SPACE SEMANTICS

An investigation into the numerical codification of space

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Abstract. “Space-Semantics” is a computational design proposition that interrogates how architectural spaces can be interpreted and codified within an adaptable semantic framework. The investigation seeks to view space through an alternate lens, abstracting architectural spaces into a set of numerical descriptions that can either be used to interpret the qualities of an existing space, or as a seed to generate a coherent network of spaces based on identified spatial patterns within a chosen site. The article comprises of two parts: a theoretical investigation into representing spaces through numerically expressed semantic descriptions and a case study in the form of a proposal for an underground metro station within an urban context.

Keywords. Space; semantics; grammar; code; generative.

1. Introduction

Space is fundamentally difficult to describe because it is intangible, and thus analysing space is often conducted through an examination of the surfaces that enclose it rather than the actual space itself (Hillier and Hanson 1984). Methods of articulating formal or spatial relations such as ‘space syntax’ (Hillier and Hanson 1984) and ‘descriptive functions’ (Stiny 1981) are effective in describing physical adjacencies and patterns, allowing the underlying logic of a spatial system to reveal itself. Whilst Hillier and Hanson (1984) contained their spatial analysis to two dimensions, extrapolating this logic to three dimensions can yield a more holistic understanding of spatial systems, particularly within the complexities of an urban context (Ratti 2003). Schrodé et al. (2007) explores urban visibility by extending the principles of ‘axial mapping’ (Hillier and Hanson 1984) into a three-dimensional space syntax. Substituting shapes for volumetric extrusions, an algorithm constructs a subset of three-dimensional axial lines around these massing buildings, and their points of intersection give form to a ‘visibility surface’ which articulates the varying level of visual range around a given site. Whilst Schrodé et al. (2007) focuses on the representation of topography and the connective space around discrete buildings, Space Semantics is concerned with the qualitative and quantitative description of the spaces themselves. It is apparent
that there is scope to integrate spatial characteristic data into an artificial language whilst maintaining its capacity to describe a host of varying spatial conditions. Adopting the methodology of another syntactical model - 'justified gamma maps' (Hillier and Hanson 1984), Space Semantics proposes how these principles can be applied in three-dimensions through a ‘discursive grammar’ (Duarte 2005) that incorporates shape, language descriptions and heuristics. Using numbers as a medium, Space Semantics allows information about a particular space such as permeability, accessibility and circulation to be condensed into an ordered string of digits. These codes are then fed into McNeel’s Grasshopper and processed through recursive functions to produce a logical spatial network that is site-specific.

2. Background

Designing a spatial grammar requires an understanding of three important aspects: human spatial perception, forms of grammatical notation and methods of computational manipulation. An artificial language is of limited use if it is purely representational, rather it should have an embedded generative potential to reveal new ways of viewing or creating spatial systems. Description grammars contain both programming and design rules (Duarte 2005). In other words, their formulation necessitates a consideration of how data can be symbolically integrated into a specific input component and how that can then be manipulated through simple rules in order to generate new compositions. It is critical that these grammars are constructed from interchangeable semantic variables so as to maintain its applicability to a wide variety of architectural situations and scales. The following theoretical exploration traces how descriptive grammars have been developed, identifying potential areas where Space Semantics can further evolve these approaches.

2.1. UNDERSTANDING SPATIAL RELATIONSHIPS

Social structures are intrinsic to the organisation of space (Hillier and Hanson 1984). Thus, an understanding of spatial relationships necessitates a consideration of how people perceive themselves in regards to others and their environment. Fundamentally, people understand space as either interior or exterior - seeing themselves as the occupant or the outsider (Hillier and Hanson 1984). It is this simple and innate dichotomy that dictates how space is demarcated and organised into logical systems. Space syntax (Hillier and Hanson 1984) relies on establishing binary relations in order to analyse and reveal the morphology of social-spatial networks. In particular, ‘justified gamma maps’ examine spatial relationships by determining whether one space is simply accessible from another. In turn, the ‘depth’ of a space can be deduced by counting the number of spaces one must pass through in order to access that space. Whilst this method of mapping a spatial system is effective in understanding its distribution, there is the potential to extend this thinking to account for more detailed information, for instance - the extent of the opening or its visual transparency. Understanding space through dichotomies - internal or external, public or private, connected or disconnected - is inherently reductive. Rather, these polarities should be perceived as two ends of a defined spectrum and a space is posited within that domain.
2.2. NOTATING SPACE

