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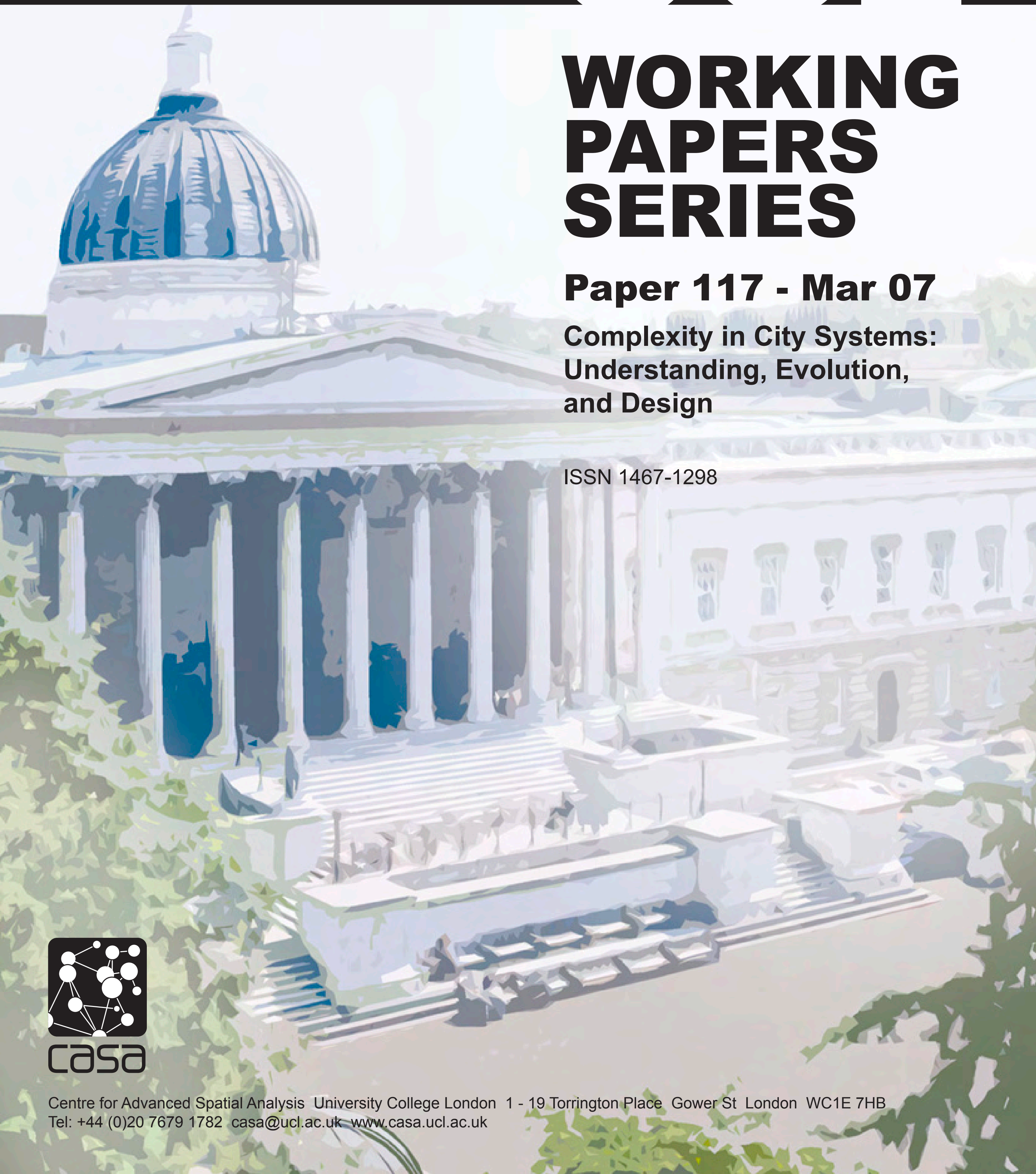

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Complexity in City Systems: Understanding, Evolution, and Design

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Complexity in City Systems: Understanding, Evolution, and Design[+]

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Abstract

As we learn more about the world and reflect on its meaning, an overwhelming sense of inadequacy in our ability to both understand and change it has developed. In many disciplines, the idea of 'complexity' as a coherent perspective for organising our knowledge has come to the fore. These 'complexity sciences' first evolved from ideas associated with dynamic systems through ideas about chaos, nonlinearity, disruptive technologies, emergence and surprise. Recently they have begun to infuse areas as diverse as postmodernism and management. Cities and planning have not escaped this force, indeed in some respects they are in the vanguard of these developments.

In this essay, we will sketch how this movement has evolved. Throughout we make a key distinction between the evolution of cities and the processes used in their planning and design, first fashioning complexity around the notion of the city as a system but then moving to examining how problems of their design and planning reveal a rather different type of complexity. We conclude with speculations about fostering change in cities in the light of this complexity. We propose a somewhat less invasive, more sensitive bottom-up style of physical planning that is in stark contrast to the institionalisation of planning and its practice which still dominates most developed societies.

[+] 8th March 2007

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> " … there is a fundamental law about the creation of complexity … (which) states simply this: *all* the well-ordered systems that we know in the world, all those anyway that we view as highly successful, are *generated* structures, not fabricated structures."
>
> Christopher Alexander (2002) *The Nature of Order, Book 2: The Process of Creating Life,* Center for Environmental Structure, Berkeley, CA, page 80.

1 The Argument, A Message

A very simple definition of a complex system is 'a system that is composed of complex systems'. This recursion makes considerable sense when we ponder systems such as economies and cities for their elements – individuals – clearly have the same order of complexity as any aggregation into groups or institutions while any disaggregation into constituent parts moves quickly into physiology and psychology. Artefacts that we build to give physical representation to cities can also be so partitioned into their component parts blurring into the material world which has its own logic and structure. In the past, we have tended to see these different levels as being systems in their own right which can be partitioned easily and conveniently from the rest of the world. But it is increasingly clear that although such an assumption might have been useful in making initial progress, as soon as this science came to be applied to human affairs, such assumptions of independence between levels are no longer tenable.

In the last thirty or so years, the complexity sciences have developed to make sense of such systems, and in doing so, have begun to fashion a theory and method which is rapidly gaining credence in the social sciences and beyond. In the mid-20th century, the prevailing view of society was one which treated social structure akin to the way machines functioned. This was not very surprising given the advances in science and technology of the previous two centuries but the metaphor of the city as a machine ignored self-determination and was only barely applicable in the most cursory ways to social problems. In the early 21st century, it is clear that a radical shift in metaphor is taking place to thinking of cities and societies as organisms, as biological rather than physical systems, echoing the quote from Alexander (2002) which introduces this chapter. This is also a switch from thinking of cities as being artefacts to be designed to thinking of them as systems that evolve, that grow and change in ways that might be steered and managed but rarely designed from the top down. This also reveals a shift from an emphasis on structure and form to one of behaviour and process and it mirrors the slow march from the physicalism which dominated city planning a generation or more ago to a serious concern for social process.

