THE HIDDEN GEOMETRY OF DEFORMED GRIDS

or, why space syntax works when it looks as though it shouldn't

35

Professor Bill Hillier
University College London, London, England

Keywords: graphs, configuration, geometry, urban, order

Professor Bill Hillier
Bartlett School of Graduate Studies
(Torrington Place Site)
University College London
Gower Street
London WC1E 6BT
United Kingdom

tel: (44) (0)171 391 1739
fax: (44) (0)171 916 1887
e-mail : b.hillier@ucl.ac.uk
www: http://www.spacesyntax.com

0 Abstract

A common objection to the space syntax analysis of cities is that even in its own terms the technique of using a non-uniform line representation of space and analysing it by measures that are essentially topological, ignores too much geometric and metric detail to be credible. In this paper it is argued that far from ignoring geometric and metric properties the 'line-graph' internalises them into the structure of the graph and in doing so allows the graph analysis to pick up the nonlocal, or extrinsic, properties of spaces that are critical to the movement dynamics through which a city evolves its essential structures. Nonlocal properties are those which are defined by the relation of elements to all others in the system, rather than intrinsic to the element itself. The method also leads to a powerful analysis of urban structures because cities are essentially nonlocal systems.

1 Preliminaries

1.1 The critique of line graphs

Space syntax is a family of techniques for representing and analysing spatial layouts of all kinds. A spatial representation is first chosen according to how space is defined for the purposes of the research - rooms, convex spaces, lines, convex isovists, and so on - and then one or more measures of 'configuration' are selected to analyse the patterns formed by that representation. Prior to the researcher setting up the research question, no one representation or measure is privileged over others. Part of the researcher's task is to discover which representation and which measure captures the logic of a particular system, as shown by observation of its functioning.

In the study of cities, one representation and one type of measure has proved more consistently fruitful than others: the representation of urban space as a matrix of the 'longest and fewest' lines, the 'axial map', and the analysis of this by translating the line matrix into a graph, and the use of the various versions of the 'topological' (i.e. nonmetric) measure of patterns of line connectivity called 'integration'. (Hillier et al 1982, Steadman 1983, Hillier & Hanson 1984) This 'line graph' approach has proved quite unexpectedly successful. It has generated not only models for predicting urban movement (Hillier et al 1987, Peponis et al 1989, Hillier et al 1993, Read 1997, Penn et al 1998), but also strong theoretical results on urban structure, and even a general theory of the dynamics linking the urban grid, movement, land uses and building densities in 'organic' cities (Hillier 1996a, 1996b). It has also yielded a practical method for the application of these results and theories to design problems (Hillier 1993), which now has a substantial portfolio of projects.

Many are, however, troubled by these results, not because the empirical correlations are doubted, or because the theoretical reasoning is thought unsound, but because the foundations of the method seem insecure. How can so much of the geometric and metric complexity of urban space be discounted, and so much weight put on a simple line representation, and a non-uniform one at that ? Why should topological rather than metric measures then be chosen, especially in view of the emphasis on movement where metric variables must be expected to play a role ? And why should so much emphasis be placed on a single type of measure, based on topological 'depth' in the graph ? Can such an apparent simplification of the geometric complexity of urban space then be considered a realistic foundation for a theory ? Is there perhaps some way in which the strategy of 'line graphs' can be given a more secure theoretical foundation ?

1.2 The structure-order problem

The external critique of 'line graphs' has also been reflected in a debate within the space syntax community about the relation of geometry and topology in urban systems, under the rubric of the 'structure-order' problem. It has always been clear that historically, space syntax analysis turned attention away from geometrical notions of spatial order in the study of buildings and cities, and pointed to spatio-functional patterns which, formally speaking, were closer to topology than to geometry. This distinction was clarified by Hanson (Hanson 1989) who distinguished between the non-geometric 'structures' identified in urban space by space syntax analysis, and the type of geometrical 'order' found in the plans of ideal towns. The latter could be easily intuited, because geometrically similar elements were put into geometrically similar relations, and this made it possible for the eye to see the pattern 'all at once'. The former could not be easily intuited as a whole, because neither locally similar elements nor relations could be easily discerned, but they were discovered practically as patterns of everyday space use and movement. It was these functional patterns of space that were picked up by space syntax analysis as 'structures'.

The 'structure-order' distinction has proved a very useful heuristic, but as time has gone by it has become clear that further clarification was needed, if for no other reason, then because the 'structures' that are found in the typical 'deformed grids' that characterise most towns and cities, have themselves strong geometric aspects. At a more general level, it is also clear that on a scale from geometrical chaos (in the old sense) to order, cities are quite close to the order pole, and utterly remote from chaos. They are 'nearly ordered', not 'nearly chaotic'. What then is the role of this geometrical order, and how does it relate to the more 'organic' structures that space syntax has identified ? How was it possible to discount this geometric order in the line graph analysis, and still obtain apparently useful results ? Is geometric order perhaps another dimension of urban structure ? Or is it constructively linked to the structure patterns which have proved so useful in deciphering the relation between space and function in cities ?

The aim of this paper is to try to answer both of these questions - the critique of the line-graph and the structure order problem - by showing that they are essentially the same question: what is the role of geometry in constructing the patterns of space that characterise cites, and how does it relate to the 'structures' identified through line graph analysis ? The answer proposed is that line graph analysis does not ignore the geometric properties of space, but internalises them into the graph, and it is precisely because it does so that it is able to pick up the nonlocal, or extrinsic, properties of spaces that are critical to the movement dynamics through which a city evolves its essential structures. Nonlocal properties are those which are defined by the relation of elements to all others in the system, rather than intrinsic to the element itself. The method also leads to a powerful analysis of urban structures because cities are essentially nonlocal systems.

1.3 Outline of the argument

The argument is presented in a series of stages. First, axial maps of cities are examined from a geometrical point of view, and shown to manifest consistent ways of relating geometric variables such as line length and angle of intersection, so that even apparently irregular cities have a surprising degree of geometric order in their axial maps. It is also shown that the emergent global structures of cities, even the largest, seem to have pervasive geometric properties which combine aspects of both orthogonal and radial grids, two of the prime 'rationalist' geometric notions by which designers have sought to create ideal cities. In spite of this apparently pervasive geometry, it in then explained, on the basis of a simple model of the 'essential urban dynamic', how space syntax seems to account for the spatial and functional dynamics of cities without reference to geometry. How can this be ? First, an investigation is made of graphs. It is shown that there are strong theoretical reasons why graphs cannot in themselves carry the weight that has been apparently assigned to them in the line graph analysis, since that would require them to be both more predictable and knowable than they are. This is an important clue. It is then shown that the general role of geometric order in cities is to create a world in which graphs do become predictable and knowable, but both are a product of geometry seen as graphs, not of graphs themselves. It is then asked how this geometric order arises, and it is shown that exactly the kinds of geometric order that have been described can be theoretically generated by the familiar need to minimise mean trip lengths in the system for two kinds of movement: circulation within the system from all origins to all destinations, and movement in and out of the system to neighbouring systems. It is then shown how the key geometrical properties generated by movement are internalised into the line graphs and create its structure as a pattern of connectivities. Once these properties are internalised into the graph, it becomes possible for the graph to do its work of bringing to light the crucial nonlocal properties of the lines and of the system as a whole.

2.0 The Geometry of Axial Maps

2.1 Counting angles, measuring lines: the pervasive geometry of deformed grids

Just how 'nearly geometrical', then, are the deformed grids that characterise most cities ? We can find the answer by the usual technique of looking carefully, counting and measuring. Consider, for example, the axial map of part of London (Hua Yoo 1991) shown in Figure 1, analysed and shaded from dark to light according the 'radius-3' integration analysis (in fact, its logarithm, since this gives a better colour distribution), that is, the integration measure calculated only for the lines which intersect the root line, and those which intersect these (Hillier, 1996a), which is also the best predictor of pedestrian movement (Hillier et al, 1993; Read, 1997; Penn et al, 1998). As in any axial map, each line ends where it is incident on the face of a

Figure 1. Axial map showing the logarithm of local integration in London.

building, and (with the exception of end lines in culs-de-sac), an incident line will normally intersect with another which is more or less parallel to the building face. This intersection will define the principal route continuation, or continuations, for the incident line. If we begin to measure the angles formed by these incident and parallel lines, we find that a surprisingly high proportion are either near right angle connections, usually within about 15° of 90°, or very obtuse angles, usually within about 15° of a direct 180° continuation. Incident-parallel angles closer to 45° occur more rarely, and where they do they usually indicate a clear choice of direction in the larger scale grid structure, and even then one of the two lines making up the fork is usually an approximately linear continuation. If we take other intersections, where neither line is incident on a building (and both therefore continue to other intersections), the range is even more restricted, with the vast majority approximating a right angle. In effect, an unexpectedly high proportion of the angles of incidence in the axial map are concentrated within little more than a third of the possible range. Such probabilistic bias in a geometric variable is unlikely to have occurred by chance. It suggests some kind of consistent constructive process at work.

Looking a little further, we find that angles of intersection have an equally improbable relation to another geometric variable: line length. For the most part, we find, highly obtuse angles of incidence are associated with long lines, and the near right angles with shorter lines. In general, the longer the line, the more likely it is to have a highly obtuse angle of incidence at (or close to) one or both of its ends. Conversely, the shorter the line, the more likely it is to have a near right angle of incidence at its end. With less consistency, though with enough to be suggestive, the 45° lines tend to be shorter than the obtuse angle lines, but longer than the near right angle lines. We

Figure 2. Axial map showing the logarithm of global integration of Hamedan

also find that these consistent relations of lengths and angles seem to form sequences or clusters. For example, if we follow a longish line to its end and find the obtuse angle of incidence that connects it to the next line, the chances are that this line will also be longish and will also end in an obtuse angle of incidence. It is this that creates the 'slightly sinuous' routes that crisscross London, and that is clearly picked out by the analysis shown in Figure 1.