There are two critical aspects to defining a shape grammar: the rules dictating how spatial elements are composed and the rules that describe these designs in terms of form, type, function and purpose (Stiny 1981). Whilst these considerations refer to the language of design, they are also applicable to the inverse - the design of language. The grammar of an artificial language is critical in determining its analytical and generative capacity. ‘Justified gamma maps’ denote spaces and their connections through a diagram of linked strings and beads which clearly depict the spatial distribution of the system (Hillier and Hanson 1984). Stiny (1981) uses a series of letters and subscripts to define a particular shape grammar—#a1#a2#a3#a4#a5#a6#a7#a8, where # is used to separate distinct elements and ai represents a specific component in the form of an integer, co-ordinate pair, list or matrix (Stiny 1981). Since each element is described discreetly, a single description can contain very disparate pieces of information - from the number of enclosed rooms, to a list of windows or the configuration of architectural elements. Furthermore, mathematical functions can be applied to specific parts of the description in order to only modify the desired components of the output. Architectural configurations can also be described through a ‘JPG grammar’—a schema based on shapes, nodes and links notated as $X_i$, node($X_i$), link ($X_i$, $Y_i$) respectively and where $i$ denotes a particular characteristic of the shape $X$ (Lee et al. 2015). The spaces, their adjacencies and their formal language are described independently, allowing individual elements to be changed without necessarily impacting the rest of the output.

2.3. HEURISTICS

Heuristics are essential in refining a pool of spatial system outputs because it allows the generation of formally and semantically correct designs (Duarte 2005). Whilst spatial ‘correctness’ is inarguably subjective, there is an inherent logic in the way that spaces are planned architecturally. As such, this raises the problem of how we define spaces that are logical or illogical and more importantly, how this may be translated into a function that can be integrated into a discursive grammar. Duarte (2005) implements a set of rules in order to generate customised iterations of Alvaro Siza’s houses at Malagueira. These functions involve the manipulation of rectangular blocks - subdividing, connecting and scaling them in order to generate housing that is formally varied. Other rules specify the programmatic functions of particular rooms, denoted by an abbreviated subscript, which can then be overrode by subsequent functions until a specified termination point has been reached. The resulting descriptions are articulated as a string of letters and numbers, separated by commas, periods and brackets. This allows the ‘fitness’ of description to be tested by inputting this data into an equation which weights spatiality and topology against each other, the values of which are derived from the lengths of walls, the distance between rooms and the area of spaces. The ability to evaluate a given design output computationally is significant, as it will allow the process of generating and discarding descriptions to become fully automated, resulting in higher quality architectural solutions.
Similarly, Lee et al. (2015) uses a series of chronological steps and rules to construct a ‘JPG grammar’ which describes variations of Glenn Murcutt’s Marie Short House both spatially and stylistically. Whilst some of these functions simply define particular components or characteristics, others are designed to check a grammatical description using conditional statements. As such, particular functions are only applied if certain criteria are not satisfactory. Furthermore, these functions can also override and modify the outputs of previous rules. For example, where a solid and transparent wall are specified in the same location, the overlap will result in a solid wall. This schema allows heuristics to be designed into the discursive grammar and as such the descriptions undergo a process of refinement and optimisation before they are finally output.

