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Pathways to creating differentiated grids: Types, benefits and costs

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Abstract
The patterns of syntactic differentiation and their causes and effects are fundamental to space syntax analysis. Often, however, differentiation is taken for granted with no reference to the dynamic process that brings it about. Here, we first show that by measuring the amount of syntactic differentiation, we can better distinguish between types of street networks. We then show that repeated local transformations of a regular street grid lead to different yet largely predictable trajectories of differentiation depending upon the rules used. Finally, we show that different paths to differentiation entail different costs in terms of undesirable properties. This allows us to better assess the likely consequences of design moves and their appropriateness relative to design intentions.

Keywords
Design space, differentiated grid, typology, superblock, space syntax

Introduction: Syntactic structure defined as a system of differentiation
By necessity or by preference, streets often differ in their linear extension, width, sinuosity, or connectivity. Such differentiation serves as the point of departure for further articulation of street types and patterns. Differentiation also gives cities (or parts of a city) unique characters, as demonstrated by Hillier et al. (1983)’s description of Apt, a small town in the south of France, which they characterized as a deformed grid:

What do we mean by a deformed grid? First, compared to an orthogonal grid, the length of sightlines from particular spaces—their one-dimensional extension—is sometimes restricted and...
sometimes extended… This one-dimensional extension we call axially. Second, the width of
spaces—their two-dimensional extension—varies considerably. This we call convexity. In Apt
the buildings seem to be arranged in such a way as to create a continuous flow of open space
with wider and narrower sections and shorter and longer perspectives… Also the layout offers a
choice of routes from any point in the town to any other, with few cul-de-sacs. (p. 50)

The variations in the length and the alignment of individual streets are the means to creating
differences in the overall pattern. Hillier (1996) calls such systematic differentiation at the
non-local scale the structure of the urban grid and shows that it can be analyzed as a spatial
configuration—that is, as relations which take into account all other relations in a system.
The differentiation of an urban grid at the non-local scale has been studied extensively from
the perspective of the spatial syntax of cities. This has led to a series of theoretical insights
about how the urban spatial syntax systematically channels the flows of movement, thus
affecting the distributions of commercial land uses (Chiaradia et al., 2012; Hillier, 1997;
Hillier et al., 1993; Ozbil et al., 2011; Penn et al., 1998; Peponis et al., 1989; Scoppa and
Peponis, 2015).

Of particular interest to the architects and urban designers is the fact that the syntactic
structure—revealed by the variation of the integration (or network closeness centrality) of
individual streets—has opened up new typologies of settlements and cities. The syntactic
structures of urban grids have been analyzed intuitively, quantitatively, and algorithmically
(Feng and Peponis, 2020; Hillier et al., 1983; Peponis et al., 1989). However, in seeking to
distill types of syntactic structure, studies often focus on the end result of differentiation
rather than the dynamic process of differentiation. The few studies that link the process of
differentiation at the local scale to the result of differentiation at the global scale do so only
from the perspective of the gains and losses of total depth of the system—that is, the
overall angular or turns distance from each space to all others in the system (Hillier,

The aim of this paper is two-fold. First, we show that by not limiting ourselves to the
analysis of the total depth of a system and considering also the amount and the degree of
syntactic differentiation within the system, we can better distinguish urban grids. Second, we
show that the interplay between the localized geometric differentiation of street grid and the
emergent syntactic differentiation (which is, by definition, non-local) can be studied as more
than a simple depth-gaining or depth-saving game. We show that by locally varying a street
grid in consistent manners, the process of syntactic differentiation can take off along dif-
ferent, yet largely predictable, trajectories. Our findings allow us to better assess the likely
consequences of design moves and their appropriateness relative to design intentions.