This makes route-finding across London a kind of 'Markov process', in which what happens next is influenced by what has already happened. The usefulness of this property in direction finding must be considerable. The more long lines and obtuse angles of incidence you have moved through the higher the chance that the next line will be similar in both respects - though, of course, with significant exceptions. Conversely, if we are in an environment in which we experience a series of near right angle connections, then it is likely that in following a right angle change of direction we will be offered another before long. Again, the Markov nature of the movement process seems helpful in understanding the kind of spatial structure we are in.

If we carry out the a similar analysis for a city which at first sight seems as axially different as possible, say, the Iranian city of Hamedan, (Karimi 1998) as in Figure 2, we find that the lines are in general shorter, and the long line angles of incidence sharper, giving the axial map a much more broken up feel, but a similar broad distribution of angles is found, the same type of relation between line lengths and angles of incidence, and the same 'Markov' tendency. In Hamedan, long wandering paths, made up of obtuse angle line and connections, pass through the city, many from central towards peripheral areas, and near right angle lines prevail adjacent to these paths, though forming for the most part local sequences rather than grids. The precise geometric parameters of line length and angles of incidence are set differently, but the general process of 'geometric construction' is in these respects strikingly similar. In general we will find that this is the case in cities. However variable the precise spatial morphology of the city, we will usually find that it is constructed through consistent relations of some kind between the two prime geometric variables of the axial map: line lengths and angles of incidence.

35.06

2.2 The geometry of direction giving

This 'geometric construction' underlying the typically deformed grids of cities tends to be confirmed by the ways in which we give directions. It is often said that direction - giving supports the 'landmark' theory of urban form, as set out by Lynch (Lynch, 1960) and others. In fact, for the most part the directions we give are directly influenced by the kinds of geometric relation we have just described. For example, if we say 'carry on in this direction', we imply not that the road is straight but that there is the kind of 'more or less' linearity we have noted, that is a fairly straight continuation through oscillating obtuse angle connections, approximating if not an overall line then at least a consistent direction. We might add a landmark - say, keep going past the windmill - but it will be secondary to the overall shape of what we are saying. If we then say 'turn right', we imply that the 'turn' will be more or less a right angle. Since this will often imply more than one possibility, we mark it in one of two ways: either we say: 'take the third on the right', or 'turn right at the Hog and Hound'; for redundancy, we more likely we say: 'Turn right at the Hog and Hound - I think its the third on the right'. When we say fork left, we do not indicate a number, since the direction: 'Take the third fork on the left' is absurd without advice on how to deal with the two previous forks - unless, of course, they were particularly clear choices between a 45° fork and a 'nearly linear' continuation. In all cases, the form our directions take reflects the underlying geometry of the situation.

One possible implication of this, is that our knowledge of the urban grid as a whole may in some sense be geometrical. We are of course familiar with cases where this is clearly so: the regular orthogonal grid. Interestingly, the more regular the grid, the more likely it would be that our directions would rely on numbers, rather than landmarks. 'Three blocks west, four blocks south' would be enough to identify a precise location in Phoenix, where landmarks are in any case few. We might call this type of strong geometrical knowledge 'Phoenix knowledge' in contrast to the weaker - but still marked - kind we seem to find in deformed grids. But knowledge of deformed grids seems still to retain some degree of geometry. For example, the classic test for candidate taxi drivers learning 'the knowledge' of London is: 'Manor House to Gibson Square', a route which must cross the dominant grid diagonally, and in a metrically efficient way. It is a Phoenix type problem applied to a deformed grid situation. It is hard to see how it can be solved without knowledge of something like a geometrical approximation of the grid.

And what about the wry story told by an Irish comedian about asking the way in Dublin. Walking down Bolton Street he asks 'How do I get to O'Connell street'. 'Well now' comes the answer 'if you want to go there, I wouldn't start from here if I were you'. This story is meant to illustrate the simplicity of locals. In fact it shows the complexity of urban knowledge. The direction giver thinks at once of Bolton Street, O'Connell Street and a third, hypothetically better starting place, one among many such possibilities, and simultaneously evaluates all these relations before giving advice that is good in all senses except one. Such knowledge clearly does not depend on landmarks, or even make the slightest use of them. This would only come in the next stage, of telling the inquirer how to get from somewhere else to where he wants to go. As it is, we may directly compare such 'Irish knowledge' of deformed grids with 'Phoenix knowledge' of regular grids, in that the role of the geometric pattern seems clear. This knowledge seems to be not only about the geometric construction of the grid, but also about its overall structure.

2.3 A global near-invariant: the orthoradial grid ?

If we then return to the 'objective' grid we find these suspicions are confirmed. It is not only at the level of the pervasive geometric construction that we find an unexpected degree of order in the axial map. It also appears at the global level. If we consider the whole visual pattern formed by the most integrated lines in the line graph analysis - the integration core - we find that in both cases it is composed of two dominant elements: on the one hand, the obtuse angle sequences form radial routes from more central to more peripheral areas, sometimes intersecting with each other, and sometimes not; on the other a more grid-like central area, at once more orthogonal and (at least in part) smaller in block scale, to some part of which most radials connect. An integration core formed by these two element, a central more orthogonal grid as the focus for centre to edge radials, in common to both cases. Studies of urban system large and small, including very large systems such as Tokyo (Nishibori & Iida, 1997), Santiago (Rosso, Serpell and Desyllas, 1995), Athens (Karvounzni, 1992) and Baltimore (Shah, 1995), suggest that, described in these broad terms, integration cores of this kind are very common indeed, and may even be, at some level, a near-invariant in evolving urban systems, including in American cities (Major, 1998).

If this structure does turn out to be as common as it seems at present, then it will need to be described by a term which reflects its complex dual properties. Pro tem, we would suggest it should be referred to as the 'ortho-radial' grid, because in seeking terms to describe its structure, we find ourselves invoking the two key rationalist ideas that have always characterised the ideal forms of cities, and which underlie most concepts of 'ordered' (as opposed to structured) urban systems: the orthogonal grid and the radial grid. This suggests an intriguing possibility: that these two 'ideal' notions of regular urban systems are not simply rational types formed by speculative thought, but are found or inferred as deep structures in much less obviously ordered systems. Whatever the case, it is strange indeed that such a rationalist 'order' should be discovered through line graph analysis, which, as we have seen, takes no apparent account of geometrical variables. It is even stranger that a globally geometrical deep structure should arise as an emergent structure in organically evolving systems.

2.4 Line graphs and the essential urban dynamic

It is no less puzzling that many recent research results suggest that all this geometry may indeed safely be ignored in investigating the relation between space structure and function in urban space. It seems to be the mere existence of relations between elements, without considering such matters as angles or lengths, that captures dynamic

35.08

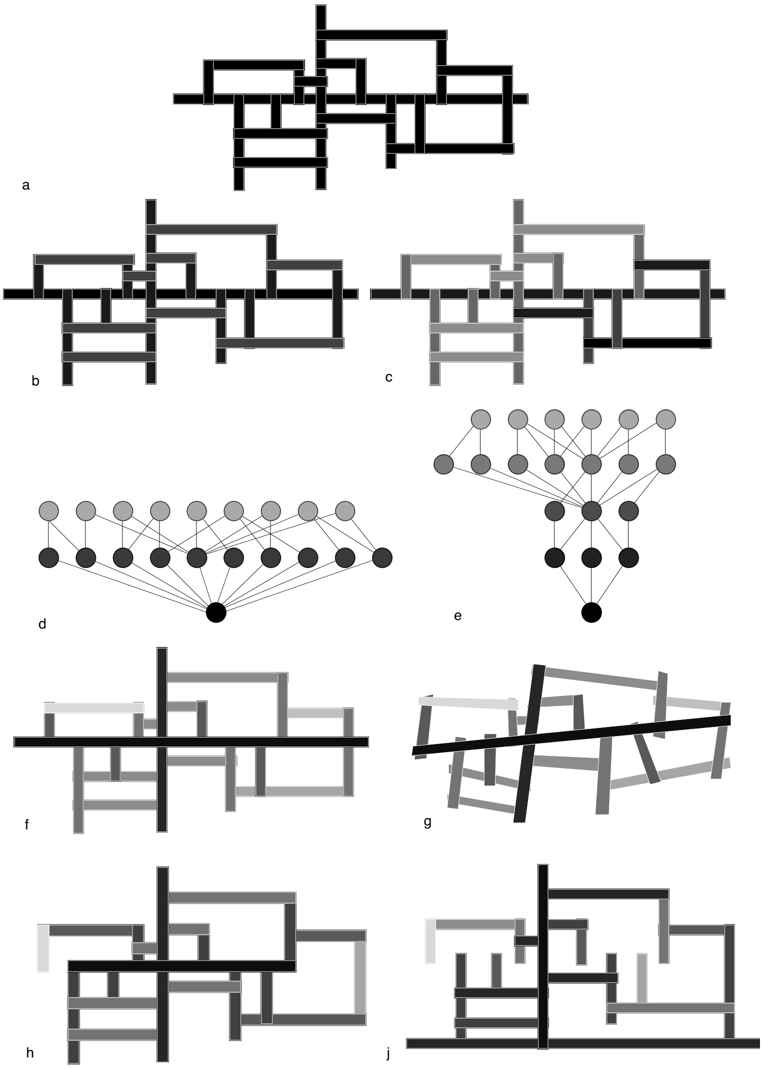


Figure 3. Simple notional street grid.

processes by which evolving space structure influences movement, leading to effects on land-use patterns and through multiplier effects back on movement to further elaboration of space structure, and eventually to the distribution of intense mixed use central and sub-central areas and less intense areas with fewer uses which seems to characterise cities in general, (Hillier, 1996a; Hillier, 1996b).