At the same time, these changes in perspective have been paralleled and sustained by a profound move in western societies from top-down, centralised structures of government and management to much more decentralised organisations which suppose that effective action comes from the grass roots, from the bottom up. This accords closely with the notion that cities grow from the bottom up, the concerted action of millions of individuals and agencies that generate structures of complexity that are virtually impossible to manage, control or redesign from the top down. At the same time, the development of technologies that enable much larger fractions of the population to gain access to information than hitherto, has given added impetus to the notion that systems evolve and grow from the bottom up, the world wide web being the seminal example. We continually need to be reminded of course that Adam Smith's (1776) view of the emergent modern economy in his *Wealth of Nations* published over two hundred years ago was in similar vein. The 'hidden hand' of coordination which he argued enabled the economy to grow and function without falling apart, became the cornerstone of general equilibrium theory which is the classical edifice on which contemporary economics is constructed.

No one would pretend that cities and societies only grow in competitive and uncoordinated fashion from the bottom up for individuals act in groups, they form institutions with governments of various kinds acting in top-down fashion but at different levels. The complexity paradigm simply changes the focus from top down to bottom up, emphasising that actions are as much local as global but with structure and order emerging as much, if not more, from the bottom up. In fact the leitmotiv of the complexity sciences is that the order we observe 'emerges' from actions and decisions where individuals and agents respond to their environment and each other, competitively and collaboratively from the bottom up. Here we will sketch this logic for cities and their planning. We will begin by describing the development of a systems perspective fifty years ago, indicating how it was found wanting in important ways. The systems approach espoused the notion of the city as a machine and planning as its controller but it took the move from thinking of systems as physical entities to biological to generate the kind of insights that complexity theory is now bringing to our world.

After a sketch of this history, we will define the rudiments of complex systems and complexity theory, following this with some pertinent examples relating to urban structure at micro and macro levels. Our argument then veers towards the design of better cities, to planning and the problems that it attempts to alleviate. We then show how planning needs to respond to the ways in which cities evolve and change such that new styles need to be fashioned from the bottom up. This leads to the notion that in the solution of urban problems, far fewer interventions at much more appropriate entry or 'leverage' points are required, echoing many clichés from the past which as Anderson (1972) has argued, are widely applicable to the complexity sciences: 'less is more' and 'more is different'.

2 The Systems Approach

The notion that there might be a general theory applicable to the structure and behaviour of phenomena forming the subject matter of many different disciplinary perspectives is an old idea. But apart from some philosophic speculation, little was done in articulating such a theory until the early 20th century when enough momentum had been reached in the biological and engineering sciences to make such a quest feasible. Various physical processes in engineering and biological processes in the life sciences involved the transmission of 'information' rather than 'materials' and the fact that such diverse systems seemed to manifest a common structure arranged as an ordered hierarchy of parts and their interactions, quickly led to the notion that it was only the material composition of such systems that marked their difference. In fact, the idea that such systems had more commonalities than differences suggested that they were simply different realisations of some more general system based on the transmission of information, an idea that has developed very rapidly in the last half century with the convergence of computers and communications.

By the mid 20th century, 'general system theory' fashioned using biological analogies by von Bertalanffy (1968) and 'cybernetics' based on communication and control as articulated in engineering, principally by Weiner (1948), marked the beginnings of a perspective on science that came to be called the 'systems approach' (Churchman, 1968). This theory was attractive to the softer sciences, particularly those where their subject matter had developed in more *ad hoc* ways. Consequently through the 1950s and 1960s, the social sciences (with perhaps the exception of economics) and various professional fields from management science to urban planning each developed their own variety of systems approach as a basis for underpinning their structure and practice. Systems were conceived of as having subsystems tied together by interactions, thus invoking the idea of a network, but recursively ordered invoking the idea of hierarchy. Processes acting through subsystem interactions kept such systems in balance, in equilibrium, with the controller a special subsystem responsible for coordinating all the others. The behaviour of such a system was largely considered to be ordered with the controller acting to restore balance if the system should move away from its implicit goals or targets.

Cities were extremely suggestive artefacts for such a theory. Its components were individuals or groups tied together spatially and economically through transportation and socially through various friendship networks. Some of the key problems of the 1950s and 1960s manifested themselves in terms of congestion and the need to ensure effective transport, and the first steps towards rudimentary simulation models based on land use-transportation linked to the way populations created demand and supply for such uses were built with this image of the city as an interacting system in mind (Lowry, 1968). The idea that systems could be controlled or 'planned' to meet certain goals or targets was a natural extension of such logic. The goal of minimising interactions between home and work, for example, linked these transportation based models to optimisation procedures being developed in operations research and some rather neat solutions were revealed to exist if cities were conceived in this way.

The problem of course was that casting most urban problems into such narrowly defined domains was simply not sensible or feasible and much of our understanding of cities and their planning remained beyond the systems approach. In Britain, for example, the approach sustained by developments in planning theory and method, was popularised in various texts such as McLoughlin's (1969) *Urban and Regional Planning: A Systems Approach*, Chadwick's (1971) *A Systems View of Planning*, Faludi's (1972) *Planning Theory* and so on. Intellectually too, it was clear that what had emerged was a rather narrow view of the way systems behaved: most systems were not in quiet and passive equilibrium but in turmoil much of the time while the idea of evolution to new conditions implying different structures and behaviours simply lay beyond this kind of thinking.

Yet there were the seeds of a more sophisticated view right from the beginning and this was bound up with the working cliché of the systems approach contained in the mantra 'the whole is greater than the sum of the parts'. The argument implied by this gestalt was that system structure 'emerged' from the parts but that this was not simply a process of adding up the bits to get the whole. The processes themselves generated emergence and in this sense, general systems theory alluded to a dynamics that was well beyond anything that it actually specified. Simon (1962) anticipated this in an early statement of complexity which Alexander (1964, 2002) drew on his discussion of systems that grow from the bottom up. His focus was on design as evolution culminating in his recent magnum opus *The Nature of Order* but it was Jane Jacobs (1961) who really broached the question head on in her *Death and Life of Great American Cities*. She argued that the mechanistic way in which cities were conceived and planned was entirely counter to the diversity that made up vibrant and living cities, with the result that post-war urban planning (and modern architecture) were killing the heterogeneity and diversity that characterised urban life.