3. Semantic Framework

3.1. OBJECTIVES

The proposed discursive grammar, Space semantics was developed in response to the limitations and potential of space syntax (Hillier and Hanson 1984). The diagramming of ‘justified gamma maps’ (Hillier and Hanson 1984) abstracted space and spatial relationships into a system of connected points and lines. Whilst this method of representing spatial relations revealed patterns of distribution within these systems, it neglected to capture other non-visual characteristics of space. Furthermore, Space syntax relies on the input of an existing architecture in order to derive a diagram of spatial relationships. As a function, the rules only operate in one direction, limiting its capacity to generate new spatial propositions. The proposed space semantics code is a framework to interpret and articulate space both quantitatively and qualitatively, embedding symbolic meaning into a new artificial language. It posits an alternate method of describing space without geometric constraints by focusing on spatial utilisation and permeability. It democratises our perception of space and allows individual spaces to be considered through a different lens within a broader system. As a framework that functions in both directions - it is a tool for analysing and interpreting existing sites, but also a device that can produce multiple schematic iterations of spatial systems. This translation from a diagram of numerical codes to a physical form can manifest in a multitude of ways; the proposed method is just one of infinite interpretations.

3.2. NUMERICAL CODE

Space semantics is premised on the assumption that spaces can be described through a range of characteristics and therefore are codifiable. Each space is represented by a string of \( n \) digits, where each digit is a rating of a particular spatial quality. In order to lessen the computational load, we have limited the case study to seven digits or characteristics, however, these codes could theoretically contain an infinite amount of numbers.

For each digit, there is a maximum domain of 0-9. These integers can have a smaller domain depending on the nature of the characteristic. For the purposes of this study, we have allocated three characteristics to measure the utilisation of a space, and four for assessing the permeability of the space. See Table 1 and 2;
Table 1. Space Semantic Code Breakdown.

<table>
<thead>
<tr>
<th>Integer Domain</th>
<th>Permeability: 0-9</th>
<th>0-9</th>
<th>0-9</th>
<th>0-9</th>
<th>0-1</th>
<th>0-3</th>
<th>0-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>.</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Numerical Digits and Corresponding Spatial Characteristics.

<table>
<thead>
<tr>
<th>Digit</th>
<th>Spatial Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visual Permeability</td>
</tr>
<tr>
<td>0</td>
<td>0-9.9%</td>
</tr>
<tr>
<td>1</td>
<td>10-19.9%</td>
</tr>
<tr>
<td>2</td>
<td>20-29.9%</td>
</tr>
<tr>
<td>3</td>
<td>30-39.9%</td>
</tr>
<tr>
<td>4</td>
<td>40-49.9%</td>
</tr>
<tr>
<td>5</td>
<td>50-59.9%</td>
</tr>
<tr>
<td>6</td>
<td>60-69.9%</td>
</tr>
<tr>
<td>7</td>
<td>70-79.9%</td>
</tr>
<tr>
<td>8</td>
<td>80-89.9%</td>
</tr>
<tr>
<td>9</td>
<td>90-100%</td>
</tr>
</tbody>
</table>

This set of criteria can then be used to evaluate the quality of spaces on an existing site, producing strings of numerical codes that can then be analyzed for trends. In this sense, deriving spatial patterns becomes a task of recognizing number patterns, a computational exercise that can be handled through digital means. The proposed case study is situated in two disparate locations of Sydney’s Central Business District, and hence the trends for each site vary, reflective of their programming and location. Each of these number patterns can then be translated into a function that will be used to refine the new generated codes for each specific area.

3.3. MATRIX

Hillier and Hanson (1984) depict their space syntax models two-dimensionally in plan, however this has obvious limitations in capturing more complex, multi-storey spatial systems. Space semantics arranges points in a three-dimensional gridded matrix, allowing spatial relationships to be read in both plan and section simultaneously. The dimensions in the X, Y and Z axis are controlled in McNeel’s Grasshopper and can begin to reflect the physical parameters of the project. This case study utilizes an $8 \times 8 \times 8$ matrix to model a potential 8 storey underground train station.