Let us look carefully at the structure of this argument on the basis of a simple model. Consider the notional street grid shown in Figure 3a, made up of a main horizontal street, a secondary vertical axis, and some interconnected back streets behind the blocks. Imagine the grid to be loaded everywhere with buildings that both generate and attract movement, and assume that movement tends to take the simplest available routes. It is clear that more routes will tend to pass through the main horizontal street than any other, with more passing through the central than the peripheral segments. It is equally obvious that very little 'all to all' movement will pass, say, through the horizontal street at the bottom right of the grid. Once we see this, we can move around the plan making reasonable intuitive guesses as to how much 'all to all' movement is likely to pass through each street. In simple cases, it is in effect easy to intuit that the way in which each line fits into the grid is an important determinant of how much movement each, other things being equal, would get. It is no surprise, then, that such effects are also found in the larger and more complex kinds of grid that we find in real cities, though here the effects are harder to intuit. Even so, the example shows the proposition that the structure of the grid itself influences the flows of movement seems only to be expected.

The power of the grid structure to influence events can be made formally clearer by using the justified graph. In Figure 3b-c we hatch one street in each, the main street and the bottom right horizontal, and shade each other street from dark to light according to its 'depth' from the hatched street. We then translate this, complete with shadings into two j-graphs, as in Figure 3d-e. The two j-graphs immediately shows not only that the shallower the graph is to the 'root' space of the graph, the more probable it is that a trip of n-line segments will include a segment of the root line in that sequence, and vice versa, but also that the shallower the j-graph is to its 'root' space, the more accessible that root space is as a destination from all other spaces, and vice versa. It is this combination of accessibility and potential permeability - that is, of to- and though-movement - that is captured by the j-graph, and which has proved so effective in analysing real systems of space and understanding how they work. It is also of course this, that is expressed by the various measures of integration. The integration value reflects the shape of the justified graph from each space.

In shading our notional grid from dark to light, then, to represent integration, as in Figure 3f, we are conscious that we are representing the potential of the different grid elements both for accessibility and movement. Seen this way, the relation between grid structure and movement seem thus to be entirely to do with syntax, as captured in the j-graph, and little to do with geometry. If, for example, we deform the grid geometrically by changing the angles of incidence without changing any of the j-graphs, as in Figure 3g, no difference is made to the analysis, and it is difficult to see intuitively why it should make any difference at all to the movement pattern.

We note of course that the influence of the grid on movement is subject to other conditions being satisfied: that the grid is more or less equally loaded in its different parts with buildings, that is, with origins and destinations, and that movement can be from all origins to all destinations. If the grid were differentially loaded, then we would expect this to bias the distribution of movement in the grid. The proper way to conceptualise the relation is to think of the grid structure itself as creating movement potentials, which may or may not be actualised by the distribution of built forms and facilities in the grid. In practice, of course, grids are not equally loaded. They tend to concentrate different types of facilities in different parts to some degree. However, studies have shown that these biases are themselves influenced by the biases of grid, so the relation between grid structure and movement is retained, though not in linear form (Hillier, et al 1993; Peponis, 1989; Read, 1997).

This is the root of what can be called the 'essential urban dynamic' by which grid structure, movement, land use patterns and densities become interrelated. The urban grid evolves and creates a pattern of movement potentials, and, to some degree, movement. Land uses which are movement dependent, like retail, then select high movement locations, and others, such as residence, lower movement locations. Because movement dependent land uses like retail are essentially public spaces (in that they seek to attract everybody), this creates attractor effects in high movement locations

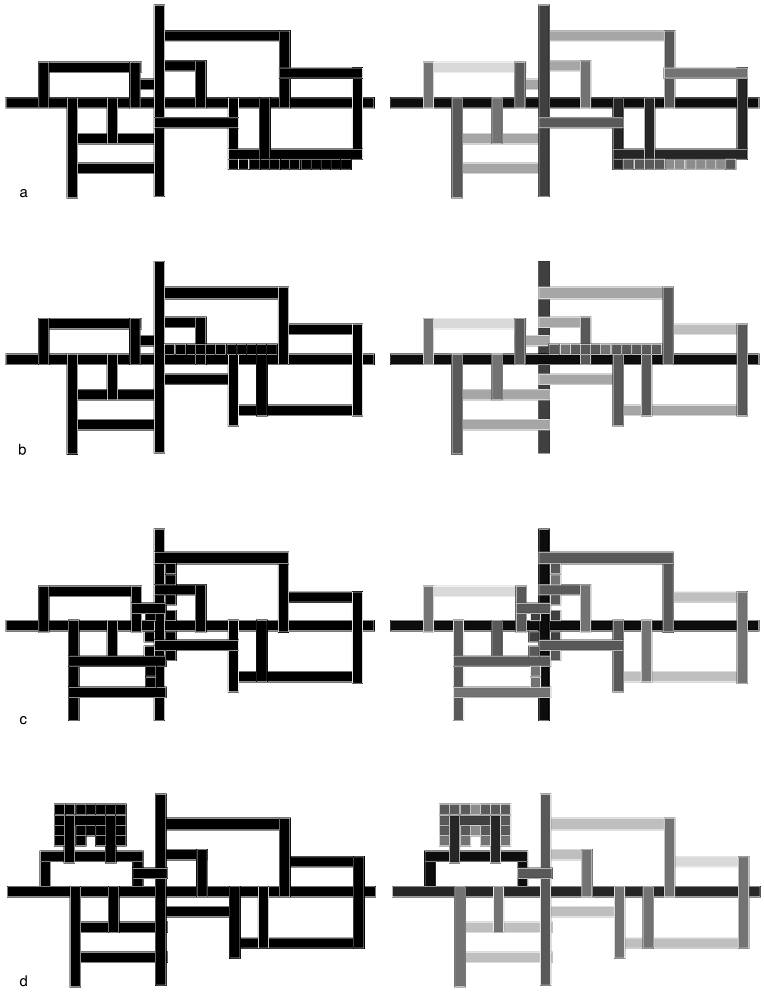


Figure 4. Notional street grid loaded with retail in different locations

and, through this, multiplier effects on movement. These multiplier effects then feed back on other land use patterns, and create increased densities and mixed movement dependent uses in high movement locations. This dynamic feedback cycle initiated by the grid structure is a key to the 'organic' growth of city patterns, and to the sense that space, movement, land uses and densities seem somehow to work together.

Because space syntax models only the topology of connections of spaces, we can illustratively model the land use aspects of the process by simply adding land parcels representing, say, retail units, as spatial elements in the appropriate locations. Since these will not normally allow through movement, we are in effect adding new, more or less accessible destinations in certain parts of the grid. The effects, as shown in Figure 4 a-d, will be to weight locations according to the number of elements added, and to increase the integration value of those locations. Note that the addition of these weighings will create distortions in the whole pattern of the grid, making segregated locations more integrated (Figure 4a and 4d), and integrated locations even more so (4b and 4c). These effects are not confined to the space to which the new elements are added, but also affect other streets in the vicinity, and through this, increases the integration of this area at the expense of others. If the process prioritises the most integrated spaces, as it of course does in most 'organic' towns, then this will make the line adjacent to the main integrators the most likely locations for the next stage of retail location, and this will begin to develop either a clustering or linear distribution, depending on the available structure of space. Further multiplier effects will follow, leading to more diversification of the grid, and so on.

Once this process is understood, it becomes clear that an urban grid is not simply a spatial framework for human activity, but a record of a historical process of evolution based on a dynamic process. This is why a simple integration analysis as in Figure 1 gives a picture of the urban grid which is not only informative about movement, but also about where the main shopping streets are (on, or adjacent to, key local and global integrators, depending on the historical operation of the attractor effect), and which parts of the grid will have greater concentrations of residence. The urban grid is not just a configurational shell for human activity. It is already alive with the history of human activity.

This is a very good result for space syntax theory, but very bad for our hope of understanding the role of geometry in the spatial form of the city. We seems to have described the 'essential urban dynamic' not only without reference to any of the geometric properties that we noted were pervasive in real cities, but we have gone some way to showing that the process seems independent of geometric form. Here we see the full scope of our problem: cities seem to be intuitable and constructible as geometries, but to work as graphs. Intuition seems to stand on one side, that of geometry, functionality on the other, that of graphs. Somewhere, somehow, it seems, there must a link between the configurational, or graph, nature of the city and its geometric nature. Where might we look for it ?

