

[DesignSpace]—Internal Documents. (2010) 1–32
Publisher: Mehul Bhatt

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Spatial behavior and linguistic representation. Ed. T. Tenbrink, J. Wiener, C. Claramunt.

Explorations in Language and Space, Oxford University Press, 2010-2011.

The ‘*Space*’ in Spatial Assistance Systems

Conception, Formalisation, and Computation

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<http://www.sfbtr8.spatial-cognition.de/designspace.html>

General keywords: artificial intelligence, qualitative spatial representation and reasoning, cognitive models of space, spatial assistance systems, design semantics and creativity, intelligent CAAD, decision-support for architecture design

Call specific keywords: language as a representation of spatial thought, representation and modelling frameworks, formal and computational models of space, behaviour and action in space

Abstract. This chapter is about ‘*space*’: empty space, spatial structures, and the process of structuring. We organize empty space by building-up structures and artefacts of our everyday existence, and structuring transforms and organizes empty space into something of a desired *form* (e.g., a balanced room, a visually pleasing scene), *function* (e.g., easily navigable) and *semantic connotation* (e.g., of a ‘place’). The chapter is written from the perspective of spatial informatics and addresses space at the scale of everyday human perception and thinking.

The core of this chapter is to present the informatics of spatial structure; this is done at three levels: (1) the conception of structural form, as it accrues in the minds of people, and its expression, using spatio-linguistic modalities; (2) the formalization of space, using representational means for spatial abstraction; and (3) the computation of structural forms in a manner that constructively assures, assists, and empowers those who conceive of those forms.

The chapter is grounded to reality with respect to a particular class of spatial systems, e.g., architecture design, where our interpretations of creative and constructive assistance are applicable. We also present case studies in domains such as design creativity for media pre-production, and real-time emergency assistance, though architectural design remains an area of special emphasis throughout the chapter.

1. The Spatial Premises: Introduction and Overview of Chapter

Spatial thinking, conceptualisation and the linguistic communication of commonsense as well as expert knowledge about the world is one of the most important aspects of everyday human life. Philosophers, cognitive scientists, linguists, psycholinguists, ontologists, information theorists, computer scientists and mathematicians have each investigated space through the perspective of the lenses afforded by their respective field of study. Interdisciplinary studies on spatial cognition, e.g., 'language and space', 'spatial memory', 'spatial conceptualisation', 'spatial representations', 'spatial formalisations', 'spatial reasoning' are extensive and enormous to say the least. Within this book itself, other chapters present an elaborate review of the state-of-the-art for some of these fields of study.¹

We address 'space' from a formal modelling and computational viewpoint, i.e., space, as it is interpreted within the computer science disciplines concerned with the investigation of artificial intelligence and knowledge representation in general, and formal methods in spatial representation and reasoning in particular [1, 12, 21, 27]. Indeed, the connections between formal models of space, and space as it occurs in language, are themselves a matter of intense research activity, e.g., within initiatives concerned within generalized linguistic ontologies of space – this is an aspect that we do not directly address in this chapter. However, the chapter does not lose sight of the inherently 'linguistic' aspects and presents several examples of spatio-linguistic discourse material within a broad range of case-studies coming from domains with a real application impact. Against the backdrop of this material, we build practically grounded case-studies and strive to concretely present the relationship between the conception, formalization and the computational aspects of '*space*', as it occurs within systems of human assistance, assurance and empowerment.

Assistance Systems. The core of our perspective in this chapter is rooted in our interpretation of a general class of systems concerned with assistance, assurance and empowerment of humans in their everyday professional and personal lives. Confining the discussion to the spatial domain, these are systems of human-computer interaction involving the representation of space from several different perspectives — the psycholinguistic and cognitive perspective of humans, the abstract knowledge-centric (symbolic) perspective of an intelligent software construct, and the all too complex and inherently numerical or quantitative perspective of the computer (read: real world). In our terminology, spatial assistance systems are cognitive agents that 'know' the properties of physical space and are skilled to deal with them in such a way that they can support humans. A special requirement for spatial assistance systems is that they are able to empathize with their human partners to a certain extent; i.e. they should adapt to the needs of people rather than require people to adapt to their needs.