Following Weaver's (1948) threefold characterisation of science as dealing with problems of simplicity, problems of disorganised complexity, and problems of organised complexity, she argued that urban problems could not be treated like the first two. These in fact were the methods of classical and contemporary science respectively but she argued that the problems of cities needed to be treated as ones of organised complexity, the subject of the life sciences. In a way, this was a profound and insightful critique of the then emergent systems approach. It implied that cities should not be treated like machines but like living systems with the implication that life, hence city form, emerges from the bottom up following the Darwinian paradigm. Indeed, almost as soon as the systems approach was articulated, its limits became evident in that thinking of cities as systems in equilibrium with planning aimed at restoring this equilibrium, clearly conflicted with innovation, competition, conflict, diversity and heterogeneity, all hallmarks of successful city life. This led to the new paradigm that we will now elaborate.

3 The Complexity Sciences

Our preliminary definition of a complex system as being composed of complex systems certainly illustrates a recursion to an infinite regress or infinite expansion but it still ducks the question of what a complex system actually is. We first need to be clear about the fact that complex systems can never be precisely defined which lies at the basis of any attempt to understand such complexity. We can demonstrate this through the notion of variety, defining a system in terms of a number of components, say n, and the number of states, say m, which each component can take on (Ashby, 1956). The simplest demonstration is to compute the number of combinations of states when a state can exist or not $(m = 2)$ given by the combinatorial $C = \sum_{k=1}^{n} \left(n! / k!(n-k)! \right)$. In Greater London for example, there are something in the order of 4.9 million building blocks and this formula counts the total number of different urban forms – arrangements of these blocks – when they are switched on or off. This varies through all combinations from the city composed as one block at one extreme to all 4.9 million as one at the other. This number is enormous, many orders of magnitude greater than the 10^{69} atoms in the universe. This might seem fanciful but all we are envisaging is all realisations of a city composed of any combinations of blocks up to this total number of buildings.

This number of combinations could be elaborated in countless ways and although it can be reduced simply by introducing constraints on what is feasible and what is behaviourally acceptable, it is still huge and to all intents and purposes infinite. This is one of the key challenges of complexity theory: understanding, grappling, and managing this sort of combinatorial explosion. Ashby (1956) calls this number of combinations variety and he makes the essential point that to control such a system, one needs as much variety in the controller as in the system. In theory, this means that to control such a system, we need as many elements in the control as there are states the system can take on. In fact, we can sometimes design good controllers that take account of the structure of such a system for it is most unlikely that the system can exist in all of these combinations with equal probability. The structures of the systems we deal with are hardly random and the trick for designing good controllers (or good plans) is to exploit this structure. Ashby refers to this as the law of requisite variety (Chadwick, 1977).

Coping with infinite variety is only one aspect of complex systems. Given such orders of magnitude, it is impossible to imagine that this kind of variety could be generated in any top-down fashion. In Alexander's introductory quote, it is impossible to envisage that such variety can be created by anything other than a bottom-up generative system. Life itself is the best example of such variety and most of us would now agree that the kind of diversity we see around us could only be generated by genetic variations that are consistent with neo-Darwinism. The corollary to this is that there is no way one might 'fabricate', in Alexander's terms, such complexity. Thus evolution from the bottom up is a hallmark of complexity and this too is consistent with the idea that order and structure emerge from actions and interactions in such systems. Generative systems are in fact central to simulating complexity and recent developments of agent-based models in cellular environments which have been quite widely developed in urban science of late are good examples of how complexity science is beginning to influence empirical work. Indeed Epstein (2007) argues that generative approaches are becoming central to social science with good theory being demonstrable by growing social structures from the ground up. Page (2005) captures this in the cliché that: "if you didn't grow it, you didn't show it".

If magnitude and bottom-up evolution are crucial to complex systems, so too is dynamics. All that we have said about complexity implies that dynamics is central to their development, hence their form and structure. In fact in the development of urban simulation models from the 1960s, temporal dynamics was always in mind in that static structures in equilibrium although appearing as reasonable approximations to urban structure, were widely regarded as first approximations. Equilibrium was in some senses regarded as a convenience. The development of dynamic urban models began with Forrester (1969) who simply used ideas from systems dynamics where feedback – positive and negative were central – to model inner cities and although his models were criticised for being non-spatial, he demonstrated the power of exponential and logistic growth. After that there was fascination with the notion that dynamic systems need not progress smoothly but could generate discontinuities such as catastrophes and chaos while notions about how systems admitted novelty and surprise from the bottom up began to develop using ideas from bifurcation theory (Wilson, 1981). Much of this kind of theorising did not lead to operational urban models while the development of cellular automata and agent-based models came from rather a different source as we will sketch below (Batty, 2005). Nevertheless the idea that cities could and should not be treated as being in equilibrium, began to penetrate the field pushing it towards the burgeoning sciences of complexity.

The context then is that complex systems have too many variables and too many interactions to be handled by traditional methods that seek to simplify and progress through parsimonious models. Phase spaces in which their realisations or solutions exist are effectively infinite and cannot be traversed. Such systems are thus unpredictable in the sense of classical science, but despite this, such systems are intrinsically temporal in that their dynamics is what makes them complex. As might be expected with such uncertainty, there is no widespread agreement as to precise definitions but there is a general consensus that there are quite well defined characteristics that such systems necessarily display. Durlauf (2005), himself a mild sceptic of complexity theory, identifies four key features which such systems must portray to be seriously considered as complex. He states these as *non-ergodicity*, *phase transition*, *emergence*, and *universality* and these provide a brief but useful primer on what a complex system is as we will now explain.

Systems which are ergodic are those whose dynamics are predictable in that they are well behaved and often converge to some stable equilibrium. In fact this criterion was stated by Harris (1970) as a key requirement for good urban models despite the fact that real cities only appear to be stable at spatial scales where micro-change is averaged away. Durlauf in fact has a much more precise definition of *non-ergodicity* which he defines as systems that lack any kind of probable behaviour over the long term. This means that such systems can be characterised by exogenous shocks that affect long term behaviour. Such shocks are often said to generate path dependent behaviour where historical accidents in the form of initial conditions or unpredictable shocks determine the long term behaviour and structure of the system. Endogenous change through positive feedback can also generate such unpredictability in that feedbacks can trigger surprise or novelty as new varieties of behaviour emerge. Such systems can also 'lock in' on end states which are generated through such feedbacks. In economic terms, path dependence through positive feedback is sometimes called increasing returns. In social systems, this is often captured in the cliché that 'the rich get richer and the poor get poorer'.

