

A Computational approach to ‘The Image of the City’

Gabriele Filomena, Judith Verstegen and Ed Manley

Gabriele Filomena^{a,b}, Judith Verstegen^a, Ed Manley^b

^a*Institute for Geoinformatics, University of Münster, Germany*

^b*Bartlett Centre for Advanced Spatial Analysis, University College London, UK*

Abstract

In *The Image of the City* Lynch describes how individuals perceive and recall features in urban spaces. The most distinctive elements in the urban landscape - categorised in paths, nodes, edges, districts and landmarks - give shape to individuals’ mental representation of the city. Lynch’s approach has stimulated research into spatial cognition, urban design and artificial intelligence, and still represents an essential pillar in the analysis of urban dynamics. Nevertheless, an explicit link between *The Image of the City* and GIScience has not been completely explored yet. In this paper, a computational approach to *The Image of the City* is proposed. Different perspectives in spatial cognition and GIS research are integrated, to obtain a complete Image of the City, in which the most salient elements are shared by a large part of citizens. Nodes, paths and districts were identified through network science techniques. Methods drawn from the information approach to *The Image of the City* are used to detect landmarks, integrating the complexity of points of reference in their visual, structural and semantic components, as conceptualised by Lynch and successive research. The methods were applied to the central area of Boston and built using freely available spatial datasets. Results were compared to Lynch’s maps to evaluate the methodology: beside a considerable discrepancy with regard to landmarks, a good correspondence for paths, nodes, edges and districts was

*Corresponding author

Email address: gabriele.filomena@uni-muenster.de (Gabriele Filomena)

found.

Keywords: Image of the City, cognitive maps, Kevin Lynch, street network, GIScience

In 1960, Kevin Lynch published *The Image of the City* [31], one of the most ~~exhaustive and~~ influential theories in spatial cognition and behavioural geography ever written [43]. Lynch ~~devotes himself~~ ~~dedicates his work~~ to understanding how people perceive and represent a city, and from what external
5 urban artefacts the mental image of the city arises. Specifically, Lynch analyses two qualities of the built environment: legibility, ‘the ease with which its parts can be recognised and can be organised into a coherent pattern’ and imageability, ‘that quality in an object which gives it a high probability of evoking a strong image in’ the observer [31, p. 60].

10 Studying the city form of Boston, Los Angeles and Jersey City, the author finds out that individuals’ mental images can be overlapped to form a community cognitive map. The resulting skeleton is formed by five types of elements: paths, edges, nodes, districts and landmarks. The mental image mediates in the interaction between humans and their environment: ‘The environment sug-
15 gests distinctions and relations and the observer (..), selects and organizes and endows with meaning what it sees’ [31, p. 6] Since the 1970s, the five elements have constituted the core of spatial cognition theories, grounding the spatial knowledge organisation in landmark, route, and configurational knowledge [51]. Successively, Lynch’s model has been reformulated in behavioural geography
20 [e.g. 48, 6, 56]. *The Image of the City* has furthermore inspired research in environmental psychology [8] and ~~-. Lynch has~~ prompted the development of contemporary cognitive mapping research [57, 27], ~~and facilitated the overcoming of the classic cognitive science paradigm~~: cognitive maps are seen as auto-organising systems that mediate the human-environment interaction [42].

25 Inevitably, this framework has stimulated research in artificial intelligence and robotics, where computational models such as TOUR [28] and NAVIGATOR [17] have been developed to reproduce and comprehend human mental pro-

cesses ~~, while the series of Conferences on Spatial Information Theory (COSIT) and on Spatial Cognition, have prompted mutual collaborations amongst cognitive science, AI and GIScience, amongst the others, for more than 20 years.~~ Nevertheless, there has not been a thorough attempt to integrate Lynch’s theory directly into GIScience, nor to support a quantitative formulation of *The Image of the City* relying on conventional spatial datasets. ‘A generalisation of these (Lynch’s) ideas could advance geographic thinking in general and GIS software in particular’ [11, p. 3].

The aim of this work is to provide such a quantitative formulation of *The Image of the City* to foster an inclusion of the concept of *The Image of the City* in GIScience. In the first part of this paper, a set of works that have attempted to reformulate Lynch’s theory is reviewed. Following this, an integration of such different reformulations is devised. In the second part, a computational method, built upon conventional geospatial data, is proposed for each Lynchian element in reference to the original definitions. The methods are applied to the central area of Boston and thereafter the results are discussed and subjectively compared to Lynch’s qualitative maps.

1. Background

A number of research communities have been involved in the quantitative formulation of memorability and in extracting cognitively salient urban features. These approaches can potentially contribute to the development of a framework for extracting Lynch’s five elements.

1.1. Space Syntax

The relationship between the external space and ~~the mental representation~~ *social phenomena* is the driving force of Space Syntax, a set of theories and techniques ‘for the representation, quantification, and interpretation of spatial configuration in buildings and settlements’ [21, p. 363]. In this perspective, the street layout and the configuration of space have a strong impact on the

development of mental representations [26]. The association between street configuration and cognitive mapping is not unprecedented. What distinguishes Space Syntax research is the focus on topology rather than metric properties.

Within this community, Dalton and Bafna [7] attempt to redefine Lynch's
60 five elements through the constructs of axial lines [22] and isovists [2]. They suggest to study and detect first order (spatial and structural) elements, that give shape to the mental representation, and second order (visual) elements, that enrich the image. The elements could be captured employing axial lines and isovists sorted in order of significance.

65 Jiang [24] theorises that the scaling law of artefacts [61] supports the identification of the primary elements in the city. He tested his hypothesis on paths, transforming streets into axial lines and ranking them by connectivity. Consistently with his assumptions, many more less connected than well-connected and memorable streets exist, regardless the city examined and the street morphology.

70 The Space Syntax approach has been questioned for excluding metric information from the analysis, heights of buildings and land use properties from the analysis [44]. Moreover, although road-centre lines have been recently adopted [55], axial lines have obstructed the integration of space syntax techniques into GIS [25]. Yet, the emphasis on configurational aspects is an illuminating argu-
75 ment in the transition towards a computational approach to cognitive maps.

1.2. The Information Approach

Haken and Portugali [19] have advanced a framework to *The Image of the City* that integrates the synergetics approach [18] and contemporary trends in cognitive science with Lynch's theory. The researchers make the link between
80 the concepts of imageability and *affordance* [14] explicit, on one side, and employ Shannon's information theory, on the other, for studying how the mental image is formed from specific urban elements. In this information approach, legible cities are composed of informative and significant artefacts or urban configurations. City nodes, paths or districts are 'information carriers' that shape the
85 mental image. Here, the original measure of information [50] - a form of entropy

that quantitatively measures the unexpectedness of an event - is adjusted with an index that incorporates semantic information. This component represents the result of biological, cultural, social and pragmatic categorisation processes.