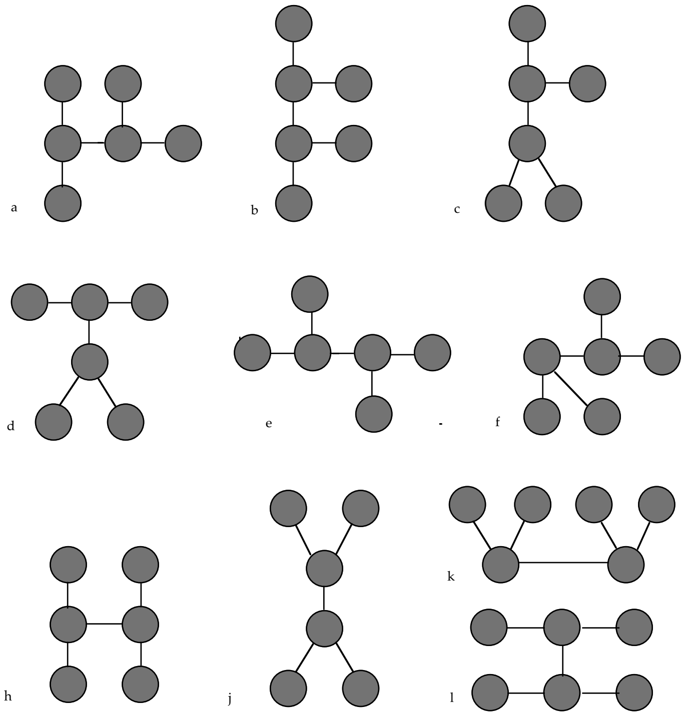


Figure 5. Ten identical graphs with different geometries

3.0 Problems with Graphs

3.1 Graphs as knowables

One place where we are unlikely to find the answer is in the nature of graphs themselves. They are the least geometric of entities. Consider the set of small graphs shown in Figure 5. Even though the ten graphs are very simple, it is very far from obvious that the graphs are all the same graph. We are deceived by the geometric differences into thinking that the graphs are different. Even after it has been said that the graphs are all the same, it is painfully difficult to try to trace through the relations in each graph to check whether or not this is the case. And these are very simple graphs.

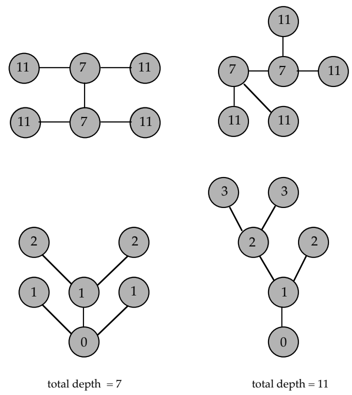


Figure 6. Total depth calculations for two cases selected from Figure 5, and justification of the two j graphs within each.

One way to understand graphs is of course to analyse them 'syntactically'. In Figure 6, two graphs are selected (h and f) and the total depth from each node calculated. We immediately see that each node totals either 7 or 11. The upper of the two graphs makes it immediately clear why this is so. There are two linked 'central' nodes, and two dead-end nodes attached to each. We can then justify from each of these nodes, and see that all of the graphs are in fact made up of these two j-graphs and nothing else. Once we know this we can return to the graphs to check that they all have this structure. But even with this knowledge it is sometime quite difficult to satisfy ourselves that the graphs really are the same. For example, graphs h and j in the third row clearly satisfy the requirement, but are they really the same graph. The difficulty is that we try to turn one into the other the wrong way, because we want to keep the two top or bottom nodes in the middle graph together as top or bottom (or left and right) nodes, when what we have to do is to put one at the top and the other at the bottom. There can hardly be a simpler transformation than this, but even so we may find it initially awkward.

35.12

But this is in any case analytic understanding, and does not give us the intuitive feel that we have grasped the structure of the graphs. This seems to depend on the presence of exactly what was missing from the graphs: a sense that the geometry expresses the graph relations in a consistent way. If we look at graphs h and l in row three of Figure 5, for example (missing the awkward middle one) both are constructed so that the same graph relation is expressed in the same geometric way. Because this is the case, we easily see the transformation from one into the other. We do not need to move nodes separately. We simply make a partial rotation of the whole graph. We can explore this further through Figure 7a-f, in which the sense that we understand the graph is first preserved under minor geometric perturbations (of the kind we find in cities), and then progressively lost by the introduction of greater differences in the geometric interpretation of the graph, including one partial rotation. These examples suggest both that it is internal geometric consistency that allows us to grasp the structure of the graph 'all at once', and to handle the whole object in comparisons. This is interesting because this is exactly the property we have called 'order'. On reflection, we can see that the analysis of the graph gave us its 'structure', the geometric consistency of the graph its order.

These are simple examples, but they are powerful enough to suggest that our ability to grasp patterns can work in at least two ways. The first (perhaps we should put it last) is the level of analytic or step by step understanding, which is essentially linear (j-graphs are essentially linearisations of the structure of the graph) and work on a step by step, or procedural basis, for example by trying to transform one graph into another by shifting nodes one at a time. The second is syncretic, or all at once understanding, which seems to depend less on a procedure and more on the ability to grasp a pattern instantly due to the manifestly consistent ways in which it has been put together. It is only where the geometry gives an internally and externally consistent account of the graph that we have the sense of a syncretic understanding of the graph, and can confidently compare it to others. While the j-graph is essentially linearised, and leads to analytic understanding, the geometrised graph is, as it were, justified in two dimensions, so that it appears as an object with an internal 'order' through which it immediately 'explains itself'. It is through this order that it is possible for us to read and understand it without reflection.

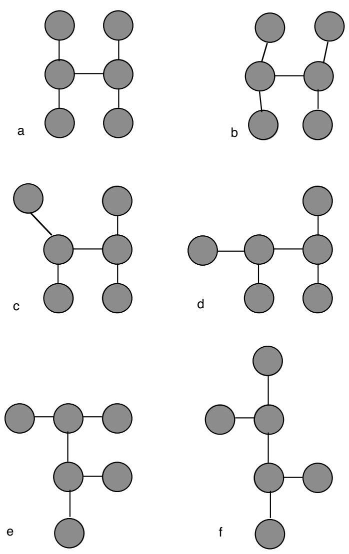


Figure 7. A series of geometric changes to a simple graph to show how the sense that we recognise it 'all at once' can be lost.

3.2 *Graphs and functionality*

The sense that we can 'know' a graph seems then to depend on giving it a geometric form which is entirely irrelevant to its nature as a graph, and can even be misleading. The situation is hardly better if we consider graphs from the point of view of functionality. Much of what we have said about the essential dynamics of cities is based on the knowledge, derived from much research, that urban grids, seen as axial maps and analysed as graphs, behave and change in a systematic and predictable way.

In fact, from a purely graph point of view, there are strong theoretical objections to this. Technically, it seems that it is impossible to know the effects of a change in a graph on, say, the crucial matter of the distribution of integration values for nodes, or even the gross morphology of the graph, without, in some way or other, checking the whole graph. From the point of view of syntax, graphs seems to be to all intents and purposes unpredictable. How then can they be the basis of systematic, predictive knowledge of cities ?

Consider Figure 8a-g for example. The top left figure, 8a, is an analysed graph with total depth values, in which the root node has three connections. We cut each connection in turn in 8b, c and d, and re-analyse to see how we have changed the structure of the graph. The total depth effect of each change is given below, and the three changed graphs are justified in the bottom row to clarify the effects of the changes. In the first case, the elimination of the link turns the graph into a pure ring in which all values are the same. The second, changes it to a smaller ring with one minimal 'tree' element. The third change brings about a much more radical transformation in the graph, turning it into a much more tree like form with the ring reduced to a very local scale. We can easily see why each of these happens, and some things we can know from principle - for example that if we cut a ring we will not disconnect the graph and that we must create at least one tree element. But to know we are on a single ring, and if so what kind of tree (shallow, as in the second case, deep, as in the third) will be created requires us to check most, and in some cases all, the other links in the graph. Even in as simple a case as this, to understand the effects of a change, whether minor and local as in the first two cases, or major and global, as in the third case, we need knowledge of at least a whole complex of local relations, and perhaps of the whole graph. Worse, what we need to know cannot be specified in advance. In complex graphs such as cities we will find that we need, in effect, to re-justify the graph from every node in turn if we are to be sure of the effects of a change. To understand the effects of a change in a graph, then, we seem to require an empirical procedure rather than a theoretical model. How can this possibly be reconciled to the ideas that cities, when represented as graphs of their line structures, seem to behave in a regular and predictable way.

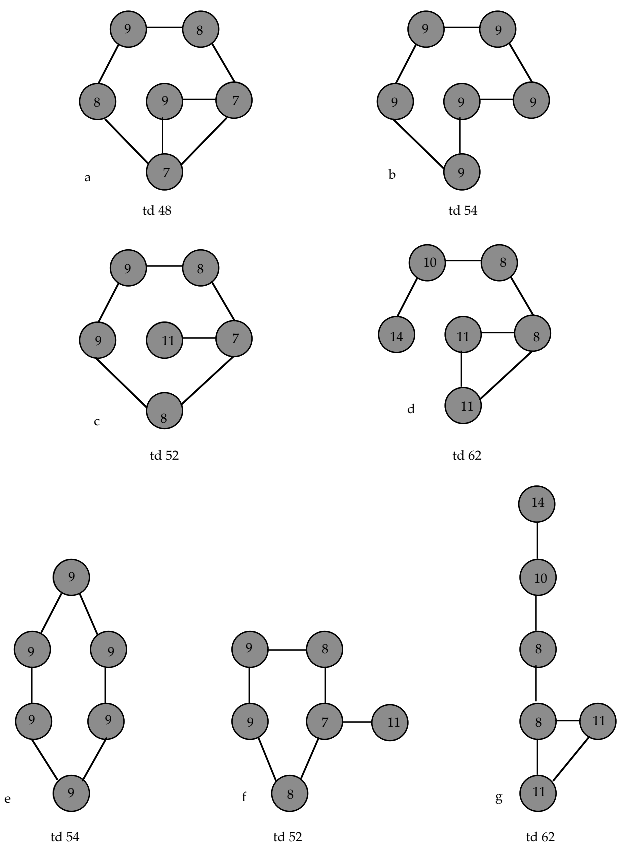


Figure 8. Series showing the the different 'global' effects of three simple 'local' changes on the same graph.