This kind of dynamics can also lead to turbulence which characterises qualitative change in the form of *phase transitions*. Such transitions occur often abruptly implying some form of threshold which if a system reaches or breaches, leads to qualitatively different structures and behaviours. A classic example in the physical sciences is water turning to ice or to steam which involves dramatic changes in structure at very specific temperatures, freezing and boiling points respectively; or in spatial systems, percolation through porous media which occurs once a certain level of network penetration becomes possible as threshold densities are reached. Novel change is thus triggered by small events. Another way of saying this is that complex systems have 'tipping points' where unusual sets of conditions come together and fire the system in one way or another. Gladwell's (2000) popular exposition of these phenomena are suggestive of such complexity in the social world. Furthermore, the rates of change and their turbulence imply intrinsic nonlinearity in temporal behaviour which again limits predictability. Finally phase transitions are also associated with qualitative changes such as that generated often endogenously within the system such as the development of disruptive technologies or dramatic switches in human behaviour and preferences.

In one sense, both non-ergodicity and phase transitions are consistent with the notion of *emergence*. Usually emergence comes from the action and interaction of system components at lower levels in the absence of any higher level coordination functions but it can in fact happen at any level. In another sense, emergence is also akin to self-organisation, the generation of spontaneous order from the parts for which the mantra – the whole is greater than the sum of the parts – is central and essential. Such organisation depends not only on evolution but on co-evolution which reflects competition and conflict between system entities with such processes essential to the kind of positive feedbacks that lead to innovation, novelty, and surprise. In a way, the kinds of mutation that characterise genetic processes in human and animal populations reflect such spontaneity with the emergence of ever higher orders. Recent developments in fact suggest that the survival of the fittest, the term associated with Darwinian theory, must be dramatically qualified when dealing with human and social systems.

The last feature is *universality*. This is a characteristic defining the degree of order in a complex system and as such it is measured by a number of different signatures that show how the order in such system is manifest at different spatial and temporal scales. According to Durlauf (2005), a property of universality exists "… if its presence is robust to alterative specifications of the microstructure of the system." This means that if the system exists under different realisations of its components, either in the past, present or future, then the system is universal in that there is no doubt that we are dealing with the same system. This is a rather weak condition which is probably more applicable to models of the systems than systems themselves but the way we recognise systems in fact is through this property. A much more specific definition is that the system has invariant properties in time and space. If it is quite clear when we examine the system at different times and spatial scales that the system is the ‘same’, then it is universal. In fact complex systems in very different fields might show the same structure and it is this that makes such complexity universal. This is no more or less than saying that analogies between systems that differ radically in material terms, can be very similar in more fundamental, informational terms.

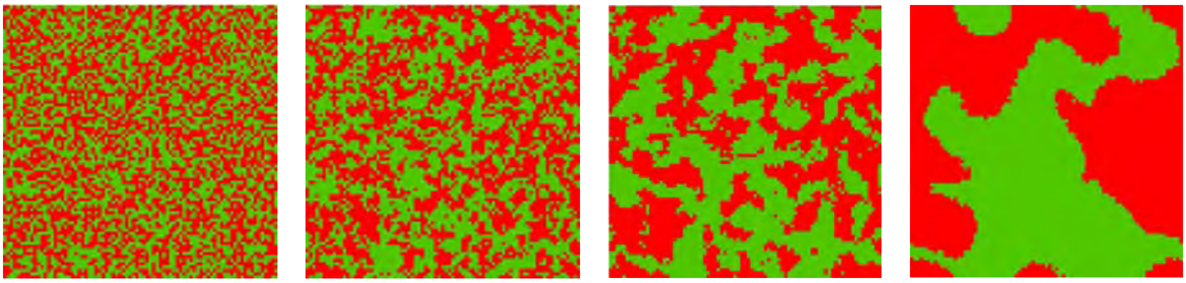
A good but narrow example of universality relates to self-similarity of spatial structure. Cities exist in space in that they are structured around points of economic exchange, traditionally markets which form a hierarchy of types and sizes. This hierarchy although differentiated by size shows similarities at different scales in terms of the way cities of different sizes depend on each other. Central place theory suggests as much and this hierarchical order is also consistent with scaling of the city size distribution. In terms of spatial structure, cities distribute their resources in space in such a way that their networks of distribution fill space efficiently, moving goods and people along dendritic networks which fill space the most economically. These networks exist in the same form with the same space filling properties at different scales and through different times in terms of city growth. The whole idea of the fractal city which has a structure that manifests itself in the same morphology at different scales is entirely consistent with this kind of universality. In fact one of the key signatures of universality is the self similarity that is contained in scaling associated with fractals with measures of density and fractal dimension providing some meaning to this kind of theory (Batty and Longley, 1994).

4 Exemplars of Complex Systems

There are many signatures of complexity revealed in the space-time patterning of cities (Batty, 2005) and here we will indicate three rather different but nevertheless linked exemplars. Our first deals with generative systems which build order and pattern from the bottom up which necessarily involves generation in space but also through time. Were we to order the size of the components that are used in constructing cities physically, this would follow a rank-size rule with most components being very small in size with the least number of components being the largest in size. One could argue that most of the action –the decisions – would be associated with the smallest components and that this is indicative of the fact that most decisions are made from the bottom up. Imagine a large number of individuals who fall into two groups based on those who wish to live in a red house and those who wish to live in a green house, and let us assume that the initial distributions of houses are randomly coloured as either red or green. Now each individual is quite tolerant and would gladly live in an area where the number of houses which were painted in a colour different from their preference was the same as their personal preference. But if the number of their neighbours with a personal preference for a different coloured house began to dominate, they would be uncomfortable and would think about moving to a neighbourhood that had a more preferable balance.

Of course in real life, they would probably not move but repaint their houses and the situation would be a lot more messy. But it is easy to imagine that it is not the colour of their house but the political or social attitudes of their neighbours that is the issue (despite the fact that the colour of one's house is not as unimportant as one might think!). Now let us see what happens when we set up a simple rule for making decisions about such a situation and let us imagine that if a person in a green house finds themselves living in a neighbourhood with a majority of red houses, they will conform – not move – by painting their own house red. A symmetric situation exists for a person living in a red house in a neighbourhood dominated by green houses. In fact we could complicate this situation by some sort of tit-for-tat iteration in house painting but eventually we imagine that some sort of balance would take place through a combination of house painting and moving. If we implement this model on a fine lattice of cells in which we start with a random distribution of reds and greens as houses at points on the lattice, then using the rule that if a person in a house whose colour is not in the majority in the cells around their house repaints their house to the majority colour, then the situation moves rapidly to extreme segregation as we show in Figure 1.

This is Schelling's (1969, 1978) model, first demonstrated nearly forty years ago, which contributed to his winning the Nobel Prize for Economics in 2005. Essentially it is a perfect demonstration first, of how order emerges from randomness using simple but plausible rules of behaviour and second, of how an undesirable state implying extreme segregation and thus extreme preference emerges from rules that show only mild preferences for segregation. It is perhaps the classic model of ghetto formation and how individual actions can lead to unusual and perhaps surprising outcomes. It is also a very good example of cellular automata in that it reveals that specific actions in highly localised neighbourhoods generate global order of a kind that is surprising and cannot be anticipated from the basic rules. The models described by Elisabete Silva (this volume, 2007) follow these ideas where spatial pattern and order emerge from the bottom up. In fact, this style of modelling also forms the basis of the field of artificial life (Langton, 1989) which builds on John Conway's early demonstration that such automata could sustain a great magnitude of patterns, some of which emerge spontaneously from a random soup, like life itself (Gardner, 1971).