Their theory reinvigorates the idea that city elements may be remembered
90 for symbolic and social meanings [1], but also for their pragmatic functions. Moreover, it introduces a computational framework to *The Image of the City* that takes into account the combination of these traits and their contribution to the legibility of cities. The drawback of their approach is that it contemplates a measure of entropy, suitable for the city- or district-level but unfitting for
95 computing the individual scores of the elements.

1.3. Automatic Landmark Extraction

Sorrows and Hirtle [52] refine the notion of landmark. The authors differentiate *visual landmarks* - objects used as spatial points of reference for their visibility - from *cognitive landmarks* - relevant for their uncommon and meaningful content - and *structural landmarks* - recognisable for their advantageous
100 and prominent position in the space. This work has inspired a vein of research in GIS community interested in automatic identification of landmarks for wayfinding design and navigational support: Raubal and Winter [45] advance a model that measures the salience of buildings in relation to perceptual and cognitive
105 properties. Winter [58] ameliorates the model, recommending to consider 3d visibility as another property. Elias [9] presents a similar approach based on machine learning algorithms that inspect geometric, topological and semantic attributes of buildings to establish landmark hierarchies. Furthermore, Winter et al. [59] integrate the previous approaches to construct a hierarchy of
110 landmarks, emphasising the distinction between local-landmarks and city-wide (global) landmarks.

In summary, while these works have moved landmark research forward, the other Lynchian elements are of little interest and rarely mentioned here.

1.4. Contributions and Gaps

115 Even though automatic landmark identification models have been disseminating [46], presumably due to their potential applicability in navigation systems design, none of the approaches have offered a set of methods and tools to quantitatively derive the five elements of *The Image of the City*.

- 120 • Space Syntax, when reformulating *The Image of the City*, has mostly considered visual aspects, neglecting important implications regarding the genuine human-environment interactions and focused on paths identification.
- The information approach, whilst being based on the usage of geospatial dataset, returns a macro-level index of legibility.
- 125 • Edges have generally received a little attention, [or been considered a particular type of landmark and assessed for their structural properties \[e.g. 47, 45\]](#); districts have been translated in *Voronoi* partitions, whose cognitive salience is disputable.
- More importantly, in the literature discussed above, when an application 130 of the methodologies is presented, the dataset usually refers to small areas, it is created ad-hoc by the researchers or based on questionnaires, which makes it hard to reproduce the study for new areas.

2. Methodology

In the following section, network science techniques are presented for the detection of nodes, paths and districts, from the street configuration. In addition, 135 a comprehensive landmark detection method is proposed following Sorrows and Hirtle’s framework [52] and the models discussed above. These approaches were enriched performing a 3d visibility analysis and integrated with insights derived from the information approach; semantic and pragmatic properties were here 140 considered for the first time in a large geo-dataset. Lastly, a set of rules to extract edges is described.

2.1. Nodes

Nodes are the strategic foci into which the observer can enter, and which are the intensive foci to and from which he is travelling. They may be primarily junctions, places of a break in transportation, a crossing or convergence of paths [31, p. 47].

Space Syntax scholars have shown that elements stored in people’s cognitive map are related to centrality measures [20, 60]. In this framework, topological properties of degree, closeness and betweenness are usually computed employing a dual graph representation, wherein street segments are represented by vertexes and junctions by links. However, Porta et al. [41] argue that the primal representation approach - wherein street segments are represented by links and junctions by vertexes - is more effective in exploiting centrality indices to capture the skeleton of the urban structure and identify crucial intersections.

Centrality acts as a driving force in the development of the urban structure, and central locations are prone to become genuine urban nodes [38]. Lynch’s nodes could be viewed as places that are structurally made to be traversed, nodes (vertexes) with the highest *betweenness centrality* scores in the street network. In our approach betweenness centrality was calculated in an undirected planar graph, as:

$$C_i^B = \sum_{j,k \in G, j \neq k \neq i} \frac{n_{jk}(i)}{n_{jk}} \quad (1)$$

Where, in an undirected graph G , n_{jk} is the number of shortest paths between the vertexes j and k , and $n_{jk}(i)$ is the number of shortest paths between the vertexes j and k that pass through i .

2.2. Paths

Paths are the channels along which the observer customarily, occasionally, or potentially moves. (..). People observe the city while moving through it, and

along these paths the other environmental elements are arranged and related [31, p. 47].

170 Paths are the main lines of movement in the city; they guide people’s movement, supporting orientation. In low-legibility contexts, when a path is not characterised by vivid activities or peculiar properties, perceptual continuity comes into play: people rely on this functional quality to successively travel across the city. The concept of continuity recalls the idea that people tend to
175 choose routes that minimise angular change rather than distance [49, 16, 23]. In this sense, angular betweenness is described as the best predictor of pedestrian and vehicular movement when only the street network is at disposal of the researcher [5]. Betweenness centrality, as defined above (see eq.1), was computed for vertexes in a dual graph representation so generated:

- 180 • Street segments are converted to vertexes;
- When two street segments cross each other in the road network, a link connecting the corresponding vertex in the dual representation is created.
- The amplitude of the angle of incidence formed by two street segments is assigned to the corresponding link as weight.

185 Finally, the centrality values of the vertexes in such a network were reassigned to the originating segments. Therefore, it is assumed that the major paths are those which minimise angular change in travels across the city. Here, we did not take into account the road-type class (e.g., major-road, secondary-road, etc.), assuming that street segments which form angular-continuing lines
190 [e.g. 40, 10] belong to the same category or have similar structural properties [53].

2.3. Districts

Districts are the relatively large city areas which the observer can mentally go inside of, and which have some common character [31, p. 66]. The characteristics that determine districts are thematic continuities which may consist of
195 *an endless variety of components [31, p. 67].*

Space Syntax suggests that the topology of the street network is associated with people’s perception of places and regions: Law [29] illustrates a process for generating sub-graphs from the street topology applying community detection techniques. The so formed *Street-based Local Areas* (SLA) [55] are regions whose
200 internal homogeneity has social and functional foundations [15].

