dick P K 1995 How to build a universe that doesn't fall apart two days later in Dick P K ed *The shifting realities of Philip K. Dick: selected literary and philosophical writings* Pantheon, New York 259–80
- Embree A T 1988 *Sources of Indian tradition* Columbia University Press, New York
- Escobar A 2007 The 'ontological turn' in social theory: a commentary on 'human geography without scale', by Sallie Marston, John Paul Jones II and Keith Woodward *Transactions of the Institute of British Geographers* 32 106–11
- Foley D K 2003 *Unholy trinity: labor, capital, and land in the new economy* Routledge, New York
- Gibson-Graham J K 1996 *The end of capitalism (as we knew it): a feminist critique of political economy* Blackwell, Cambridge
- Glassman J 2003 Structural power, agency, and national liberation: the case of East Timor *Transactions of the Institute of British Geographers* 28 264–80
- Gunderson L H and Holling C S eds 2002 *Panarchy: understanding transformations in human and natural systems* Island Press, Washington DC

- Harris M** 1979 *Cultural materialism: the struggle for a science of culture* Random House, New York
- Heffernan W D** 1998 Agriculture and monopoly capital *Monthly Review* 50 46–59
- Hoeffle S W** 2006 Eliminating scale and killing the goose that laid the golden egg? *Transactions of the Institute of British Geographers* 31 238–43
- Hofstadter D R and Dennett D C** 1981 *The mind's I: fantasies and reflections on self and soul* Basic Books, New York
- Jonas A E G** 2006 Pro scale: further reflections on the 'scale debate' in human geography *Transactions of the Institute of British Geographers* 31 399–406
- Jones J P, Woodward K and Marston S A** 2007 Situating flatness *Transactions of the Institute of British Geographers* 32 264–76
- Kauffman S** 1995 *At home in the universe: the search for laws of self-organization and complexity* Oxford University Press, New York
- Kaufmann W and Baird F E** eds 1994 *Ancient philosophy* Prentice Hall, New Jersey
- Kilduff M** 2004 AIDS as an agent of reform? (www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2004/07/27/EDGIJ7SHA.G1.DTL) accessed 11 August 2008
- Koch C and Laurent G** 1999 Complexity and the nervous system *Science* 284 96–8
- Kurtz H** 2002 The politics of environmental justice as a politics of scale in **Herod A and Wright M** eds *Geographies of power: placing scale* Blackwell, Oxford 249–73
- Lansing S J** 2003 Complex adaptive systems *Annual Review of Anthropology* 32 183–204
- Latour B** 2005 *Reassembling the social: an introduction to actor-network-theory* Oxford University Press, New York
- Leitner H and Miller B** 2007 Scale and the limitations of ontological debate: a commentary on Marston, Jones and Woodward *Transactions of the Institute of British Geographers* 32 116–25
- Levin S** 2003 Complex adaptive systems: exploring the known, the unknown and the unknowable *Bulletin of the American Mathematical Society* 40 3–19
- Lewontin R C** 1998 The maturing of capitalist agriculture: farmer as proletarian *Monthly Review* 50 72–85
- Marston S A** 2000 The social construction of scale *Progress in Human Geography* 24 219–42
- Marston S A and Smith N** 2001 States, scales and house-holds: limits to scale thinking? A response to Brenner *Progress in Human Geography* 25 615–19
- Marston S A, Jones J P III and Woodward K** 2005 Human geography without scale *Transactions of the Institute of British Geographers* 30 416–32
- Marx K** 1904 *A contribution to the critique of political economy* Kerr, Chicago
- McCarthy J** 2005 Scale, sovereignty, and strategy in environmental governance *Antipode* 37 731–53
- McMichael P** 1998 Global food politics *Monthly Review* 50 97–112
- Murdoch J** 1998 The spaces of actor-network theory *Geoforum* 29 357–74
- Purcell M** 2003 Islands of practice and the Marston/Brenner Debate: toward a more synthetic critical human geography *Progress in Human Geography* 27 317–32
- Rihani S** 2002 *Complex systems theory and development practice* Zed Books, London
- Rind D** 1999 Complexity and climate *Science* 284 105–7
- Saperstein A M** 1995 War and chaos *American Scientist* 83 548–57
- Sayer A** 1984 *Method in social science: a realist approach* Hutchinson, London
- Sayre N F** 2005 Ecological and geographical scale: parallels and potentials for integration *Progress in Human Geography* 29 276–90
- Simpson D** 2000 *Rethinking economic behaviour: how the economic system really works* St Martin's Press, New York
- Smith N** 1989 Uneven development and location theory: towards a synthesis in **Peet R and Thrift N** eds *New models in geography: the political economy perspective* Taylor and Francis London, 152–75
- Smith N** 1992 Contours of a spatialized politics: homeless vehicles and the production of geographic scale *Social Text* 33 55–81
- Smith T S and Stevens G T** 1996 Emergence, self-organization, and social interaction: arousal-dependent structure in social systems *Sociological Theory* 14 131–53
- Stewart J Q** 1956 The development of social physics. *American Journal of Physics* 18 239–53
- Swyngedouw E** 1997 Neither global nor local: 'glocalization' and the politics of scale in **Cox K** ed *Spaces of globalization: reasserting the power of the local* Guildford New York, 137–66
- Thich N H** 1988 *The heart of understanding* Parallax, Berkeley
- Ulanowicz R E** 1990 Aristotelean causalities in ecosystem development *Oikos* 57 42–8
- Watts M J** 2000 Afterword: enclosure. in **Philo C and Wilbert C** eds *Animal spaces, beastly places: new geographies of human-animal relations* Routledge, London 292–304
- Weng G, Bhalla U S and Iyengar R** 1999 Complexity in biological signaling systems *Science* 284 92–6
- Werner B T** 1999 Complexity in natural landform patterns *Science* 284 102–4
- Whitesides G M and Ismagilov R F** 1999 Complexity in chemistry *Science* 284 89–92
- Wilson E O** 1975 *Sociobiology: the new synthesis* Harvard University Press, Cambridge
- Wittgenstein L** 1949 *Tractatus Logico-Philosophicus* Routledge, London
- Wolfram S** 2002 *A new kind of science* Wolfram Media, Champaign
- Zimmer C** 1999 Life after chaos *Science* 284 83–6
- Zwerdling D** 2002 McDonald's new farm: the fast food industry and animal rights. (www.americanradioworks.org/features/mcdonalds/index.html) accessed 19 July 2007