Time t=1 *t=2* *t=5* *t=20*

Figure 1: Order from Randomness

Emergence of Extreme Segregation from Local Cellular Automata Rules Implying a Mild Preference for Living Amongst One's Own Kind

Schelling's model demonstrates many features of complex systems and that is why it is so powerful. First there is the idea that fragile equilibria exists which, when perturbed, moves rapidly to a stable equilibrium – the random starting pattern of red and green cells is not an equilibrium but imagine a checker board distribution of alternative red and green cells with a single dual cell perturbation of this pattern. The whole system would then unravel into the kind of clusters shown in Figure 1. Moreover such a fragile equilibrium is a tipping point in Gladwell's (2000) terms, ready to flip the system into a new state: very little change in two cells, in this example, leads to massive change in a much larger proportion of cells, a phase transition reminiscent of percolation. Changes are clearly emergent, generated from the bottom up, and in this sense are unexpected. Such change is also based on positive feedback in which local changes in pattern, one cell at a time, build up to the tipping point in any local neighbourhood.

Our second example deals not with locations but with networks which link locations and thus introduce notions of movement or transportation. Just as a lattice represents an idealised representation of locations, a graph built from arcs connecting nodes is an idealised form of network. These simple models enable us to study the properties of networks in analogy to the properties of graphs which focus on their connectivity. Imagine a world where people are linked into tightly organised clusters, reminiscent of the sorts of links one might find in small villages which can then be generalised to a landscape of small villages, essentially a landscape of clusters. The clusters have dense connectivity but because transportation in such a world is limited by how far one can walk to work in a day, villages are spaced at something like 6 miles from one another. The linkages between people in different villages are much less than within a village and this world thus resembles something akin to the settlement landscape of Western Europe in medieval times. If we measure these properties of connectivity, we see that the connectivity of each cluster is much higher than the whole network. In short this is an inward looking world where travel between the clusters is difficult, thus representing some limit on its economic development. We show such a world in Figure 2(a) where we measure the average path length of each cluster separately, and then we compare this to the total average path length of the whole network. Each cluster has an average path length of 1, much greater than the overall connectivity which has a path length of about 3.

a) b)

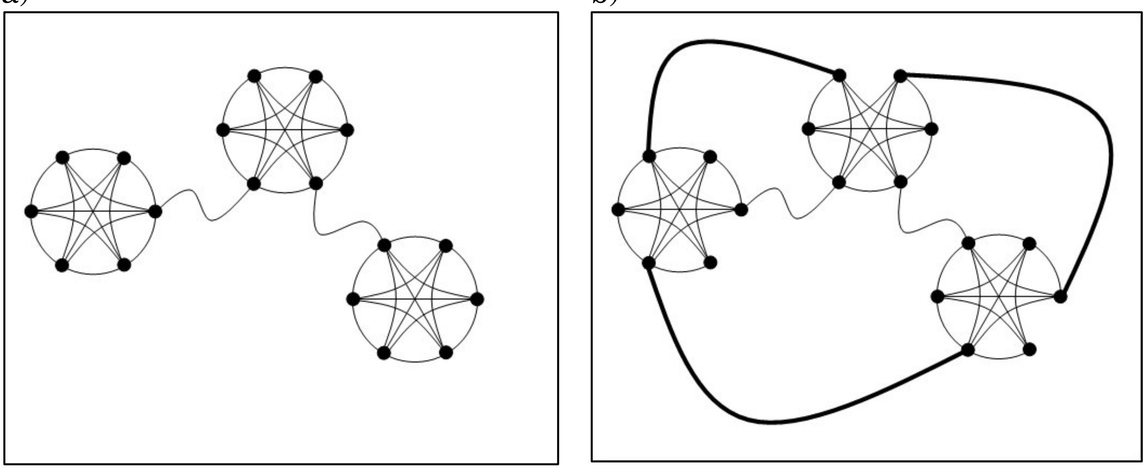


Figure 2: Evolution of a Small World Due to Technological Change

Here the network in (a) has low connectivity despite the presence of several clusters with high connectivity. In (b) because of the addition of only three long distance links, the network connectivity dramatically improves with the local clusters remaining largely unchanged. This is the best of both worlds and is referred to as a 'small world'.

Imagine a change in technology such as that introduced by steam power as in the Industrial Revolution. Fast links are established between some of the villages and we show three such links in Figure 2(b). When we recompute the average path length, the clusters still remain about the same but the overall network connectivity increases dramatically with the average path length falling from about 3 to about 2. This is what Milgram (1967) first defined as a small world: a network which has the benefits of high local density but also relatively short overall paths where people can connect up to one another. In cities, technical change is necessary to build networks which connect people and goods at different levels and bypass (at high speeds) lower level links. Indeed the very fact that cities still build bypasses and beltways is tantamount to saying that they are attempting to increase their efficiency by reinforcing their small world properties. In fact, a useful way of looking at cities is by measuring the connectivity of their transport networks at different scales and using such measures to assess their efficiency.

Small world properties of networks also indicate how such systems evolve from the bottom up. In a sense, this can be seen as an optimal process for generating structure. Like patterns generated from cellular automata, it is a process of efficient space filling without connecting everything in sight. Indeed, there are some who argue that many systems evolve in this way to an efficient threshold and that everything from brains, to nervous systems, to arterial transport in the body and the city are small worlds (Watts, 2003). Friendship networks too are small worlds with such nets bound together by critical links – weak ties in one sense but strong in another. We do not have time here to demonstrate in detail how a small world emerges from one which is highly clustered and then loses its qualities as more and more network links are built. But in essence, there is a threshold of connectivity where the benefits of high local cluster density/connectivity are retained in the presence of low overall average paths through the graph. As more links are built, the local cluster density and the overall connectivity of the network converge. If one were to argue that the cost of links is fixed, then a clear trade-off can be measured between connectivity and cost and it becomes clear that there is a point where adding more links leads to less and less improvements in connectivity. In short, thresholds can be defined which indicate optimal points of investment in the network, and there are strong links to percolation theory (Batty, 2005). There is a good example in London at present which suggests that adding some key links which have not evolved spontaneously, could make very dramatic improvements in travel: so called Cross-Rail, a high speed link from the west of the CBD to the east, is a case in point.