In this discussion, it is assumed that the different districts of a city can be identified analysing the road layout. The *modularity optimisation* function [3] is adopted to extract SLAs. This algorithm optimises modularity [15], an index
205 that measures the goodness of a network division. Modularity (Q) computes the difference between the edges within a community and the expected numbers of edges in a network with the same structure but random connections. When the number of within-community edges is nothing more than random, the structure of the communities is poor and Q is equal to zero. ~~Otherwise,~~
210 ~~greater the difference, greater Q , stronger the division.~~ On the contrary, high values of Q represent strong division amongst well-structured communities. The implementation of the modularity optimisation technique follows these steps ~~for more details~~:

1. Every node i is considered a community.
- 215 2. For each node i , the algorithm evaluates the gain in modularity (Q) that would be obtained by joining the node with each of the neighbour communities j .
3. If no possible gain is detected, the node i stays in its original community, otherwise, it is placed in the community, wherein the modularity gain
220 would be maximised.
4. The nodes in the same community form a new super vertex.
5. The previous steps are repeated until the modularity cannot be optimised any more (merging communities does not produce positive gain).

The function was run in an undirected dual graph. Partitions were extracted
225 from a network where weights were based on the angles of incidence between

pairs of segments, as described above. Thereby, districts are the sub-graphs obtained from the street network, optimising modularity.

2.4. Landmarks

Landmarks are point references considered to be external to the observer. They are more easily identifiable, if they have a clear form; if they contrast with their background; and if there is some prominence of spatial location [31, pp. 78-79].

The present work follows Sorrows and Hirtle’s framework ([52]) in the distinction of three type of landmarks: visual, structural and cognitive (pragmatic and cultural meanings). Indeed for Lynch, an edifice may become a landmark when it stands out from the background. Additionally, activities and historic references may contribute to reinforcing the legibility when visual attraction is insufficient. Raubal and Winter’s ([45]) set of techniques have been enriched to allow for topological relations, visibility, semantic and pragmatic aspects in landmarks identification. Our analysis was performed on a dataset containing exclusively buildings; other elements such as trees, benches or bridges were not considered.

Visual properties includes height, façade area and visibility. The maximum height of a building was used for computing 3d visibility: for each edifice, the length of the longest unobstructed line was kept and used as a coarse value of visibility. For what concerns structural and topological properties, advance visibility - a 2d area of visibility, without obstructions, around a building -, minimum distance from the road, the number of adjacent buildings (at least partially contained in a buffer of x metres) and the area of the polygon were computed. The cultural meaning of a building was obtained counting the number of listed historic elements located within its boundaries. Finally, pragmatic significance was calculated following a simplification of the information approach, as an index of unexpectedness:

$$Ps_b = 1 - \frac{N_b}{N} \quad (2)$$

255 Where, in a buffer of x metres around the building b , N_b is the frequency of the land use class of b and N is the number of buildings. The scores of the indexes were scaled and combined in the relative component, and, subsequently, in the overall score (see table 1 for details).

2.5. Edges

260 *Edges are linear elements not considered as paths: they are usually, boundaries between two kinds of areas. They act as lateral references. Those edges seem strongest which are not only visually prominent, but also continuous in form and impenetrable to cross movement [31, p. 62].*

Edges are authentic organising features whose primary trait is linear continuity. 265 Nevertheless, edges could be permeable and crossable, they can coincide and align with paths. In the current analysis, the following linear elements, with a predefined minimum length, were extracted as edges:

- Sections of railway structures as bypasses or other visible structures.
- Sections of large roads (e.g. dual-carriageways roads).
- 270 • Sections of motorways.
- River banks or generic waterfronts (lakes, sea-coast).

2.6. The case study

The methods delineated above were applied to the city centre of Boston, MA (USA), on the area studied by Lynch (figure 1). The results of the analysis are 275 presented, discussed and compared to the map depicted by Lynch, who asked 30 residents and workers to describe customary itineraries and experiences, and recognise places (see figure 2).

Our analysis mainly relies on the street network and buildings footprints. While the datasets are Boston-specific, the sources employed are generic (and 280 often available as open data) so to allow application of this approach for other case study areas. The sources are:



Figure 1: The city centre of Boston and the surrounding areas. Source: Mapbox, OpenStreetMap.

- The road network [35], clipped with two buffers of 4000 and 8000 metres around Boston City Hall. The smaller network was used to identify nodes and paths, the vaster to detect regions.
- Building footprints [34] this dataset includes a simplified representation of buildings footprints, along with their maximum height.
- Buildings main land use [39] and Boston Historical landmarks register [4]. The land-use classes used to compute the pragmatic score were: *attraction, commercial, cultural, eating & drinking, education, emergency service, entertainment, hospitality, industrial, library, manufacturing, medical care, military, place of worship, public, residential, sport, transport, university*.
- Railways [36] and water [37] to detect edges.

We subjectively defined weights for each landmark component, as specified in table 1, coherently with Lynchs observations. Yet, the weight definition may vary with the urban structure, the social context and so forth, and can

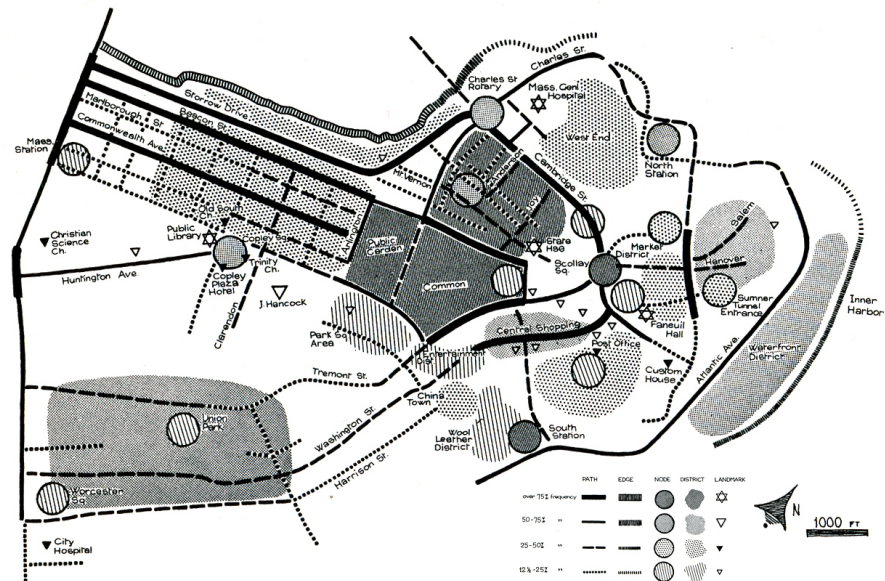


Figure 2: The Boston community map as emerged by verbal interviews. Lynch, Kevin, *The Image of the City*, Figure 35 and corresponding legend, pp. 145-146, 1960. Copyright Massachusetts Institute of Technology, by permission of The MIT Press.

be manipulated correspondingly for other case studies. Finally, to obtain the overall Image of the City, the range of original values was rescaled in the range from 0 to 1, on the bases of the maximum and minimum feature across each element; the percentile ranges used by Lynch were applied to the scaled scores of nodes, paths and landmarks, to colour and rank them. Due to the nature of the methods, districts and edges were not ranked.