This is the nadir of our argument. Geometry seemed to be involved in how cities are constructed and how they are known, but not in their functionality. Here graphs seemed paramount. But we have now seen that graphs cannot carry the weight that this placed on them. Left to their own devices, they seem too unknowable and too unpredictable to be the sources of either urban order or structure. Since then both geometry and graphs seem to have a clear role in urban spatial form, but neither can account for it on its own, it follows that we probably need to understand how they interact, and perhaps how they are interdependent in creating urban order and structure. We can then begin by examining a theoretical case where they clearly interact: the 'theory of partitioning' set out in Chapters Eight of Space is the Machine, and developed for urban systems in chapter Nine (Hillier 1996a).

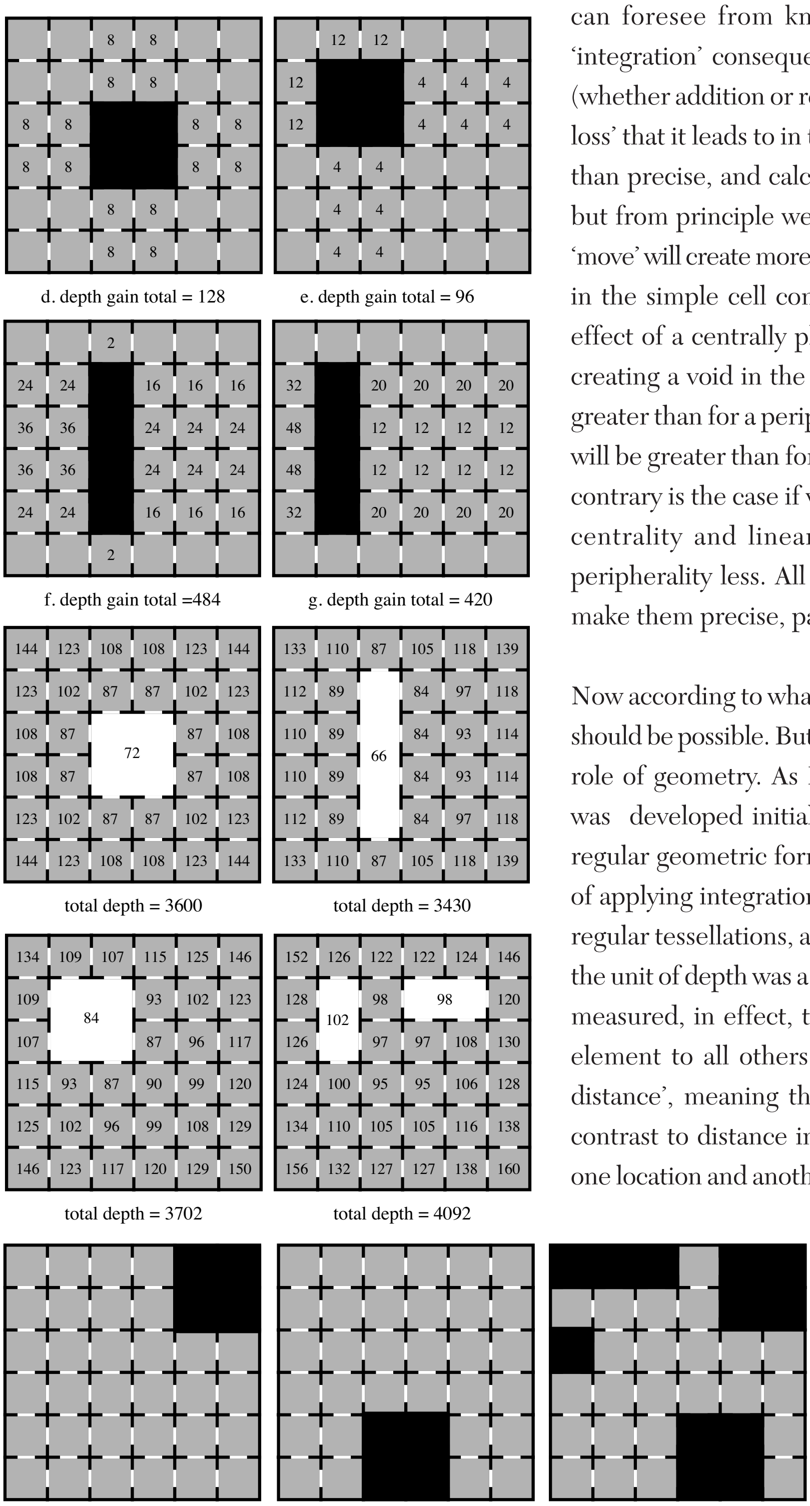
4.0 How Geometry and Topology Interact

4.1 The law of sufficient geometry

For those who have read these chapters, the theoretical unpredictability of graphs, as just reported, will come as a surprise. The 'theory of partitioning' set out in Chapter Eight shows how we can foresee from knowledge of a few principles the kind of 'integration' consequences that will follow from any partitioning (whether addition or removal) in terms of the 'depth gain' or 'depth loss' that it leads to in the system. The predictions are broad rather than precise, and calculation is needed to predict precise effects, but from principle we can usually know whether one partitioning 'move' will create more or less segregation than another. For example, in the simple cell complexes shown in Figure 9, the segregative effect of a centrally placed block (a closed cell of four partitions, creating a void in the system) will be known from principle to be greater than for a peripherally placed one, and that of a linear block will be greater than for a square block of the same area. Exactly the contrary is the case if we introduce larger spaces instead of blocks: centrality and linearity will integrate more, squareness and peripherality less. All these predictions, and the calculations that make them precise, pass through the intermediary of the graph.

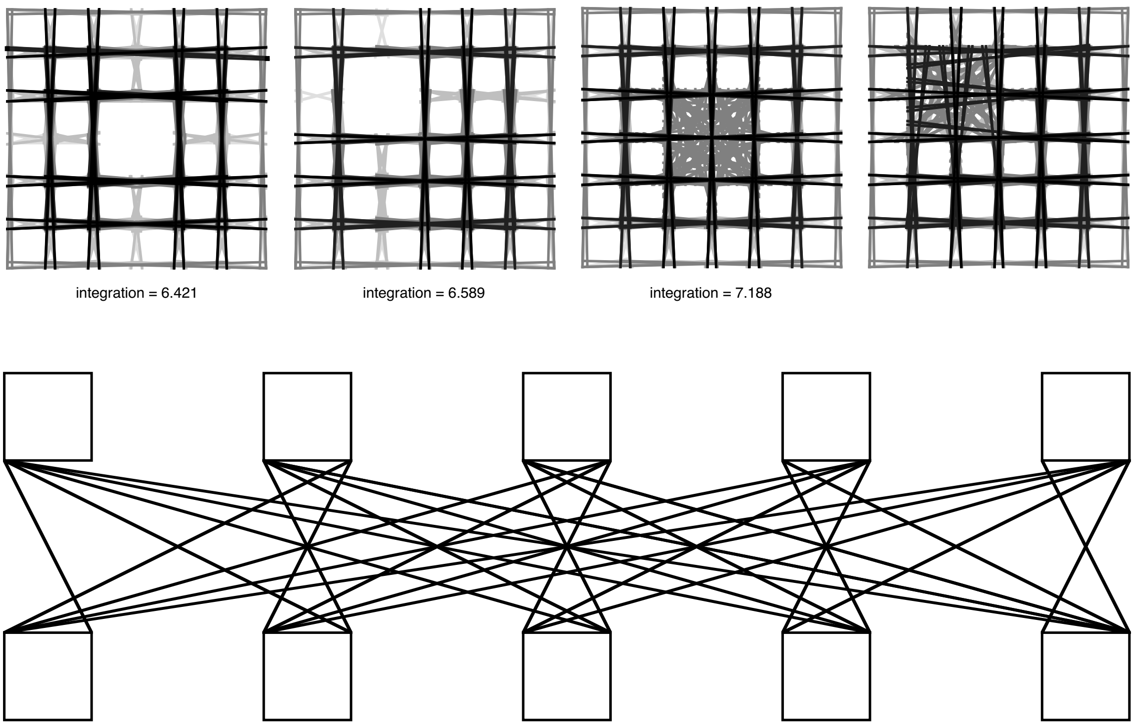
Now according to what we have just said about graphs, none of this should be possible. But it works. Why ? The answer lies in the hidden role of geometry. As Figure 9 shows, the 'theory of partitioning' was developed initially on the basis of spatial complexes with a regular geometric form. This was developed from the earlier idea of applying integration analysis to shapes by representing them as regular tessellations, and treating the tessellation as a graph. Since the unit of depth was a standard metric element, integration analysis measured, in effect, the modular distance from each tessellation element to all others. This gave rise to the notion of 'universal distance', meaning the distance from a location to all others, in contrast to distance in the normal sense of the distance between one location and another. By analysing shapes as tessellations, using the concept of universal distance, it was possible to show that certain geometrical properties of shapes, such as area-perimeter ratios, symmetries, degree of compactness, and so on, could be given a reasonable, and useful, interpretation in configurational analysis (Hillier, 1996)

Figure 9. Series showing the effects of introducing blocks and larger spaces of different sizes and shapes on total depths from constituent cells of a uniform 6x6 cell complex. In the top layer, the figures in the cells show the depth gained by that cell from the introduction of the block, thus decreasing it 'integration' in the complex. The sum of the gains is given below, showing the effect on the whole complex. In the second layer, the figures show the total depth of each cell with the introduction of a larger space, with the resulting total depth of the complex given below. These show the gain in integration (depth loss) for the complex from the introduction of the different spaces.