All differentiated grids are not the same: A divergent pattern of syntactic differentiation

An intuitive observation

We use the term differentiated grids to indicate the layouts in which street segments are
geometrically or syntactically differentiated. This study focuses on the differentiated grids at
the scale of a superblock—a rectangular piece of urban area bounded by arterial roads or
major streets. The sides of a superblock can vary between 600 m (close to 0.5 mile) and
1600 m (1 mile), while the interior of a superblock can contain many urban blocks circum-
scribed by intersecting local streets (Peponis et al., 2015, 2017). As organizing units of
urbanism, superblocks can be found in many cities around the world.
As shown in Figure 1, while the internal street networks of the superblocks are all differentiated grids, the manner of differentiation varies. At the local scale, streets are differentiated either in sinuosity or in continuity (and by implication, connectivity). In Doxiadis’s (1968) design for Sector G-7 of Islamabad, most streets are straight, running parallel, or perpendicular to each other. They differ, however, in continuity—some streets are long and span across more than a dozen blocks, while many are short and abruptly discontinued. By contrast, in Perry and Whitten’s design for an exemplar “neighborhood unit”, it is often

**Figure 1.** Internal street networks of 10 superblocks. Their syntactic structures are revealed by DDL analysis. The color spectrum from red through orange and yellow to green and blue corresponds to the range from high integration (low DDL) to low integration (high DDL).
hard to tell where a street starts and ends. Nevertheless, the street grid is continuously differentiated via rotation of street segments (Perry, 1929).

The closeness centrality or integration of each street segment is measured by calculating the length-weighted average of directional distance (DDL) to all the other street segments in the superblock, using 20° as the degree threshold to determine whether there is a directional change between two street segments (Feng and Zhang, 2019; Peponis et al., 2008). In cases such as the superblock found in Chicago, the internal street network is close to a perfect grid—for the most part of the network, people can get from anywhere to anywhere else without making more than two-directional changes. Consequently, the majority of the streets are only weakly differentiated from each other. And when they are truly differentiated, the difference is dramatic (see the contrast between the short streets contained within a single urban block and those spanning across the entire superblock). By contrast, the internal streets of the superblocks in Gangnam of Seoul, Korea, are more richly differentiated (Peponis et al., 2016). A variety of intermediate conditions lies between the most and the least integrated. Differentiation unfolds gradually within a highly connected structure and is both subtle and somewhat unpredictable. One would never be trapped in disjoint enclaves in such a grid—because it rarely takes more than two or three turns to get from the most segregated streets back to the most integrated ones. This is in sharp contrast to the way streets are differentiated in the superblocks found in Los Angeles and Phoenix (Figure 1).

**Quantitative characterization: Relationships between measures**

The different kinds of differentiation observed intuitively can be assessed quantitatively. We measure the amount of syntactic differentiation in a differentiated grid by the proportion of unique DDL values present in the grid and measure the degree of syntactic differentiation by the standard deviation of the DDL values. To link the local sinuosity and connectivity of streets to the amount of overall syntactic differentiation, we introduce a new measure which we call fragmentation. We define the fragmentation of a grid as the ratio between the total number of continuity lines and the total number of line segments present in the grid. Our definition of a continuity line is similar to that offered by Figueiredo and Amorim (2005). A continuity line contains one or more street segments that collectively form a continuous quasi-linear path (depending upon the angular threshold that defines a direction change, as in the calculation of DDL). The total number of continuity lines in a street grid is the minimum number of continuity lines that encompass all the street segments in the grid. Figure 2 shows the total number of continuity lines, the total number of line segments, and the corresponding fragmentation value for several simple, hypothetical street grids. Except for the one that lies on the extreme left, all the grids have exactly eight continuity lines and only differ by the total number of constituent segments. From a design perspective, the key to reducing the fragmentation of a street grid is to align the line segments as much as possible.

The fragmentation of a street grid turns out to be an excellent indicator of the proportion of distinct DDL values in the grid. It is not surprising as the segments which comprise the same continuity line also share the same (or almost the same) DDL value. Therefore, as long as the continuity lines in a grid all bear different DDL values (which is frequently the case in real street networks), then the fragmentation of a grid should be identical to the proportion of distinct DDL values in the grid. As shown in Figure 3, there is a near-perfect correlation between the fragmentation and the proportion of distinct DDL values observed in the superblock examples. We can thus conveniently use fragmentation as a reliable estimate of the amount of syntactic differentiation of a street grid.
As we will show next, street networks inside the superblocks can be distinguished by the relationship between the amount of fragmentality, the standard deviation of DDL values (degree of differentiation), and the mean DDL (integration).