Each point in the matrix is first assigned a code by randomly selecting an integer from the given domain for each digit of the code. For example, the first digit is always an integer from 0-9, whilst the fifth digit is either 0 or 1. The ratio of integers can then be skewed in favor of particular spatial characteristics. For example, a train station typically has a higher proportion of public space, and hence
the probability of choosing a larger integer for the seventh digit is higher. This is scripted in McNeel’s Grasshopper by duplicating data for each of the integers to a variable ratio, generating a pool of numbers to randomly select from. The script to generate a single code is looped recursively (Zwierzycki 2015), where the number of recursions is set to the number of points in the matrix. The result is an ordered, discrete list of codes which describe a potential spatial system.

3.4. CODE TO DIAGRAM
Spatial relationships are diagrammatically represented with a polyline that carves a path within the matrix. It is composed of smaller line segments that connect points (representing spaces) within the matrix, be it vertically or horizontally. The path begins with selecting the start point in the matrix. The first line segment is generated by randomly selecting one of the closest points to the start (previous) point and joining them together. The script is programmed such that the previous point cannot be re-selected, in other words, the polyline cannot travel back onto itself. Non-naked points will have six points of choice, whilst naked points in the matrix can have three or four. Looping this process through the Anemone plugin in Grasshopper generates a string of consecutive segments of the polyline, the length of which is determined by the number of recursions. See Figure 1;

Figure 1. Space Semantics Diagram - Proposed Martin Place Station, Sydney, Australia.

3.5. TROUBLESHOOTING
Inherent code patterns were discovered through Spatial semantic mappings undertaken at Martin Place and World Square, Sydney. These deduced number
patterns were reincorporated back into the script as a means of not only creating a sequence of spaces that have rational relationships to each other, but to create spaces with logical characteristics. This was achieved by systematically checking each code and adjusting the number patterns through an override in the Grasshopper script. Generally:

- If the fifth digit is 0, then the space is a void, hence it is also an egress and therefore the sixth and seventh digit in the code is also 0. For example,

  6128.014 → 6128.000

- If a space is represented by an endpoint of a vertical line, it is vertically or diagonally traversable. Hence the sixth digit in the code must be a 2 or 3. For example,

  6128.114 → 6128.124 or 6128.134

- The 7th digit of adjacent spaces must have consecutive or equal numbers. This reflects the gradual transition between public and private space. For example, in a sequence of three codes:

  - 6128.114 → 6128.114
  - 8315.116 → 8315.115
  - 9473.112 → 9473.116

3.6. DIAGRAM TO FORM

*Space Semantics* provides a schematic spatial diagram from which a form can be generated from. The following architectural manifestation of this case study is just one of infinite methods of interpreting the code in a formal sense.

3.6.1. FLOOR PLATES

The floor plate of each space is determined by the seventh digit of its corresponding code. This digit represents a rating of public accessibility - the higher the number, the more public a space is. Therefore, in order to create spaces that are more generous towards the public domain its size must be proportional to its seventh digit. The line between two adjacent spaces is divided by the sum of the seventh digits of the codes representing its end points.

For example, a line between 2356.114 and 7812.115 would be divided into $4 + 5 = 9$ segments. The edge of the rectangular footprint is determined by the ratio of the two numbers on that line. See Figure 2;

3.6.2. THRESHOLDS

The size of the threshold openings between two adjacent spaces is calculated using the second and third digit of these two codes. The height of a threshold is determined by the second digit (environmental permeability) and the width is controlled by the third digit (physical permeability). Therefore, the higher the numbers are, the larger the threshold opening, and thus the more permeable it becomes. Since a space can be connected to multiple thresholds, each interface
also takes into account the values given to spaces that are not immediately adjacent. The numbers are weighted differently depending on how close each space is to the threshold being calculated.