This geometrical framework is carried forward into the theory of partitioning. The partitioning model was developed on the basis of what was essentially a uniform tessellation of square spaces, amongst which partitions could be erected or removed. The concepts used in the theoretical model for predicting the effects of partitionings on spatial configuration are all essentially geometric: centrality, extension, contiguity and linearity. Centrally placed partitions reduce integration more than peripherally placed ones; partitioning more extended lines reduces integration more than partitioning shorter lines; contiguous partitions reduce integration more than non-contiguous partitions; and linearly contiguous partitions reduce integration more than 'curled up' partitions; and vice versa in each case for the creation of continuous spaces.

The partitioning model, in effect, works not on the basis of graphs per se, but on the basis of geometric shapes represented as graphs. The effect of this geometrisation of the graph is to create a world in which graphs behaved in a predictable and transparent way. The fundamental reason for this is that the measure of integration has been rendered metric: it measures not just the topological distance from each point to all others, but real distances, at least as measured in a rectilinear grid (rather than 'as the crow flies'). The pattern of topologically simplest paths in the graph, for example, has became isomorphic to the metrically shortest paths, and because both are put



into correspondence with geometric relations, both are made accessible also to intuition and prediction. Geometry has been used to tame the wild, disorderly world of the graph, to make them work lawfully and to access them to human intuition.
In Chapter Nine, the same model was shown to apply to urban type systems of block layouts by using the 'all line' map, that is the line complex that results from drawing every straight line that is tangent to a pair of block vertices, and subjecting the resulting - usually highly dense - line matrix to integration analysis. Such a system will follow the same principles as the partitioning theory, and this is demonstrated through a

Figure 10. Series (upper layer) showing that the effects of introducing blocks and spaces with different shapes and location in a uniform grid analysed by the all-line method follows the same pattern as those shown in the cell complexes in Figure 9. The lower figure magnifies parts of the all line map to clarify its construction.

series of case studies involving changing the block structures of a notional urban system - for example, joining two blocks together, or removing them to create larger spaces. Figure 10 shows how it works. The all line analysis generates a line for every pair of vertices that can see each other, and this means that there will be more lines that intersect in the central areas and fewer near the edges. The same effects are also shown to occur in the 'deformed grids' that characterise most urban systems.

There is then a profound sense in which geometry and graphs interact. By representing geometric shapes as systems of graphs through the intermediary of the regular tessellation, we can show how graphs can express the movement logic of the system. We can call it the law of sufficient geometry. In principle, it seems that something similar seems to have happened in cities. Their spatial layouts seem to have acquired 'sufficient geometry' to make the graphs behave in a regular way. We have already noted that cities are nearly geometrical, and that they are knowable and predictable through their geometric properties. We also know that if graphs are to behave in a predictable and knowable way, there must be enough geometry in the system. We can be quite precise about this. There must be enough geometry to give an interpretable and consistent meaning to the geometric terms of the theoretical model: centrality, metricity, contiguity and linearity. This can only be done in principle by a single strategy: by bringing the geometric and metric properties of the system into a reasonable correspondence with the topology of relations described by the graph.

From their geometry and their functional behaviour, it seems that something like this happens in cities. But to understand its exact nature, we need to understand how it happens. Is there perhaps some process by which the city creates its own geometry as it grows, and in this way ensures that its global configurational structures, as represented by its graphs, behave in a more or less knowable and predictable way. We have an important clue. If there is such a process, then it seems likely that it lies in the nature of movement.

4.2 Two reflections on movement

Or more precisely, in the geometry of movement. This reminds us of what was said in the opening sentences of this paper: that a key task of the researcher was to decide on a representation which might capture the functional logic of the system of interest. This reflects a key element in the metatheoretical foundation of space syntax: that space is not to be treated as a background to either objects or human activities, but as an intrinsic aspect of both. Thus we converse in convex spaces, we see isovist fields - and we move in lines. One implication of this is that movement is not simply a functionality in the system, arising only as a consequence of the system. It also has its own natural geometry. The selecting of the line representation in the first place was intended to reflect the natural geometry of movement and so internalise it into the spatial representation. A line matrix thus becomes a configuration of possible movement.

At a very basic level, the line representation seems also to be called for by the most obvious single basic fact about the morphology of cities (and probably of most spatial systems as they grow large): the fundamental organisation of space is linear, in that buildings are arranged in paired rows to permit linear movement between them.

Even in the most tortuous cul-de-sac sequences of spaces in, say, a traditional Islamic town, the linear principle still holds. This is so much the basic principle of urban spatial organisation, that it is difficult to see how it could have escaped the attention of generations of urban historians. It is even more difficult to see how some twentieth century theorists could have contemplated the historical city and claimed that the enclosed space, such as the square or plaza, is the basic spatial element. Even at the most local level, settlement space is shaped linearly by buildings arranged in rows to facilitate movement. It is obvious that it should be so, and it is.

4.3 Linear and grid movement processes

It is not difficult to see how the evolution of settlement space then follows the logic of movement and reflects its geometry. The two types of consistency that we noted as pervasively urban systems - the obtuse angle sequences and the near right angles local complexes - are both products of the natural geometry of movement operating on the line combination processes by which the structure of settlement space - and its axial map - evolve. All we need to consider is an old and familiar principle: the need to make movement as efficient as possible by minimising mean trip length.

But to understand the effect of this on the urban grid, and how it gives rise to the distinctive geometry of the city, we must consider two kinds of movement: movement from edge to centre (and back again), which is a matter of moving from a specific origin, namely one of the peripheral entry points to the city, to a specific destination, and therefore requires an essentially linear form if trip lengths are to be minimised; and movement within urban areas, where the grid must respond not to the need for efficient movement from a specific origin to a specific destination, but the need for efficient movement from all origins to all destinations. It is clear that the radial structure that we have noted as one of the geometric elements of the integration core of the city is generated by the first of these processes, and in doing this it may well make use of or adapt pre-existing paths between settlements. It is less clear that the 'more or less orthogonal' central grid is generated by the second. Nevertheless, it is central to the argument here and must therefore be considered in great detail.

Suppose built forms are being generated randomly on a surface (which for the moment we will assume is isotropic) then we can conceive of each new building as both an attractor and a source of potential movement. Assume there is some distance decay function by which shorter journeys are more likely and longer journeys less likely, then there is likely to be some local subset of built forms which are all likely to be destinations (and therefore sources) for each other, and others, more remote, some of which, but not all, will be destinations for this subset. It follows that there will always be a local subset of blocks where if the space organisation is to maximise trip efficiency, then it must create the spatial pattern which minimises all to all mean trip length. We know already that this will be the system that maximises metric integration. In partitioning theory, all depth gain (which is the same as distance gain in mean trip length) results from making relations from origins to destinations non-linear - in effect, causing deviations from 'the shortest distance between two points'. We also know from partitioning theory (Hillier, 1996a) the principles for block placing to minimise non-linearity: block short lines rather than long; block peripherally rather than centrally; avoid contiguity, since this will increase non-linearity; and if you have