The amount of syntactic differentiation vs. the degree of syntactic differentiation. As shown in Figure 4, the degree of syntactic differentiation in each grid tends to increase as fragmentality increases. The degrees of syntactic differentiation in two grids can, however, differ widely even when they have similar fragmentality. For instance, the two superblocks from Gangnam are similar to the superblocks from Phoenix and Los Angeles in fragmentality, yet
with very different degrees of differentiation. Intuitively, Phoenix and Los Angeles comprise more polarized syntactic conditions than the gradually differentiated Gangnam superblocks. The amount of syntactic differentiation vs. the level of integration. Figure 5 shows that the correlation between the fragmentality and average integration of grids is not tight. The Chicago superblock has the most integrated street structure with the least fragmentality. The superblocks sampled from Phoenix, Los Angeles, and Chandigarh encompass a variety of syntactic conditions at the cost of reducing overall integration. By contrast, the superblocks sampled from Gangnam and Beijing have diverse syntactic conditions while maintaining a relatively high overall integration. Doxiadis’s design for Sector G-7 of Islamabad has relatively low integration and modest differentiation. At a similar level of integration, Perry’s design has a much richer blend of syntactic conditions. The internal street networks of the superblocks, therefore, can be distinguished by their relative scores along the multiple dimensions of syntactic differentiation. More importantly, the divergent pattern of syntactic differentiation exhibited in the superblock examples suggests that the same amount of syntactic differentiation can be realized in different ways, leading to higher or lower degrees of syntactic differentiation and higher or lower levels of integration. The quantitative characterization is useful in evaluating and comparing differentiated grids, but it tells us little about how one could deliberately differentiate a street grid in desirable ways. To tackle this question, we study the syntactic effects of the repeated application of simple, localized design moves.

The generation of differentiated grids
We generate differentiated grids by taking a $9 \times 9$ square grid measuring 800 m on the side as a starting point. Such a grid is syntactically neutral or undifferentiated, because each street is of equal length, connects the same number of other streets, and has the same DDL value. To

\[ R = 0.63, p = 0.05 \]
\[ y = 0.2 + 1.7x \quad R^2 = 0.4 \]

Figure 4. A scatterplot showing the relationship between the standard deviation of DDL values in each grid and the fragmentality of each grid based on the superblock examples.
create local differentiation, we developed eight different kinds of localized design moves which we call syntactic operators (Figure 6).

To implement these operators, we first need to represent the street grid as a street graph that contains vertices, edges, and cells. An edge represents a straight segment in a street centerline map. A vertex lies wherever two edges intersect. It also lies on the “dead-end” of a cul-de-sac. A cell is simply the polygonal area enclosed by a chain of edges and represents an internal urban block. Table 1 describes what each operator does and the design intention behind it.

We generated the majority of the differentiated grids by repeatedly applying a single operator on the original square grid a certain number of times. At each step of application, the operator was applied at a random location. Eight distinct groups of differentiated grids were thus generated, each comprising 600 designs. Each group has six sub-groups of designs, corresponding to the number of times the operator was applied (Table 1). In addition, we generated 600 designs by randomly applying the operations of disjoining vertices, linking edge to edge, shifting vertex, splitting vertex, and cross-concatenating vertices for a number of times. Thus, we generated a total of nine groups of designs collectively, comprising 5400 differentiated grids. We will refer to each group of designs by the name of the syntactic operator used. The group generated by randomly applying different syntactic operators will be referred to as “mixed”.

**Integration costs of different pathways to syntactic differentiation**

Based on this universe of designs, we study, for each group of designs, how the syntactic properties vary with respect to the same increase of fragmentality, or amount of differentiation.
Figure 7 shows that for most groups of designs, there is a strong positive linear relationship between the degree of syntactic differentiation and the amount of fragmentality per design. Despite the consistent relationship, the slopes of the regression lines are different. In other words, by applying different operators, the same amount of increase in the fragmentality of a design can lead to different amounts of increase in the degree of syntactic differentiation. For example, in the case of linking edge to edge, one unit increase in the fragmentality per design increases the standard deviation of DDL values by 2.3 on average. By contrast, in the case of contracting edge, one unit increase in the fragmentality per design increases the standard deviation of DDL values by only 0.29 on average. In the case of disjoining vertices, the relationship seems to be more complex—the slope becomes steeper as the fragmentality per design increases.