Table 1: Landmark extraction: Indexes and weights.

Component	Index	Index weight	Component weight
Visual	3d Visibility	0.50	0.50
	Façade area	0.30	
	Height	0.20	
Structural	Area	0.30	0.30
	2d advance visibility	0.30	
	Neighbours (150-mt buffer)	0.20	
	Road distance	0.20	
Semantic	Historical importance	1.0	0.10
Pragmatic	Land Use (200-mt buffer)	1.0	0.10

3. Results

3.1. Nodes, paths and districts

We found some crucial nodes (figure 3) in the city as Charles Street Rotary and the junction between State Street and Congress Street. The complex whole of ramps and interchanges nearby Charles River Road and Martha Road confers high betweenness centrality values to other intersections in the area: this cluster of nodes is represented by Lynch as one node at the south-east extremity of Charles River Road (see figure 2). Likewise, the Sumner and Callahan tunnels, essential links to and from East Boston, give emphasis to the nodes at their entrances and the nearby junction (Congress and North Street).

Like Lynch, we detect a lack of main nodes in the western area of the city. Nonetheless, the output of our analysis does not point Worcester Square and Union Park as crucial nodes, nor the intersections of Huntington Avenue and Columbia Avenue, respectively with St James Avenue and Stuart Street. Be-
 315 sides, Copley Square, Scollay Square and South Station do not stand out as they do in Lynch map (see figure 2). While most of this nodes were mentioned by just a few interviewees (12-25% cluster), South Station (over 75%) and Cop-
 ley Square (50-75%) may gain their importance in citizens' mental maps for
 320 their role in the public transport network, which is not take into account in our analysis.

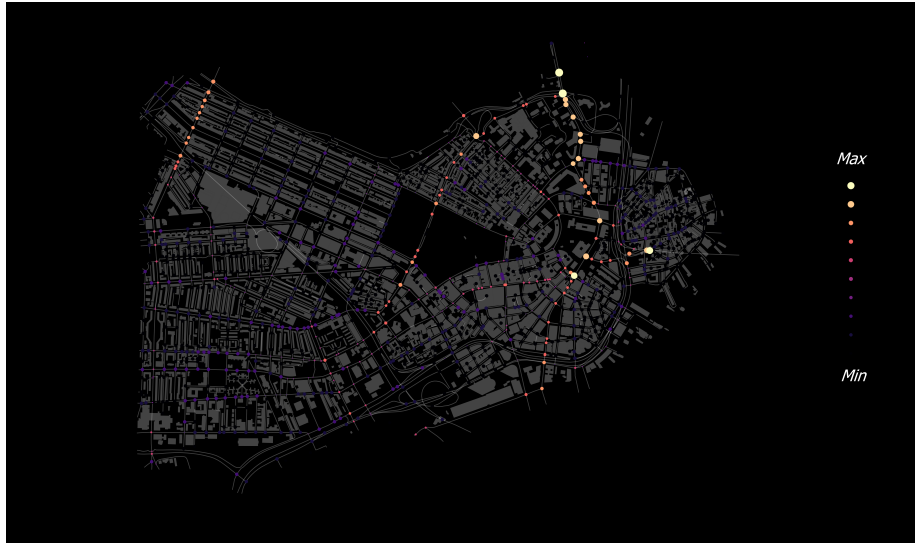


Figure 3: Nodes: Street junctions coloured by betweenness centrality.

Lynch describes the system of paths in Boston as confused, but, notwithstanding, functional: major movement lines shape the overall image of the city, converging in the city centre. Here, motorways may be seen as a constraining
 325 and limiting elements, endowed with organising properties rather than being meaningful for movement.

Angular edge betweenness captured the main paths detected by Lynch as Beacon Street, Boylston Street, Cambridge Street, Charles Street, Tremont

Street and Massachusetts Avenue (figure 4). Nevertheless, Lynch also depicts
 330 as major paths Atlantic Avenue and the narrow Washington Street. While the
 first receives its importance from the sea bank and the harbour, Washington
 Street owes its legibility to the high edifices along it. The fact that architec-
 tural properties and environmental evaluations were not taken into account in
 our paths identification approach may explain this dissimilarity. In addition,
 335 our method did not identify Storrow Drive, a road also perceived as a barrier
 by Lynch’s interviewees.



Figure 4: Paths: Street segments coloured by angular edge betweenness.

Districts in Boston are vivid and orientating entities: even though their
 structure may be confusing and unclear from a purely structural point of view,
 their thematic identity is strong [31]. Because of their connection to personal ex-
 340 periences and activities, many Lynch’s interviewees indicated districts in Boston
 as the main elements in the mental representation of the city. These areas have
 central cores and undefined boundaries, sort of ‘thematic gradient’, that vanish
 gradually rather than precisely.

In our results, Back Bay, which morphologically exhibits an uncommon reg-
 345 ularity compared to the rest of the city featured by an uncommon regularity, the