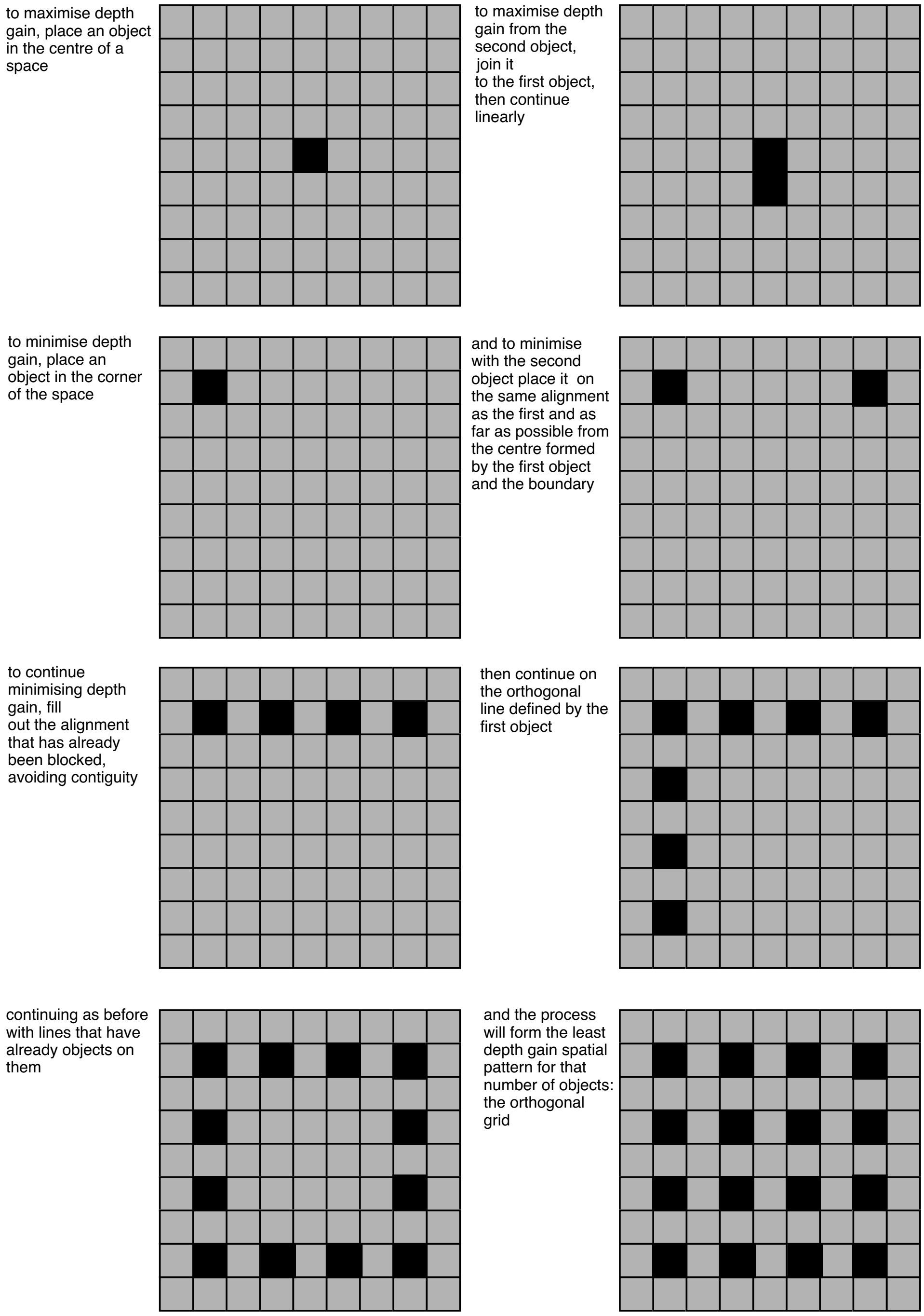


Figure 11. Series showing how the progressive placing of blocks within a uniform grid to minimise depth gain at each stage will construct a grid-like layout.

contiguity, then ensure that the composite block is non-linear.

It is not difficult to see that such a process of all to all distance minimisation, will, by constantly placing new blocks either non-contiguously between existing blocks, or on alignment with them, will inevitable maximise the linearity of all spaces adjacent to blocks, and this will lead to some approximation of the orthogonal grid. The word approximation is used advisedly because it is not the geometry of the grid that is optimal, but its topology. Deviation from strict rectilinearity will make no difference provided the connectivity topology of an orthogonal grid is realised. This process is illustrated notionally for a closed system in the sequence of captioned figures shown in Figure 11. This illustrates clearly the primacy of line topology over geometry, and perhaps shows it to be common sense. Suppose for example we retain the geometry of street alignment in Mayfair, but fail to connect them to Oxford Street by building a wall. It is clear that the entire movement characteristics of the area will be transformed. Of course it is the topology of connection that is critical, first to movement, and from there to the dynamics of urban evolution.

It seems then that the two line processes generated by the logic of movement tend in themselves towards the kind of 'orthoradial grid' that space syntax analysis identifies as a deep structure in cities of all kinds, including the largest, that is a more or less orthogonal central grid area, linked by radial alignment to more peripheral and external locations. In other words, the logical outcome of trip minimisation, provided we specify the two kinds of movement, is exactly the generic geometric global structure that we tend to find in cities as their 'integration core'. Since it is clearly the topology of connections created by the geometric processes of trip length minimisation that creates this global geometry, it is not surprising that the structure is brought to light by topological analysis of the line structure. But surprising or not, we can say that far from concealing the geometric structure of cities, it is the analysis of the line topology that brings it to light.

4.4 Exactly how geometry gets into the graph

In other words, the geometry gets into the graphs. Exactly how does it do so ? We may begin by noting another common objection to the axial map as the basis of urban analysis: the non-uniformity of line elements. We have already seen that the topological property of connectivity is far more important than any geometric property in creating that line's potential for carrying movement in the system. One of the most pervasive correlations found in axial maps of cities is that between the length of lines and their connectivity. Exactly what this correlation is depends on how it is measured, and exactly what is measured. For example, the straight r-squared for line length and connectivity for Tokyo is .78 and for London .64. For a sample of American cities, the r-squared for mean length and connectivity is .773, and for a sample of European cities it is .637 (Major, 1998). However, if both variables are logged to normalise the distribution and so diminish the influence of the 'supergrid' lines, then Tokyo becomes .65 and London .61. In other cases, such as Amsterdam, the correlation is harder to asses due to the effect of interventions such as the ring road, which, in the manner of ring roads, is a set of long, integrated lines which at the same time are poorly connected. In general, however, in those parts of towns where the process of growth has been organic (grown street by street) or semi-organic (grown in lumps, as parts of the west end of London were), the degree of agreement between the length of lines and their connectivity is one of the foundations of order in the system.

Given this pervasive correlation, it is clear that it is precisely the non-uniformity of the lines that allows line-length to be internalised into the graph as different degrees of connectivity. From the point of view of the whole system, the translation of the axial map into a line graph has the effect of translating each line not into a node per se, but into a distinct set of connectivities, and how this set of connectivities relates to all the other connectivities in the system is of course the critical property from the point of view of movement.

But it is not only the variable length of lines that is internalised into the structure of the graph. Angles of incidence are also approximated in the graph in the following way. If the connection from a line is close to a right angle connection, and it is not a cul-de-sac (which in fact will of course immediately appear in the graph) then the likelihood is that it will link to at least one line that will link back to the original line, that is form a local ring in the graph within one or two more connections. If the connection is an obtuse angle, and approximates a linear continuation, then the likelihood is that it will link to lines which then link to lines which have no other connection back to the original line within a reasonable number of steps. On the contrary, it will find lines which are remote from other connection to the original line, and this will be consistently true as obtuse angle connections continue into remote parts of the graph.

Both prime geometric variables, length of line and angle of incidence, thus appear as distinct pattern formers in the graph. In fact, characteristic axial configurations have very distinctive graphs. A useful place to start is the orthogonal grid, which has the important graph property of being bipartite, meaning that the nodes can be divided into two groups such that all connections are from one group to another, and none are within groups. Since in the orthogonal grid these groups are symmetrical, it is useful to represent the graph as two vertical lines of nodes, with each node of each line connecting to all nodes in the other, but to none in its own, as in Figure 12a. The same graph will also of course apply to the non-orthogonal version on the right, which still satisfies the topology of the orthogonal grid. The standard modifications

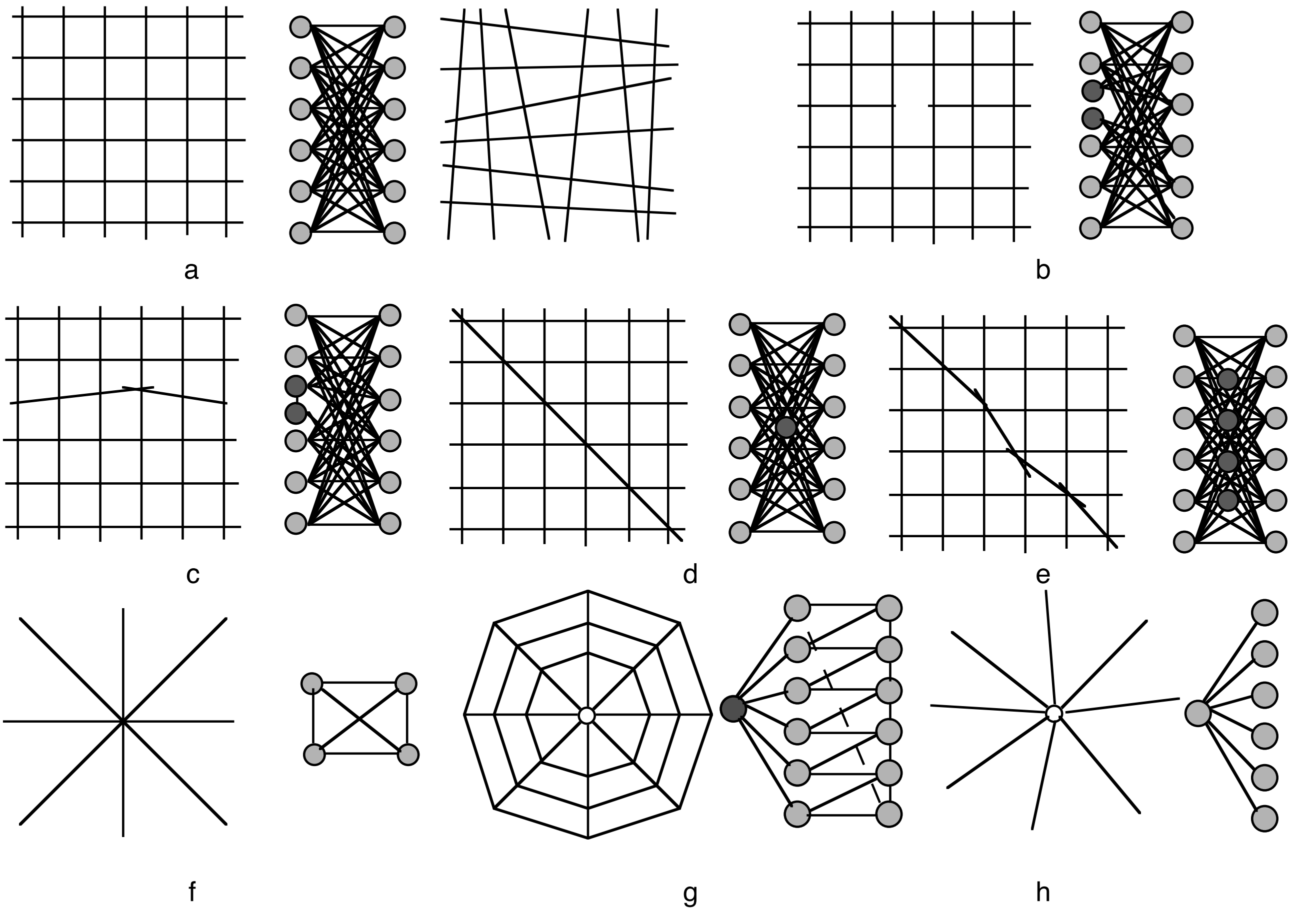


Figure 12. Graph representations of simple grid geometries.