Fragmentality vs. the level of integration

Figure 8 shows that for most groups of designs, there is a strong positive linear relationship between the level of integration and fragmentality per design. Despite the consistent relationship, the slopes of the regression lines, again, vary. Depending on the operator applied, the same amount of increase in fragmentality can lead to different mean DDL values. For example, in the case of splitting vertex, one unit increase in the fragmentality
per design increases mean DDL by 6.3 on average. By contrast, in the case of contracting edge, one unit increase in the fragmentality per design increases mean DDL by only 1.7 on average.

There are also differences in the way the data points (representing the generated grids) are clustered around the regression lines. For those generated by shifting vertex, the data points are closely grouped around the regression line indicating that the choice of location for applying an operation has no effect. In the case of disjoining vertices, however, data points deviate more from the regression line as the fragmentality per design increases. Here, there is a scope for design judgment and design freedom since strategically applied moves can outperform randomly applied moves—where we apply the operation matters.

Linear regression may not always be the best statistical tool for modeling the relationship between distance and fragmentality for each group of designs—especially considering that

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Table 1. Descriptions of the syntactic operators and the rules used to generate the universe of differentiated grids.

<table>
<thead>
<tr>
<th>Operator name</th>
<th>Description</th>
<th>Design intention</th>
<th>Frequency of application</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift vertex</td>
<td>Move a vertex to a new position</td>
<td>Create curvilinear streets and introduce variation in street vistas</td>
<td>8, 16, 24, 32, 40, 49</td>
<td>600</td>
</tr>
<tr>
<td>Contract edge</td>
<td>Press the two endpoints of an edge together</td>
<td>Create a focal point of visual interest and radial street patterns</td>
<td>3, 6, 9, 12, 15, 18</td>
<td>600</td>
</tr>
<tr>
<td>Cross-concate-</td>
<td>Join two non-adjacent vertices that belong to the same cell</td>
<td>Create a focal point of visual interest and radial street patterns</td>
<td>5, 10, 15, 20, 25, 30</td>
<td>600</td>
</tr>
<tr>
<td>Disjoin vertices</td>
<td>Remove an edge</td>
<td>Reduce street density and connectivity; consolidate blocks to accommodate special building programs</td>
<td>11, 22, 33, 44, 55, 66</td>
<td>600</td>
</tr>
<tr>
<td>Split vertex</td>
<td>Split a vertex in two and separate them by “swinging” an incident edge</td>
<td>Discourage uninterrupted movement; allow but limit access to a space</td>
<td>8, 16, 24, 32, 40, 49</td>
<td>600</td>
</tr>
<tr>
<td>Link vertex to</td>
<td>Add an edge to connect two vertices that belong to the same cell</td>
<td>Create diagonal streets; improve local circulation in grid cities</td>
<td>11, 22, 33, 44, 55, 64</td>
<td>600</td>
</tr>
<tr>
<td>vertex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Link vertex to</td>
<td>Add an edge to connect a vertex and an edge that belong to the same cell</td>
<td>Create a local focus of visual interest</td>
<td>10, 20, 30, 40, 50, 62</td>
<td>600</td>
</tr>
<tr>
<td>edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Link edge to edge</td>
<td>Connect two edges that belong to the same cell</td>
<td>Introduce short streets to improve local circulation; increase street density</td>
<td>14, 28, 42, 56, 70, 84</td>
<td>600</td>
</tr>
<tr>
<td>Mixed operation</td>
<td>Randomly apply disjoin vertices, link edge to edge, shift vertex, split vertex, or cross-concate-vertices</td>
<td></td>
<td>N/A</td>
<td>600</td>
</tr>
</tbody>
</table>

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the assumptions of linearity and homoscedasticity may not always hold. Furthermore, the comparison of the slopes of the regression lines should take into account the fact that some groups only exhibit a very narrow range of values for the independent variable (i.e. fragmen- tality per design). Nevertheless, linear regression reveals the diverging trends set off by the different kinds of local differentiation.