Spatial Computing. The physical spatial domain that we are engaged with in all of our activities deserves special attention for a variety of reasons. Unlike in abstract mathematical spaces, the dimensions of physical space exhibit strong interdependencies. This is owed to the fact that – from a certain perspective – the three spatial dimensions share the same quality: an object that is long in the x-dimension will be long in the y- or z-dimension by simple re-orientation in physical space; the (nature of the) object itself needs not to be changed. As far as we can tell, comparably simple operations are not available in other spaces. Furthermore, the number of spatial dimensions is limited to three; thus, in whatever ways we move objects in space, we will stay within the interrelation of three spatial dimensions.

The main message of these considerations is that physical dimensions are strongly interrelated and that physical space is severely constrained. This can be viewed as a strong limitation in comparison to abstract spaces in which arbitrary configurations of feature values and arbitrary transitions between them are con-

¹In particular, chapters most directly related our work include: (1) the chapter by Gally et al. on navigation assistance systems for blind pedestrians; (2) the chapter by Barclay and Galton on reference object selection for locative expressions; and (3) the chapter by Taylor and Brunyé on the cognitive underpinnings of survey and route description comprehension. Further comments on the relationship with these works are included as they accrue in the rest of the chapter.

ceivable. However, in some domains, such as design, these constraints can be considered a great advantage, as they considerably reduce the space of design decisions. We use the notion of 'spatial computing' in a way that exploits the intrinsic constraints of spatial structures in such that only those structures will be generated that are realizable in physical space and that do not require a computational reduction from conceivable structures to physically realizable structures.

Multi-Perspective Semantics. In order for (our select) class of assistance systems to achieve their functional objectives of human assistance, assurance and empowerment, the perspective of each stakeholder within the human-computer interaction process has to be adequately accounted for. This must be achieved in a manner of representation and ontological conceptualisation that is consistent with the respective '*spatial*' interpretation of a specific stakeholder. We refer to this notion as *multi-perspective representational semantics*, or simply, multi-perspective semantics for short.

Take the case of an *architecture design assistance system*: here, a designer conceptualises and abstracts the *structural form* of an environment with respect to an abstract and innate understanding of the shape, layout and the connectivity of a *spatial structure* – here, the *designer* represents one perspective consisting of, for instance, concepts and relationships from the design domain. By a complex mysterious process we term 'creativity', the designer's abstract notion of structural form is then translated into a real design within a tool for spatial design in the form of a floor-plan consisting of some geometric feature hierarchy consisting of points, line-segments and polygons – these geometric elements are a part of what constitutes another perspective with the system, namely, the perspective of the *design tool*. Now imagine a symbolic design reasoning module that is aimed at deriving the independent as well as inter-related inferences about the perspectives of designer and the design tool, e.g., the reasoning system may be entrusted with the responsibility that a particular design requirement such as *spacious* or *private* in the context of a particular Room within the design are indeed satisfied. Here, the conceptual constraints expressed by the designer need to be validated with respect to the realizations within the design tool, with respect to the perspective of the *design reasoner*. In the case of this example, the design reasoner utilises its own perspective, minimally consisting of qualitative abstractions about the topological, relative orientational and other spatial aspects of the quantitatively modelled design.

What multi-perspective semantics suggests is that the ontological viewpoints of each of the stakeholders – *designer*, *design reasoner*, *design tool* – involved within the assistance system are important, and have to be accounted for in their own right. Taken together, these perspectives constitute the essential nature and character of 'space' within a spatial assistance system. Multi-perspective semantics is further elaborated on in Section 4.

Language as a Representation of Structural Form, and Behavioural Function. Continuing with the architecture design assistance scenario, consider an architect or an interior designer confronted with the objective to design an office environment in response to a pre-specified set of client requirements. The expert designer, either individually or within a group interaction, conceptualizes the design task bearing in mind the structural form of the environment with respect to the corresponding functional expectation, which the conceptualisation is expected to produce. That is, a structure is envisioned with respect to an anticipated behaviour, and the behaviour or a set of behaviours satisfy a desired function.²

Interior Space Description. As an example, consider either an architect, an interior designer, or more ambitiously, a system concerned with interpreting, annotating or understanding the spatial semantics of an interior space description:

²This view of the *functional* aspects of a design bears close relationships to the ontological framework of the Function-Behaviour-Structure (FBS) [30, 31] model of the design process.