of the orthogonal grid can then be simply represented within this convention. An 'interruption' in the grid, as in Figure 12b shows as a split of one node in one of the lines into two, without a connection between them, with the connections to the other line split between the two nodes. A geometric 'deformation' of the grid, as in Figure 12c, shows as a split of one node into two, but this time with a connection between them, again with the links to the other line split appropriately. A diagonal line across the grid, as in Figure 12d, shows as a single node (for graphic convenience, located between the two vertical lines) connection to each node in both lines. A 'wandering diagonal', as in Figure 12e, splits the diagonal node into a series with each connected to its neighbours, and to each of the two lines of nodes as appropriate. A radial grid is one in which one of the two line groups of the graph connect to each other and become a clique (all connect to all others), while each of the other group of 'lateral' lines connects to its 'lateral' neighbours and to the neighbouring pair of radials, with a separate line of nodes needed for each circuit. At the theoretical limits, a set of lines which all link to each other (as in the radial group) are a clique, that is a graph in which all nodes connect to all others, while a wandering radial will be a sequence of nodes in which each leads in either direction to exactly one other, and these are the two integration limits for connected graphs. With a little skill we can learn to recognise elements of these patterns in the graph.

The line graph analysis does not then ignore the geometric properties of space: it internalises them into the graph. There is a pervasive geometric order in the axial maps cities, constructed out of the lengths of lines and the angles of intersection, and it is exactly these properties that are in effect translated into the structure of the graph, that is, into its overall pattern of connectivities.

4.5 Internalising attraction

In internalising the geometry of the system into the graph it seems likely that the graph also internalises another key property of the system: the distribution of attraction, that is the distribution of the potential destinations (and origins) for movement. Attraction has never been a key concept in the space syntax methods for predicting movement. In fact, it has always been a quirk of the method for predicting movement that it seemed to do away with the need for laborious origin-destination analysis. Looking more closely, we see that origins and destinations are not ignored in the method: they are assumed to be more or less homogeneously distributed through the system, and only to the degree that this is so (with inhomogeneities due to the differential operation of the grid in different locations) will it be possible to predict movement from configuration alone.

This 'homogeneity assumption' is not laziness. There are good theoretical grounds for thinking it may be both justifiable and necessary. If we think of the built forms that construct the space of a settlement as attractors (and of course also as sources) of movement, this it is clear that the very logic of the evolving settlement system leads in the first place to the diffusion of this attraction throughout the system. The precondition of having a line in the axial map in a location is having built forms for it to reach. Two key points can be made about this 'attraction diffusion'. First it will diffuse very much under the influence of the linear patterns that are created by the evolving movement logic of the system. Second, for simple geometrical reasons, attraction will initially at least, be roughly proportional to the length of lines and therefore to the connectivity of the lines making up the system. In other words, to the degree that the metric properties of lines are reflected in the graph, then we should also find that the graph reflects also the degree to which the diffused attraction of built forms is present on lines.

Where we then find abnormal local attraction, for example due to the presence of shops or higher building densities, then we may expect it to be due to the multiplier effects and feedback processes identified in the 'essential urban dynamic' process. Since this process is itself set in motion by the effect of the grid configuration on movement in different locations, than we would expect these attractor hot-spots would still follow the logic of the grid (though in a non-linear way (Hillier et al 1993), and thus to be captured in the line-graph.

5.0 The Logic of the Nonlocal System

5.1 How graphs then construct the nonlocal system

The graph can then be subject to analysis. The most important thing about a graph is that it is a diagram of pure relations. We may choose to weight nodes or links, but these are refinements, not part of the idea of a graph as a general model for relational structures of all kinds. Because it is a map of pure relations, in which elements (or nodes) have no attributes apart from being connected to others, graph measures naturally measure extrinsic, or nonlocal properties of elements. Even the simplest measure of a node, the connectivity (or degree) of the node, expresses not an intrinsic property of the element which it would retain if disjoint from the system, but an extrinsic property which it would lose entirely if it was disjoint from the system. There is no limit to the degree of extrinsicity or non-locality that we can apply to measures. We can for example assign to each node its graph distance from all others. In this case we express as a property of the node its relative position in the system as a whole. This is of course the basis of the integration measures, and limiting the radius of the measure simply limits the number of topological steps away from a node in the graphs that we choose to count.

In other words, graphs, precisely because they ignore the attributes of elements and take into account only (and all) relations, are able to express extrinsic or nonlocal measures to the fullest extent. It is in the nature of a graph to give a picture of a node from the point of view of other nodes, and if we wish all other nodes. It is of course precisely this that is required in axial maps because urban spatial systems are themselves nonlocal systems. For example, as we have seen the amount of movement that will pass through a line will be a function of its depth from all other lines and its position on all possible paths from all origins to all destination, that is its potential for to- and through-movement.

Nonlocal measure are therefore required if this logic is to be captured. This means that to the degree that we assign intrinsic attributes to elements, the precision of this nonlocal description will be lost. However, assigning intrinsic attributes to elements as nodes of the graph is unnecessary (and would be harmful) because we have already expressed all the key geometric attributes of elements (those through which the topology of the system is constructed) not as properties of the node but in terms of essential properties of the graph itself, that is its relational structure.

The line-graph is then far more subtle than appears at first sight. By internalising the geometric properties of elements into the structure of the graph itself, it permits a purely relational and highly nonlocal expression of the critical aspect of the axial map: its structure of connectivities. The line is in effect not reduced to a node, but to a set of specific connectivities. In locating the line in the system as a whole we are essentially locating that set of connectivities within the total set formed by the whole system. Connectivities, as we have seen, and their topological arrangement into a network by the geometry of the system, are by far the most important formal attributes of the system from the point of view of movement. And movement, as constructed by the line-graph, drives the system.

There are then, it seems, solid theoretical grounds for the claim that line graphs succeed in representing the true geometry of cities. On reflection, we can see that cities, as spatial systems, are of their very essence nonlocal. The key attributes of spatial elements are not intrinsic to the element but extrinsic, and have to do with the position of the element in the system relative to all others. Changes in the surrounding system produce changes in the critical attributes of the element without changing its geometry. The non-locality of the urban spatial system arises from the central role that movement, which is clearly nonlocal, plays in the shaping of space in the evolving urban system.

Both the line and the topology of the graph, it is argued, are critical to capturing this non-locality. The line is the least local representation of space, because it contains the least information about the local articulation of space and the most about remote connections, while topological measures are the least localised measure because they contain the least local information about the element and the most global information about the position of the element in the complex as a whole. The reason why the line-graph combination 'works' in syntax analysis is because the two together approximate the true, nonlocal geometry of the urban system. Geometry may be the outward and visible form of urban order, but line topology gives us its inner structure. This is why space syntax works - when it looks as though it shouldn't.

References

Hanson J, 1989, 'Order and structure in urban design; the plans for the rebuilding of London after the Great Fire of 1666' *Ekistics* Vol 56 No 334-5.

Hillier B, et al 1982, 'Space syntax: a new urban perspective' *Architect's Journal*, November 30th pp 47-63

Hillier B, & Hanson J. 1984 *The Social Logic of Space* (Cambridge University Press, Cambridge)

Hillier B, et al 1987 'Creating life: or does architecture determine anything ?' *Architecture & Comportement/ Architecture & Behaviour*, Special issue on the work of the Unit for Architectural Studies, UCL, Vol 3 No 3 pp 23-250

Hillier B, Penn A, Hanson J, Grajewski T and Xu J, 1993, 'Natural movement: configuration and attraction in urban pedestrian movement' *Environment and Planning B: Planning and Design* Vol 20 pp 29-66

Hillier B, 1993 'Specifically architectural theory' in *The Harvard Architectural Review* Vol 9, pp 8-27

Hillier B, 1996a *Space is the Machine* (Cambridge University Press, Cambridge)

Hillier B, 1996b: 'Cities and movement economies' in *Urban Design International* 1 (1), pp 41-60

Karimi K, 1998 *Continuity and change in old cities* PhD thesis, Bartlett School of Graduate Studies, UCL

Lynch K, 1960 *The Image of the City* MIT Press

Major MD, 1998 'Building the American City, *Space Syntax - First International Symposium Proceedings*, Vol 3

Penn et al, 1998 Configurational modelling of urban movement networks *Environment & Planning B Planning and Design* 25 (1) pp 59-84

Peponis J, et al 1989' The Spatial Core of Urban Culture' *Ekistics* Vol 56 No 334-5; pp 43-55

Read S, 1997 'Space syntax and the Dutch city' *Space Syntax - First International Symposium Proceedings*, Vol 1, 2.1-2.13

Steadman J, 1983 *Architectural Morphology* Pion

Authors of maps

London : Hua Yoo, Bartlett School of Graduate Studies, UCL1991

Santigao: Rosso et al, Pontifica Universidad Catolica de Chile, Santiago

Tokyo: Masaki Nishibori & Sinichi Iida; Bartlett School of Graduate Studies, UCL 1996

Athens: Velentina Karvounzni, Bartlett School of Graduate Studies, UCL 1992

Baltimore: Shazir Shah; Bartlett School of Graduate Studies, UCL 1995