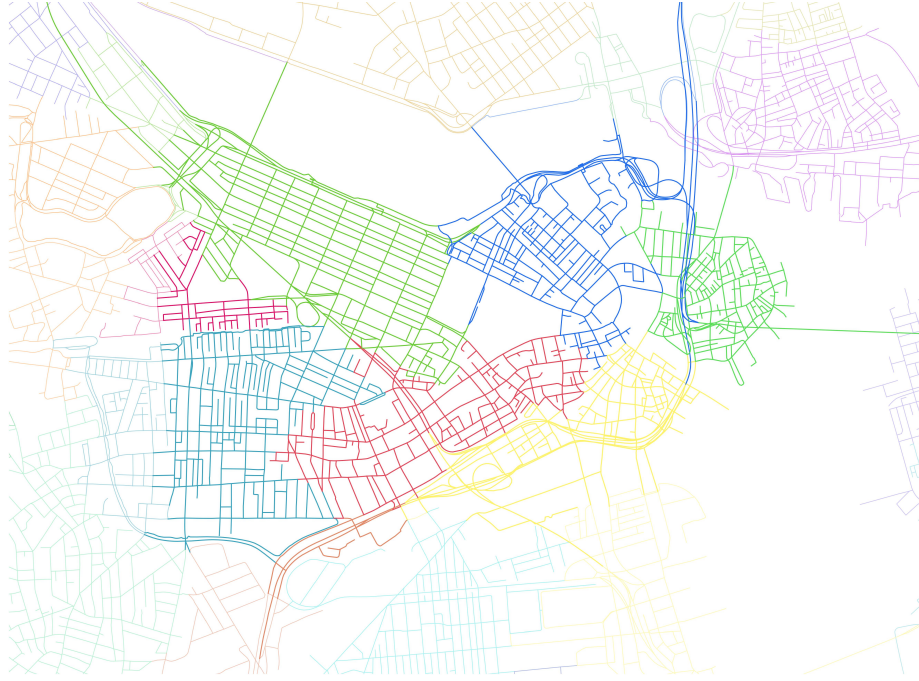


Figure 5: Districts: Street-based Local Area (SLA) in Boston city centre. Each colour represents streets belonging to a single district; semi-transparent colours indicate streets outside the studied area.

core of North End-Docks area and the Financial District clearly stand out from the rest of the city centre (figure 5). At the same time, the triangle between Back Bay and South End, portrayed in *The Image of the City* as an empty area devoid of any character, is extracted as a single entity (coloured in fuchsia) by the algorithm. These portions almost coincide with Lynch's outcomes and considerations. On the contrary, Beacon Hill and West End are here merged in a macro-region, while some micro-districts as Theatres, China Town or the Textile Leather area, are assimilated by the Financial/Shopping district in our results. Their vivid connotation, possibly due to peculiar buildings, agglomerated activities and the presence of ethnic communities, cannot be completely captured by network techniques. Since the motorways and the system of interchanges caused some distortions, a network composed only of local roads was

also used in this case; the results are displayed in the appendix (figure A1)

3.2. Landmarks and Edges

360 According to Lynch, in Boston, edifices are perceived as singular entities
when the city centre is admired from the banks of Charles River and only a few
of them have enough vividness to be identified as singular point of references. In
particular, the prominence of State House, Old John Hancock Building (nowa-
days Berkeley Building) and Custom House on the rest of city was mostly noticed
365 from external points of view: their relation with the road was not as strong as
their visibility and people preferred to take advantage of local landmarks [31].

In our landmark results (figure 6 and figure A2 for sub-component scores)
Prudential Center, John Hancock Tower, Berkeley Building, Copley Tower, Mas-
sachusetts General Hospital, South Station and the T-Garden Arena, came out
370 as main landmarks, along with a large number of local landmarks. However,
besides the Massachusetts General Hospital and the Berkeley Building, Lynch
also indicates some other major landmarks - as State House, Christian Science
Church, the Public Library, the Trinity Church and Custom House - that did
not particularly distinguish themselves in our analysis.

375 Whereas major lines of movement, street configuration and nodes may have
slightly changed since Lynchs original study, the city centre has undergone a
more consistent evolution in terms of vertical development. The large number
of skyscrapers erected throughout the last 60 years along with the general evo-
lution of the city and a possible redistribution of the activities, partly explain
380 the discrepancies between Lynch and our landmark scores. Interestingly, such
differences may disclose the dynamic nature of the mental image of the city, a
representation that vary and re-adapt, embracing new elements, meanings and
possibilities.

In Boston edges seem to play two roles. On one hand the river and the
385 harbour define the shape of the city centre; on the other hand, the motorways,
besides reinforcing the peninsula profile, represent interruptions, separate differ-
ent areas and obstruct movement. The Central Artery is described by Lynch's



Figure 6: Landmarks: Buildings coloured by the overall score.

interviewees as a fragmentary and abstract edge: even though sometimes it is not visible, people are aware of its presence and the impossibility of crossing it. North End is a shiny example in this sense. The Central Artery completely separates this area from the rest of the city centre.

The edges identified in our analysis (figure 7) correspond approximately with those discussed in *The Image of the City*. The waterfront is automatically depicted as a continuous and uninterrupted edge that draws the main contour of the cognitive representation of the city. However, Lynch illustrates how citizens rarely join Charles River bank with the harbour. The water between West End and North End is hidden by several buildings and railway structures, which make the continuity of the waterfront difficult to conceptualise and mentally represent. From our analysis, the interplay between the river and Storrow Drive emerges as well: the latter reinforces the meaning of the first but, nevertheless, causes a sense of distance between the water and the districts of Back Bay and Beacon Hill. Conversely, the edge represented by the harbour is more fluid: the presence of amenities and flourishing activities make this area a vivid and liveable edge.



Figure 7: Primary edges in Boston.

405 Finally, the computational image of the Boston, displayed in Figure 8, was obtained combining all the elements in a single, overall map in the style of the hand-drawn maps created by Lynch.

4. Discussion and conclusion

The aim of this work was to provide a quantitative formulation of Lynch's
 410 Image of the City, easily incorporable in GIS environments, that may favour a more explicit inclusion of *The Image of the City* in GIScience. In *The Image of the City*, Lynch introduces and describes five elements - nodes, paths, districts, landmarks and edges - that give shape to the mental representation of the city. A complete computational approach to *The Image of the City* was presented
 415 here and tested on a large and freely available urban-dataset, integrating a range of methods derived from previous research. The mental image of Boston was drawn ranking artefacts on the basis of network and geospatial measures. We explicitly took into consideration a semantic component in landmark extraction

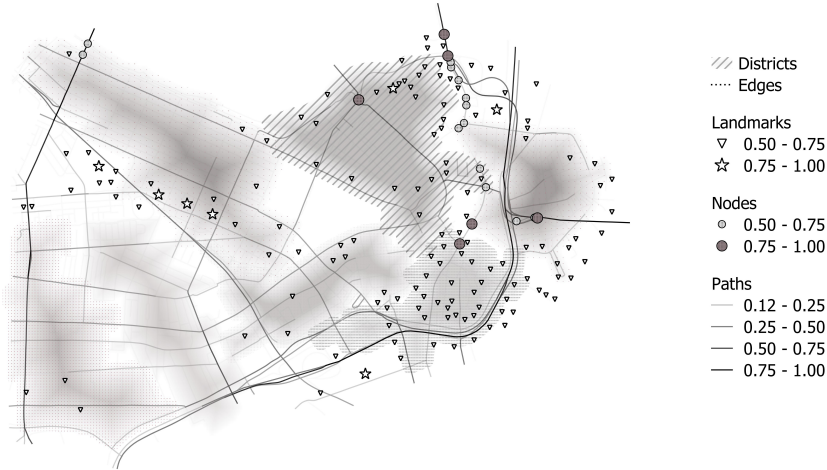


Figure 8: The computational Image of the City of Boston.