There have been some dramatic advances in this kind of network thinking in the last decade. Although the temporal dynamics of network evolution is still in its infancy, it is now quite clear that the structural properties of networks are important properties of complexity. Barabasi (2003) for example has demonstrated that many naturally evolving networks such as the internet have scale free properties which imply that the most connected nodes get richer as networks evolve and the poor get poorer. This is also consistent with the small world properties and these have important implications for how robust networks are to breakdown or attack and how strategies to leverage networks can be built. There are links to spatial epidemiology and thus to public health vaccination strategies in the preventing the diffusion of disease. Many of these ideas in cellular automata and network science tie together in the spatial domain through ideas that have been developed for several years in fractal geometry (Batty and Longley, 1994).

Our third example involves ideas about how systems evolve in time. There are many growth models which encompass the idea of positive feedback, the simplest being Malthus's model (Banks, 1994) where population change is proportional to population itself, leading to exponential growth (or decline). Many variants exist in which such growth models might be capacitated in some way, reaching limits posed by crowding where the growth rate embodying positive feedback is countered by a crowding constraint involving negative feedback. Let us begin by stating this model for the change in population $dP(t) = \lambda P(t)[1 - P(t)/\hat{P}(t)]dt$ where $P(t)$ is the population and $\hat{P}(t)$ is the maximum population permissible at time t. If we assume that $\hat{P}(t) = Z, \forall t$, then the change equation can be integrated from $t = 0$ to ∞ and it produces the classic logistic form given as $P(t) = Z/[(\eta - 1)\exp(-\lambda t)]$ where $\eta = P(t)/Z$. When there is no effective bound, that is, when $Z \to \infty$, then the equation generates exponential growth $P(t) = P(0)\exp(\lambda t)$ which is Malthus's equation. All these are standard results.

The logistic appears to be relevant to population growth in human populations in capacitated spaces such as individual cities or countries but over longer periods, there is little doubt that the capacity limit Z varies, usually upwards. In fact capacity measured in population terms belies a variety of other influences that although incorporated by this measure, involve technological change. As building technology has developed, the capacity (which reflects density), increases. The socio-economic types of population occupying cities also change while employment as well as resident population is an important measure of size. This too relates to how much time people spend in cities living or working at high densities. If population capacity is thought of as a generic measure of resource, then basic technological change – agricultural, industrial and post-industrial and in disaggregate terms, mechanical, energetic, electronic, biophysical, medical and so on – is easy to reconcile with this model where growth through new technologies can occur in spurts. The simplest way to build this in is simply to add a baseline capacity over different periods. Once population reaches a certain level, let us say ψZ, this marks the start of a new growth process where the clock t is reset to 0. This resetting of the process occurs when $P(T) = \psi Z + P(T-1)$, where T is the current time when this condition is met and $T-1$, the time when it happened previously. The logistic model can now be written as $P(\tau) = \{\psi Z + P(T-1)\}/\{Z/[(m-1)\exp(-\lambda\tau)]\}$. This simply displaces the logistic in time rather than resetting the capacity per se although there are many variants of the function that can achieve this effect.

We show such an effect in Figure 3(a) where the logistic is displaced when $P(T) = 2^{-1} Z + P(T-1)$. In 3(b), we show the overall envelope produced by this process which implies that the growth process receives a number of shocks or kick starts. With $\psi = 1/2$, this means that when the growth process reaches the inflection point – that is, when growth just begins to increase as a decreasing rate, an innovation occurs that resets the process that projects it back to the point where positive feedback with increasing returns, dominates. The process here has all the elements of complexity: phase transitions or thresholds at which innovation occurs and pushes the system into a new regime, novelty and surprise in a process that is in reality likely to be fairly random in time (for we never know when such a shock might occur), and a sense that the usual state of the system is far-from-equilibrium.

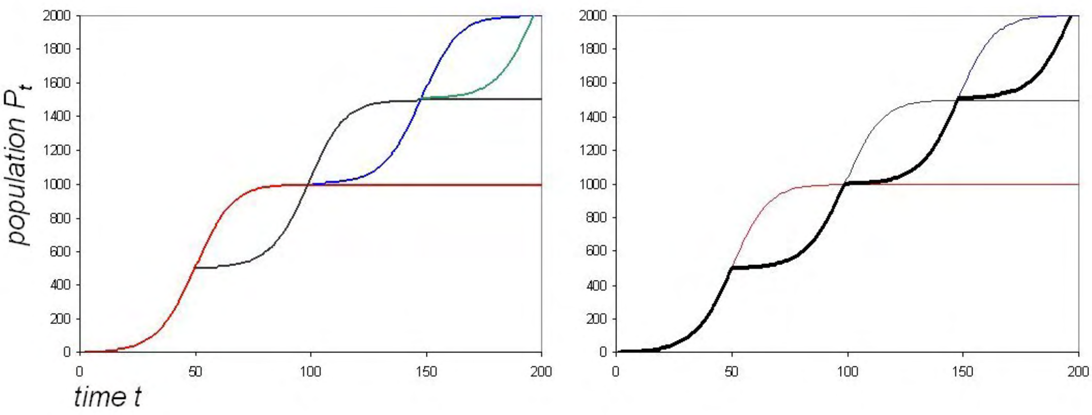


Figure 3: Population Growth with Changing Resources Due to Innovation

One of the features that this process implies is that growth is dominated by continual discontinuities or innovations, 'perpetual novelty' as Arthur (2005) refers to it. Growth is only 'locked in' to an equilibrium between the discontinuities. Over time, these changes might be considered to be a perpetual series of 'avalanches' in the sense used by Bak (1999) in his discussion of self-organised criticality or punctuations in the sense used by Eldredge and Gould (1972). A much more complete and powerful model which mirrors similar growth profiles has been developed by West, Brown and Enquist (2001) for biological populations. This has been generalised to human populations by Bettencourt et al. (2006) who show that this kind of growth behaviour characterises some cities such as New York where there appear to be spurts in growth due to new land being released which in turn are influenced by changes in technology, attitudes towards high buildings, transportation innovations, and perhaps even changes in preferences to live at ever higher densities. The West-Brown-Enquist model differs from our simple model here in that pure population change is articulated as a scaling function of population; in its non-capacitated form, change in population is a scaling function where $dP(t)/dt \sim P^{\beta}$ and it is this scaling that enables the model to generate many other effects from hyper-exponential growth leading to singularities and to exponential decline. It also maps this kind of growth model onto many other relationships that we observe for urban systems which are scaling, implying different economies of scale.

5 Evolution, Planning, and Design

So far we have considered cities as complex systems where the idea of a city is as a comprehensive entity. When we act in making plans about cities, or consider any other forms of decision-making which take place either in cities or with city development in mind, then perspectives change and with this so does the way we construe complexity. Our perspective here will be that of planning the city in expert-professional terms, more akin to designers but we will also broach complexity in other ways – from top-down controllers which imply a management perspective, from the perspective of the citizen, and from a more general, somewhat detached social science perspective. We do not have time to elaborate how each of these approaches manifests its own complexity but we will provide some simple signposts which let us put the complexity of physical planning and design in context.