Our perception of space extends beyond the space we immediately occupy, and thus if one digit in a particular code is modified, the localised change triggers a global reaction in the system. Digits of spaces closer to the threshold in consideration are given a higher weighting. The resulting numbers from the calculations are rounded to the nearest integer and used to determine the width and height of the opening, as illustrated in Figure 2.

Figure 2. Generating form from codes - Proposed Martin Place Station, Sydney, Australia.

3.7. ARCHITECTURAL OUTPUTS

Through the generation of multiple iterations, it was apparent that new building typologies began to emerge. These were largely determined by the initial seed value that dictated the polyline starting point within the matrix. Through a visual comparison between a group of iterations it is clear that there are similarities between some and others which are complete outliers. In a sample of 24 iterations, iterations 06, 13, 15 were outliers. More interestingly, iterations 11, 19, 20, 21, 22, 23 closely resemble each other with only subtle variations. Iterations 07, 08, 10 are also comparatively similar. It is interesting to note that often two iterations shared a similar formal typology despite not having consecutive seed numbers, such as 00 and 16, or, 05 and 09. The emerging similarities between iterations yields the potential to identify a particularly successful typology and filter iterations based on certain geometric criteria. This could potentially be achieved through machine learning to seek out better iterations based on previously evaluated forms. See Figure 3;
3.8. DISCUSSION

Digitally generated design has naturally evolved to become synonymous with a particular aesthetic, whereby style and form are prioritised over non-visual characteristics of architectural design, such as spatial qualities, relationships and organisation. *Space semantics* shifts the way in which we not only view computer-generated design, but also how spaces and their relationships are described. This case study of the seven digit code reveals the analytical and generative potential of *Space semantics* as the chosen architectural characteristics can be substituted depending on the architectural typology and the code can be extended indefinitely. How codes are linked can also be entirely restructured to output different formal permutations.

3.8.1. DESIRABLE CONFIGURATIONS

With such variation in the *Spatial semantic* outputs, a set of design criteria was necessary for assessing the functional appropriateness of a specific configuration. The following list outlines the design criteria used for this case study to recognise the architectural traits that constitute a functional configuration:

1. Forms with strong horizontal linear configurations at the top of the matrix are ideal because they can be integrated into the existing circulation axis at ground level.
2. Forms with 1 or 2 horizontal linear configurations at the base of the matrix are preferred as they can be translated into station platforms. The best outcome occurs when these forms connect directly to street level.
3. Forms with a strong vertical linear articulations are ideal as they can be converted into lift cores.
4. Forms with a tight cluster of points at the top or the middle of matrix are ideal because they can be translated into retail hubs or food courts.
5. Forms with two separate clusters at the top of the matrix are preferred as they can be translated or interpreted as openings at street level.

Iteration 01 for World Square Station, Sydney, consists of compact linear forms stacked on top of one another. This dominant axis is easily integrated into the existing main thoroughfare in World Square’s ground plane. Openings...
periodically cut out along the main access provide multiple entry points into the station without disturbing the existing retail spaces. See Figure 4;

Iteration 02 for World Square Station, Sydney, is a dispersed branching form. The existing staggered axis in World Square matches this iteration, offering the potential to integrate the station access points at the most critical node of World Square’s ground plane. See Figure 4;

Figure 4. Iterations 01 & 02 World Square Station, Sydney, Australia.

4. Future Applications

Whilst this initial case study explores the carving out of functional space for an underground train station, the same logic could be used for other buildings, particularly where strict structural grids must be observed or when intervening into a complex existing site. Space semantics has the potential to be incorporated into the feasibility studies of adaptive reuse sites, carving out new spatial systems for various programmatic functions. Buildings such as towers and car parks are prime candidates for such projects, whereby re-programming part or all of these buildings can inject a second life into these sites, re-connecting them with the cities they occupy. Through the selection of desirable outputs, machine learning can be integrated into Space Semantics, allowing this system to learn the unique spatial logic that architects and urban planners design with.

References