**Morphological costs of syntactic differentiation**

Marshall (2005) points out that the street pattern often found in traditional settlements and preferred by urban designers has a “characteristic structure” (p. 154). The “characteristic structure” is one of heterogeneity, with the internal streets differentiated by their continuity, connectivity, and complexity (Marshall, 2005: 146).

Our analysis suggests that, depending on the type of localized design moves, the process of differentiation can involve significant trade-offs. If we interpret an increase in the amount of syntactic differentiation in a design as a benefit and a decrease in the integration of the design as a cost (because it implies greater cognitive effort for navigation), then our analysis suggests that there are more, or less, cost-effective ways to achieve the same benefit. We can include additional morphological variables in such a benefit-cost analysis. The street length
per unit area, for example, can either increase, remain constant, or decrease, depending on the pathway to differentiation (Figure 9). Similarly, different pathways to differentiation decrease the compactness of urban blocks by different rates (Figure 10). Our analysis provides an alternative way to navigate through a design space by understanding the effects of localized design moves upon syntactic and morphological variables.

**Discussion**

This study fits into the research themes central to a syntactic interpretation of urban geometry: (a) the dynamic spatial processes in which sequences of local spatial moves give rise to specific global syntactic patterns and (b) the interplay between the geometric differentiation (e.g., the variation of line lengths and angles of incidence between lines) and the syntactic differentiation.

The focus of Hillier’s work, as presented in “Part three: The laws of the field” of his book “Space is the Machine”, was on understanding the convergence of global syntactic patterns—namely, why buildings and cities, regardless of their social and cultural origins, have certain formal characteristics that are “nearly-invariant” (Hillier, 1996). He showed how the common emergent configurational properties are rooted in the need to fulfill the
generic functions of effective circulation and intelligibility and are governed by “local-to-
global spatial laws”. In his experimental generative process, he chose the local moves
(“maneuvers” as he called them) to either maximize or minimize the depth gain for the
whole system. In this context, subsequent moves take into account the condition created
by prior moves. By contrast, we are interested in divergence as much as in convergence. In
generating the differentiated grids, we sought to randomize, as much as possible, the loca-
tion at which an operator is applied. Our analysis shows that there are different “local-to-
global” pathways: different local moves, when repeatedly applied, can have divergent syn-
tactic effects.

This leads to an enriched perspective as to how space syntax aids the design process. Usually, space syntax is used to evaluate and compare design schemes (and by definition, that happens at the end of an iteration of a design process). When space syntax is used as an inspiration for generating design, a diagram of the intended structure is often produced. An additional way of using space syntax to aid the design process is by understanding the likely syntactic effects of localized design moves. Thus, the “grand-scheme” approach to design can be complemented and counterbalanced by a better understanding of the power of “incremental steps”.

Figure 9. Scatterplots showing the relationship between the total street length per design and the frag-
mentality per design. Black lines are linear least squares regression fits to data points. In each plot, the
regression line is extended to the full range of the plot for better visibility.
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Figure 10. Scatterplots showing the relationship between the mean standardized area-perimeter ratio (SAPR) per design and the fragmentality per design. Black lines are linear least squares regression fits to data points. In each plot, the regression line is extended to span the full range of the plot for better visibility.


Chen Feng is a postdoctoral fellow in Applied Urban Design at KTH Royal Institute of Technology. He is interested in the description and characterization of urban space as well as the interaction between urban form and activity patterns. His dissertation work links generative models and analytical evaluations of designs. He has also used big data and machine learning to study urban health and urban mobility.

John Peponis was born in Athens, Greece, in 1955. He is a Professor at the Georgia Institute of Technology, Atlanta, USA. His publications address the geometric and computational foundations of space syntax, the spatial culture of buildings and cities, design formulation and design languages, and spatial cognition. As a registered architect in Greece he collaborates with Kokkinou and Kourkoulas Architects.