From our perspective of cities as complex systems, a key consideration already raised is the notion that cities manifest a variety that has to be met by a controller requisite to the task in hand. This 'requisite variety' implies that any system of control, which here largely means keeping the system within certain targets, predicates some sort of system that has the same variety or diversity of the city itself. From all that has been said, the notion of a top-down controller is simply impossible given the degree of complexity that modern cities manifest and thus any successful control must probably operate from the bottom up. In fact, as cities in large part develop this way, bottom-up control makes logical sense; the way development takes place by successive and often incremental adjustments, even in terms of grand plans, implies control of some sort at the most basic level. This is not to say that higher level controls do not have some function for there is a hierarchy of control as Simon (1962) implies. As we learn more, we intervene less and the notion of finding critical leverage points in complex systems – tipping points as Gladwell (2000) refers to them – is quite consistent with this kind of bottom-up design. This implies that as well learn more, we intervene less because 'less means more' and 'more means different' (Anderson, 1972). An excellent example of this is based on identifying critical points within a network – weak links that in fact act in strong ways to cement the system together for relatively little cost but provide great added value.

From the perspective of the planner who identifies with the planning system, then the system itself is complex in terms of its bureaucracy. Getting things done is usually the focus of this complexity in that planning is seen as being centric, or top down. Over the last fifty years such systems have been gradually hollowed out to the point where planning as a bureaucracy is often said to be part of the problem rather than the solution. Thirty or more years ago, Rittel and Webber (1973) articulated this in their definition of 'wicked problems', problems that were so interconnected that any thing one might do to alleviate or try to solve them, usually made them worse. It is in this sense then that planning is seen to be part of the problem. Wicked problems fight back and they resist solution. Wicked problems are unique and have no definitive formulation. Often the problem and the solution are the same thing, they have no stopping rule, it is hard to tell when a solution has been reached, there is no agreement about a solution, and no ultimate test that establishes whether a solution is optimal or has actually ever been reached. Such problems generate 'waves of consequences' such that there is never any end to these chains and thus problem-solving goes on forever until the problem changes out of all recognition or is deemed no longer relevant. In essence, every solution to a wicked problem is another wicked problem. These characteristics in fact are those that imply complexity both in the methods of problem solution as well as the object of problem solving itself.

From the perspective of social science in general, identifying the city as the object of complexity or in terms of the process of changing it through planning and control, are equally narrow in conception. Cities are regarded as organisational, social structures that are changed through decision-making of various kinds and it is this nexus of decisions across all scales and through all times that forms the web of complexity that is basic to the social sciences. There are many similarities to features of the complexity sciences that pervade the social sciences and to an extent this is reflected in both the substance of its inquiry as well as its methods. In these terms, there is some convergence of terminology and ideas. These are key themes that echo throughout these many perspectives such as those based on ideas about networks in particular and agents and agency in general (Bryne, 1998; Cilliers, 1998).

What all these approaches suggest is that planning, design, control, management – whatever constellation of interventionist perspectives are adopted – are difficult and potentially dangerous. If we assume that social systems and cities like biological systems are generated through a process of tinkering, through trail and error mutation which increase fitness and reduce error in the phylogeny, then interventions are potentially destructive unless we have a deep understanding of their causal effects. As we have learned more, we become more wary of the effects of such concerted action. In sense, if the development of cities is really like the evolutionary process in biological populations, then we are inevitably wary of fine tuning such evolutionary processes. We are scared of evolution, we find it complex, and we are reluctant to disturb something we do not understand at all well.

We do not have a good answer to any of this although there is rapid progress in the notion of evolutionary design, particularly in inanimate systems where there are an increasing number of analogies between the evolution of animals, plants and machines. In one sense, social evolution has been characterised in similar ways in the past but it is only recently that formal design has begun to draw on this tradition. In terms of physical planning Alexander (1964, 2002) was one of the first to exploit the evolutionist paradigm but more recently his work on generative design using pattern languages has been paralleled by other generative approaches in the social sciences based on individual and agent-based modelling (Epstein, 2007). In fact in design, there are many new approaches revolving around generative systems, for example those based on shape grammars (Stiny, 2006), on cellular automata (Batty, 2005), and on evolutionary geometry (Watanabe, 2002).

A concept that emerges quite naturally from such purposive bottom-up actions is the idea that to explore good planning and design in cities, computer models should be set up in a laboratory-like context in which the focus is on exploration of different patterns which attempt to reach different goals, laboratories in which models are available in wide area mode, across the web in a form that many people can experiment with. The notion that many people collaborating is likely to produce better design than the few is based on recent thinking about collective action through the 'wisdom of crowds', to coin a popular phrase (Surowiecki, 2005). To illustrate these notions, we can use a cellular automata model as a laboratory in which the user works with a model of urban development where there are default rules relating to how one type of development relates to another. These are rules that are based on the type and density of different land use activities in different locations/cells which in turn influence what development takes place or is removed in adjacent cells as the city changes. The model also has rules that govern the life cycle of different land use activities which in turn influence their effect on other land uses at different points in their life cycles.

If one begins with a pattern of development – the 'physical' initial conditions – the user can change the default rules to those that might pertain to different goals – plausible or not – which in turn might reflect different ideals. As the simulation proceeds, development rules do not change but they can be altered by the user to imply a sense of learning. The model we will illustrate *DUEM* – the Dynamic Urban Evolutionary Model – was developed by Xie (1994) and set up in laboratory context for such exploration by Batty, Xie and Sun (1999). What we show in Figure 4 is a branching tree of possibilities from four initial sets of conditions. The uppermost branch simply represents the development of the city in its default state with the rules set to reflect existing development process. But at each branch the rules are changed and a different path is taken. These bifurcations illustrate the incredible variety of solutions that such a model can generate with literally millions of possibilities: in fact an uncountable number and it is this style of theorising and thinking that generative social science strives for which is the hallmark of dealing with complexity. Although we have had little time to develop this here, we speculate that this is the style of simulation that living with complexity requires and that such laboratories for exploration, for growing cities in this way to meet planning ideals, must become the norm in post-industrial societies driven from the bottom up.