and tested a series of criteria to pick out edges. The results were visually compared with the maps of Boston presented in *The Image of the City*, outputs of Lynch's qualitative analysis. While it was difficult to find a common ground concerning landmarks, possibly due to the changes occurred in the city in the last 60 years, there were correspondences between the other elements extracted computationally and those reported by Lynch: firstly, centrality measures consented to detect main nodes from the street network, as well as major paths; secondly, the modularity optimisation algorithm, a community-detection technique, subdivided the area studied in portions alike to Lynch's main districts; lastly, the criteria advanced to pull out edges produced satisfying results, against the ones presented in *The Image of the City*.

Having said that, the complexity of human cognition and perception cannot be fully captured with a computational approach to mental representations. Interviews and sketch-maps are more comprehensive tools when it comes to study humans' representations, their experiences and their decisions within the environment. The fact that the waterfront of the peninsula was identified as

435 an edge, not accounting for the absence of perceptual continuity between West
 End and North End, shows the elusiveness of human cognition. Yet, there are
 various routes along which our work might be extended. The public transport
 network should be taken into account for determining crucial nodes, beyond the
 street junctions, by means of multi-layered or multiplex network. In this sense,
 440 Tomko and Winter [54] advance a formal approach to urban form representation,
 wherein they suggest to extract *The Image of the City* taking into account the
 mean transport used by the observer. Moreover, the definition of districts may
 be adjusted through incorporation of demographic and social dimensions (for
 example, Gao and colleagues [12, 13] have extracted urban functional regions
 445 employing Point-Of-Interests (POIs) check-ins and social-media data). Simi-
 larly, the definition of edges may require a more precise formalisation and the
 incorporation of elements of structural change in the urban morphology.

This framework may also undergo a more precise validation. To further
 generalise the validity of the approach here presented, the methodology should
 450 be tested and evaluated with other case-studies, allowing for differences in ur-
 ban planning approaches. Origin-destination matrices regarding pedestrian and
 traffic flows, or POI check-in datasets, might give indications on paths, nodes,
 or regionalisation [32], or indicate how to calibrate the weights in the landmark
 extraction.

455 The model developed during this paper can be manipulated in any GIS pack-
 age, enabling formal spatial analysis and modelling of the relationship between
 observed spatial behaviour and urban form. Examples might include the de-
 velopment of new simulation models of pedestrian or vehicular movement [e.g.
 33], spatial and accessibility planning, and identification of low-legibility areas
 460 (activities, movement and orientation).

The work has shown that the development of a computational form of *The
 Image of the City* is feasible. The methodology devised here can be applied to
 other cities and urban contexts very easily, manipulating just the input data and
 a few parameters. This approach makes it possible to reveal images of cities,
 465 investigated so far with qualitative and time-consuming procedures. We argue

that this tool may support spatial planning decisions in urban design, providing important insights as concerns city livability, quality of life [30], the adequate mix of land-uses, the ease of navigation and orientation.

References

- 470 [1] Appleyard, D., 1969. Why buildings are known. *Environment and Behavior* 1, 131–156.
- [2] Benedikt, M.L., 1979. To Take Hold of Space: Isovists and Isovist Fields. *Environment and Planning B: Planning and Design* 6, 47–65.
- [3] Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E., 2008. Fast
475 unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment* 1008, 1–12. doi:doi:10.1088/1742-5468/2008/10/P10008.
- [4] City of Boston, 2017. Boston Landmark Commission. URL:
480 http://bostonopendata-boston.opendata.arcgis.com/datasets/7a7aca614ad740e99b060e0ee787a228_3.
- [5] Cooper, C.H., 2015. Spatial localization of closeness and betweenness measures: a self-contradictory but useful form of network analysis. *International Journal of Geographical Information Science* 29, 1293–1309. doi:doi:10.1080/13658816.2015.1018834.
- 485 [6] Couclelis, H., Golledge, R.G., Gale, N., Tobler, W., 1987. Exploring the anchor-point hypothesis of spatial cognition. *Journal of Environmental Psychology* 7, 99–122. doi:doi:10.1016/S0272-4944(87)80020-8.
- [7] Dalton, R.C., Bafna, S., 2003. The syntactical image of the city: A reciprocal definition of spatial elements and spatial syntaxes, in: *Proceedings, 4th International Space Syntax Symposium, London*. pp. 1–22.
490

- [8] Devlin, A.S., 2001. Mind and maze: Spatial cognition and environmental behavior. Praeger Publishers/Greenwood Publishing Group, Westport, CT.
- [9] Elias, B., 2003. Extracting landmarks with data mining methods, in: Kuhn, W., Worboys, M.F., Timpf, S. (Eds.), Spatial Information Theory. Foundations of Geographic Information Science. COSIT 2003. Lecture Notes in Computer Science, vol 2825. Springer, Berlin, Heidelberg, pp. 375–389. doi:doi:10.1007/978-3-540-39923-0_25.
- [10] Figueiredo, L., Amorim, L., 2005. Continuity lines in the axial system, in: 5th International Space Syntax Symposium, Delft. pp. 161–174.
- [11] Frank, A.U., Mark, D.M., Raubal, M., 2013. Researching Cognitive and Linguistic Aspects of Geographic Space: Las Navas Then and Now, in: Raubal, M., Mark, D.M., Frank, A.U. (Eds.), Cognitive and Linguistic Aspects of Geographic Space. Springer, Berlin, pp. 1–22. doi:doi:10.1007/978-3-642-34359-9_1.
- [12] Gao, S., Janowicz, K., Couclelis, H., 2017a. Extracting urban functional regions from points of interest and human activities on location-based social networks. Transactions in GIS 21, 446–467. doi:doi:10.1111/tgis.12289.
- [13] Gao, S., Janowicz, K., Montello, D.R., Hu, Y., Yang, J.A., McKenzie, G., Ju, Y., Gong, L., Adams, B., Yan, B., 2017b. A data-synthesis-driven method for detecting and extracting vague cognitive regions. International Journal of Geographical Information Science , 1–27doi:doi:10.1080/13658816.2016.1273357.
- [14] Gibson, J.J., 1979. The ecological approach to visual perception. Houghton Mifflin, Boston, MA.
- [15] Girvan, M., Newman, M.E.J., 2002. Community structure in social and biological networks. Proceedings of the National Academy of Sciences of the United States of America 99, 7821–7826. doi:doi:10.1073/pnas.122653799.

- [16] Golledge, R.G., 1995. Path selection and route preference in human navigation: A progress report, in: Frank, A.U., Kuhn, W. (Eds.), *Spatial Information Theory A Theoretical Basis for GIS. COSIT 1997. Lecture Notes in Computer Science*, vol 1329, Springer, Berlin. pp. 207–222.
- [17] Gopal, S., Klatzky, R.L., Smith, T.R., 1989. Navigator: A psychologically based model of environmental learning through navigation. *Journal of Environmental Psychology* 9, 309–331. doi:doi:10.1016/S0272-4944(89)80012-X.
- [18] Haken, H., 1983. *Synergetics: An introduction. Nonequilibrium phase transitions and self-organization in physics, chemistry, and biology.* Springer, Berlin.
- [19] Haken, H., Portugali, J., 2003. The face of the city is its information. *Journal of Environmental Psychology* 23, 385–408. doi:doi:10.1016/S0272-4944(03)00003-3.
- [20] Haq, S., Girotto, S., 2003. Ability and intelligibility: Wayfinding and environmental cognition in the designed environment, in: Hanson, J. (Ed.), *Proceedings, 4th International Space Syntax Symposium, London.* pp. 1–68.
- [21] Hillier, B., Hanson, J., Graham, H., 1987. Ideas are in things: an application of the space syntax method to discovering house genotypes. *Environment and Planning B: Planning and Design* 14, 363–385. doi:doi:10.1068/b140363.
- [22] Hillier, B.B., Hanson, J., 1984. *The social logic of space.* Cambridge University Press, Cambridge.
- [23] Hillier, B.B., Iida, S., 2005. Network effects and psychological effects: A theory of urban movement, in: Cohn, A.G., Mark, D.M. (Eds.), *Spatial Information Theory. COSIT 2005. Lecture Notes in Computer Science*, vol 3693. Springer, Berlin, Heidelberg. 1987, pp. 553–564. doi:doi:10.1007/11556114_30.

- [24] Jiang, B., 2013. The image of the city out of the underlying scaling of city artifacts or locations. *Annals of the Association of American Geographers* 103, 1552–1566. doi:doi:10.1080/00045608.2013.779503.
- 550 [25] Jiang, B., Liu, C., 2009. Street-based topological representations and analyses for predicting traffic flow in GIS. *International Journal of Geographical Information Science* 23, 1119–1137. doi:doi:10.1080/13658810701690448.
- [26] Kim, Y.O., Penn, A., 2004. Linking the spatial syntax of cognitive maps to the spatial syntax of the environment. *Environment & Behavior* 36, 483–504. doi:doi:10.1177/0013916503261384.
- 555 [27] Kitchin, R.M., Blades, M., 2002. *The cognition of geographic space*. I.B. Tauris, London.
- [28] Kuipers, B.J., 1978. Modeling spatial knowledge. *Cognitive Science* 2, 129–153. doi:doi:10.1207/s15516709cog0202_3.
- 560 [29] Law, S., 2017. Defining Street-based Local Area and measuring its effect on house price using a hedonic price approach: The case study of Metropolitan London. *Cities* 60, 166–179. doi:doi:10.1016/j.cities.2016.08.008.
- [30] Llinares, C., Page, A., Llinares, J., 2013. An approach to defining strategies for improving city perception. Case study of Valencia, Spain. *Cities* 35, 78–88. doi:doi:10.1016/j.cities.2013.06.009.
- 565 [31] Lynch, K., 1960. *The image of the city*. MIT Press, Cambridge, MA.
- [32] Manley, E.J., 2014. Identifying functional urban regions within traffic flow. *Regional Studies, Regional Science* 1, 40–42. doi:doi:10.1080/21681376.2014.891649.
- 570 [33] Manley, E.J., Orr, S., Cheng, T., 2015. A heuristic model of bounded route choice in urban areas. *Transportation Research Part C: Emerging Technologies* 56, 195–209. doi:doi:10.1016/j.trc.2015.03.020.

- [34] Massachusetts Office of Geographic and Environmental Information, 2002. Building Footprints and Heights from LIDAR. URL: <https://earthworks.stanford.edu/catalog/mit-us-ma-bostonmet-g46bldght-2002>. 575
- [35] Massachusetts Office of Geographic and Environmental Information, 2014. Massachusetts Department of Transportation (MassDOT) Roads. URL: <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/eotroads.html>. 580
- [36] Massachusetts Office of Geographic and Environmental Information, 2015. Trains. URL: <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/trains.html>. 585
- [37] Massachusetts Office of Geographic and Environmental Information, 2017. MassDEP Hydrography (1:25,000). URL: <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/hd.html>. 590
- [38] Newman, P., Kenworthy, J.R., 1999. Sustainability and cities: Overcoming automobile dependence. Island Press, Washington, DC.
- [39] OpenStreetMap contributors, 2017. Planet dump retrieved from <https://planet.osm.org>. URL: <https://www.openstreetmap.org>. 595
- [40] Porta, S., Crucitti, P., Latora, V., 2006a. The network analysis of urban streets: A dual approach. *Physica A* 369, 853–866. doi:doi:10.1016/j.physa.2005.12.063.
- [41] Porta, S., Crucitti, P., Latora, V., 2006b. The Network Analysis of Urban