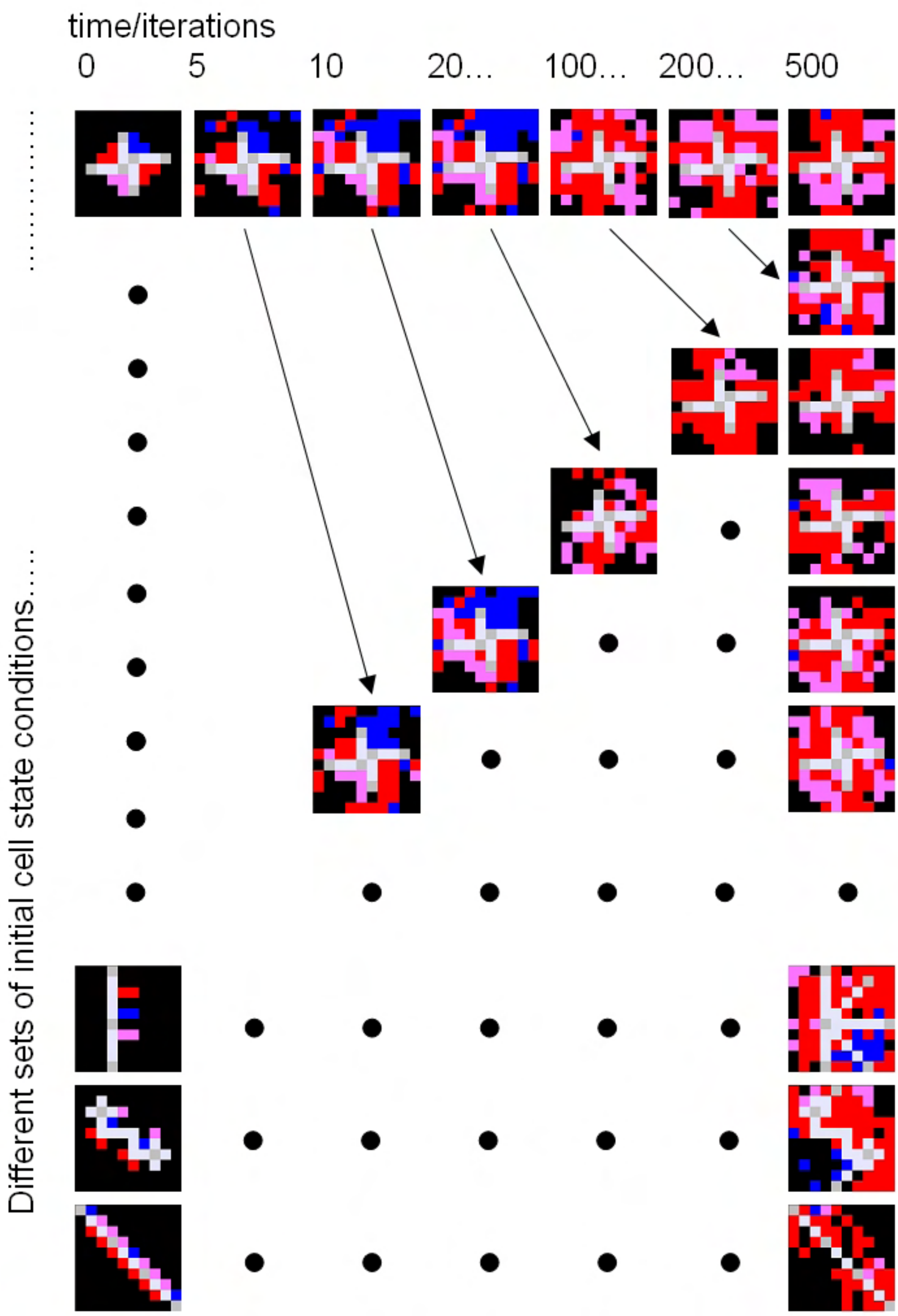


Figure 4: Generative Predictions and Designs in a Cellular Automata Lab

Each row represents a different configuration and set of land use states in a 10 x 10 cellular space. The CA rules are then applied and each simulation is run for 500 steps giving the final cellular spaces in the last column of each row. However in the first case, after 5 steps, some of the rules are changed and the model is run for another 500 steps. The rules are then changed for the original initial conditions after 10 steps, 20 steps, 100 steps and 200 steps and in each case the model is run up to 500 steps. This gives a crude picture of the kind of variety that can be generated combinatorially as the user explores the enormous phase space of possible solutions in true generative fashion.

6 Conclusions and Next Steps

Our focus on complexity has many echoes in the other contributions to this book in terms of concepts, the focus on bottom-up as opposed to top-down action and problem-solving, and the idea that planning and design are not really so very different from evolution and prediction. In fact in the last section, we argued that prediction, design and understanding are all of one piece. If we take the essential message of modern Darwinism that design is evolution, that the evolutionary process is the only process that leads to optimality in systems that grow from the bottom up, then planning must be subsumed in our theories and models. The fact that it has remained separate from the way we have tried to understand cities and make predictions in the past is part of the problem. Complexity science forces us to a more holistic view.

Several other features that we have introduced support the need for holistic theory and practice. There is little doubt that time and dynamics has come firmly onto the agenda and that we no longer think of cities as being in equilibrium. In hindsight, it is somewhat remarkable that we ever thought we could get away with the idea that we could encapsulate all our knowledge into equilibrium models because the whole point of planning is to generate change. Yet the notion that such equilibrium was non-optimal was a simplification in itself that gave planning a starting point for action. If the city is never in equilibrium as we now accept, if it is far-from-equilibrium as its social physics reveals, then this in itself casts doubt on the idea of intervention as the system may still be on course for some kind of optimality. Once again, we are drawn to the notion that intervention in complex systems must be treated with extreme caution.

The complexity sciences communicate a message to all functions and agencies that exercise control, management, planning, policy-making and perhaps design, and that is that the most effective intervention is based on small scale change which enables a system to meet its own goals. Slight changes in direction are thus preferred to radical top-down restructuring whose implications might be far reaching and completely unpredictable. This suggests broadening the remit of physical planning but there is only so far one can go. Better to set up mechanisms like the simulation laboratory sketched out above which enables stakeholders to participate in ways that are tempered by dialog and discussion and to let those affected see the consequences of their actions. Intervention is a serious matter that requires serious tools for tracing its potentially far-reaching and unanticipated implications.

What we have sought to do in this chapter is to sketch how complexity theory is beginning to inform our understanding of the physical development of cities. The growth of complexity theory as a major paradigm for science admits unpredictability and uncertainty, ambiguity and pluralism, and without being entirely relativist, it does throw doubt on the certainty of theory and science that has dominated our thinking about cities and about planning hitherto. The generic use of complexity language in articulating social affairs, policy, management and decision-making is beginning to infuse our thinking. We are now much more comfortable with using the language of science with its physical metaphors involving diffusion, mobility, liquidity, fluidity and so on as useful characterisations of the complexity of the social world we have to deal with. We have had little time here to deal with the way these currents are beginning to mesh with globalisation and the modern information economy but these are being dealt with elsewhere in this book. There is now a very positive sense in which each of these perspectives is contributing to a new paradigm which is based on its own rhetoric in which 'the whole is greater than the sum of its parts'.

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