- 600 Streets: A Primal Approach. *Environment and Planning B: Planning and Design* 33, 705–725. doi:doi:10.1068/b32045.
- [42] Portugali, J., 1992. Geography, environment and cognition: an introduction. *Geoforum* 23, 107–109. doi:doi:10.1016/0016-7185(92)90009-S.
- [43] Portugali, J., 2011. Complexity, cognition and the city. *Understanding Complex Systems*, Springer-Verlag, Berlin, Heidelberg.
605 doi:doi:10.1007/978-3-642-19451-1.
- [44] Ratti, C., 2004. Space Syntax: Some inconsistencies. *Environment and Planning B: Planning and Design* 31, 487–499. doi:doi:10.1068/b3019.
- [45] Raubal, M., Winter, S., 2002. Enriching Wayfinding Instructions with
610 Local Landmarks, in: Egenhofer, M.J., Mark, D.M. (Eds.), *Geographic Information Science. GIScience 2002. Lecture Notes in Computer Science*, vol 2478. Springer, Berlin, pp. 243–259. doi:doi:10.1007/3-540-45799-2_17.
- [46] Richter, K.F., 2013. Prospects and challenges of landmarks in navigation services, in: Raubal, M., Mark, D.M., Frank, A.U. (Eds.), *Cognitive and Linguistic Aspects of Geographic Space. Lecture Notes in Geoinformation and Cartography*. Springer, Berlin, Heidelberg, pp. 83–97.
615 doi:doi:10.1007/978-3-642-34359-9_5.
- [47] Richter, K.F., Winter, S., 2014. Conceptual Aspects: How Landmarks Can Be Described in Data Models, in: *Landmarks*. Springer International Publishing, Cham, pp. 109–135. doi:doi:10.1007/978-3-319-05732-3_4.
620
- [48] Sadalla, E.K., Burroughs, J.W., Staplin, L.J., 1980. Reference points in spatial cognition. *Journal of Experimental Psychology: Human Learning and Memory* 6, 516–528.
- [49] Sadalla, E.K., Montello, D.R., 1989. Remembering changes
625 in direction. *Environment and Behavior* 21, 346–363. doi:doi:10.1177/0013916589213006.

- [50] Shannon, C.E., Weaver, W., 1949. The mathematical theory of communication. University of Illinois Press, Urbana, IL.
- [51] Siegel, A.W., White, S.H., 1975. The Development of Spatial Representations of Large-Scale Environments, in: *Advances in Child Development and Behavior*. volume 10, pp. 9–55. doi:doi:10.1016/S0065-2407(08)60007-5.
- [52] Sorrows, M.E., Hirtle, S.C., 1999. The nature of landmarks for real and electronic spaces, in: Freksa, C., Mark, D.M. (Eds.), *Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science*. COSIT 1999. Lecture Notes in Computer Science, vol 1661, Springer, Berlin, Heidelberg. pp. 37–50. doi:doi:10.1007/3-540-48384-5_3.
- [53] Thomson, R.C., 2004. Bending the Axial Line: Smoothly Continuous Road Centre-Line Segments as a Basis for Road Network Analysis, in: *Proceedings of the 4th International Space Syntax Symposium*, London.
- [54] Tomko, M., Winter, S., 2013. Describing the functional spatial structure of urban environments. *Computers, Environment and Urban Systems* 41, 177–187. doi:doi:10.1016/j.compenvurbsys.2013.05.002.
- [55] Turner, A., 2007. From axial to road-centre Lines: A new representation for Space Syntax and a new model of route choice for transport network analysis. *Environment and Planning B: Planning and Design* 34, 539–555. doi:doi:10.1068/b32067.
- [56] Tversky, B., 1993. Cognitive maps, cognitive collages and spatial mental model, in: Frank, A., Campari, I. (Eds.), *Spatial Information Theory A Theoretical Basis for GIS*. COSIT 1993. Lecture Notes in Computer Science, vol 716, Springer, Berlin, Heidelberg. pp. 14–24. doi:doi:10.1007/3-540-57207-4_2.
- [57] Tversky, B., 2003. Structures of mental spaces: How people think about space. *Environment and Behavior* 35, 66–80. doi:doi:10.1177/0013916502238865.

- 655 [58] Winter, S., 2003. Route adaptive selection of salient features, in: Kuhn, W., Worboys, M., Timpf, S. (Eds.), *Spatial Information Theory. Foundations of Geographic Information Science. COSIT 2003. Lecture Notes in Computer Science*, vol 2825, Springer, Berlin, Heidelberg. pp. 349–361. doi:doi:10.1007/978-3-540-39923-0_23.
- 660 [59] Winter, S., Tomko, M., Elias, B., Sester, M., 2008. Landmark hierarchies in context. *Environment and Planning B: Planning and Design* 35, 381–398. doi:doi:10.1068/b33106.
- [60] Yun, Y.W., Kim, Y.O., 2007. The effect of depth and distance in spatial cognition, in: *Proceedings, 6th International Space Syntax Symposium*, 665 Istanbul. pp. 1–14.
- [61] Zipf, G.K., 1949. *Human behaviour and the principles of least effort*. Addison-Wesley, Cambridge, MA.

5. Appendix

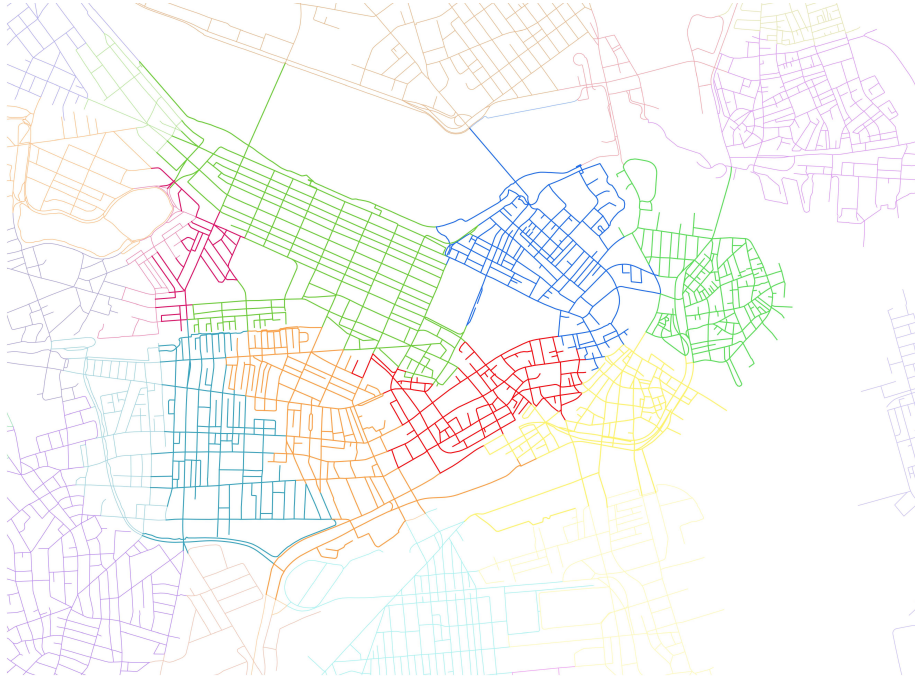


Figure A1: Districts: Street-based Local Area (SLA) in Boston city centre extracted from a street-network without motorways. Each colour represents streets belonging to a single district; semi-transparent colours indicate streets outside the studied area.



Figure A2: Landmarks: Buildings coloured by component scores.