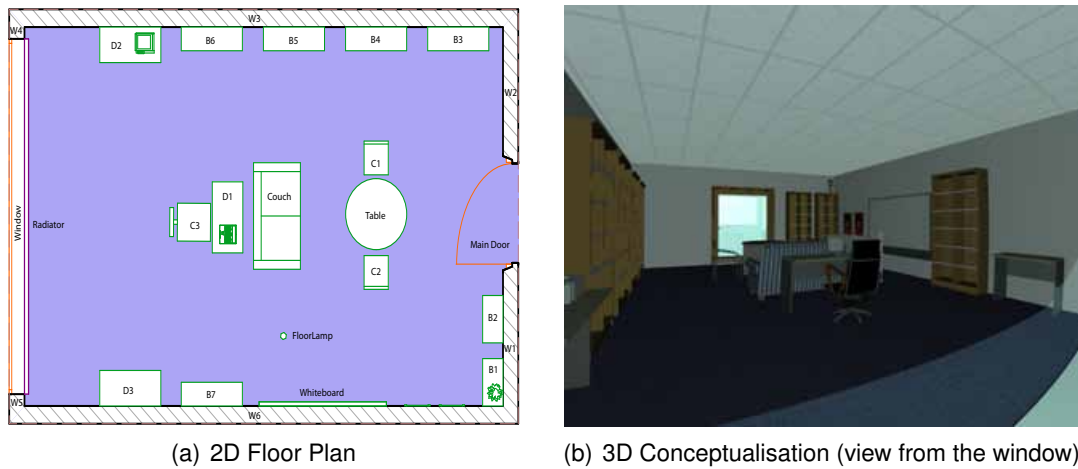


Fig. 1. Volen 258 Center Design: Role of Paths, Patterns and Commonsense Knowledge in Design

"As you enter the office, there are two tall bookcases directly to your left. Sitting on the top of the bookcase farthest from you is a potted plant that hangs down almost to the floor. The adjacent wall has two framed pictures on it and a large white board. On your right from the door are four more tall bookcases that are almost completely filled. In front of you from the door is a small round table with two chairs on either side of it. The table has a notebook, some loose papers, and a textbook on top of it. Further into the room is a small leather couch. A desk is directly behind the couch. There is also a floor lamp between the couch and the white board. The four bookcases to the right of the couch extend along that wall so that the last one is parallel to the desk. Across from that bookcase, on the other side of the desk, is one last tall bookcase. The desk that is directly behind the couch holds a laptop computer and two desk lamps. To the right of the desk along the same wall with the four bookcases is another large table with several stacks of papers on it and a printer. A large framed poster hangs on the wall above the table. There is an open path between the couch and the bookcases to get to the far end of the office. Across from the large table on the same wall as the whiteboard is a second desk that is arranged perpendicularly to the first desk. On this one are a stereo, a telephone, and several framed pictures. Above this desk is one more framed poster. The back wall of the office is mostly composed of a large window that extends almost to the floor. A radiator with a flat top is under the window. Several more potted plants are sitting on the ledge of the radiator as well as some coffee mugs and a coffee maker."

(Volen 258 Center Description. Text source: ISO-Space 2010 Workshop Documents.)

We have derived a design of the interior description on the basis of the Volen 258 text above, illustrated in Figure 1: Fig. 1(a) is a 2D floor-plan corresponding to the spatial description, whereas Figure 1(b) is its corresponding 3D interpretation. Finally, Fig. 2 illustrates the spatial descriptors – *features and relationships* – that essentially determine the overall constitution of the interior space. It is easy to see the crucial role of paths and patterns such as *circularity*, *extends_along*, *further_into*, *open_path*, *composed_of*.³ From the viewpoint of spatial computing for design, the spatio-linguistic, semantic, qualitative and quantitative interpretation of descriptors such as these acquires a significant role within systems, i.e., automated reasoning processes. In the domain of design assistance, these processes are concerned with primarily two key aspects:

- *design engineering*: this refers to the creation of a structural form that conforms to a behavioural and functional specification
- *design reverse engineering*: given a structural specification, this corresponds to inferring the extent to which a precise structure fulfills a set of anticipated functional requirements. In this form of analysis, often the easier approach is to look for malfunction, as opposed to an extensive enumeration of the functional aspects

³The design exercise illustrated in Fig. 1 have been made taking into account the 'narrative-like' structure of the text as a whole, and a consolidation of all the 'perspectives' that are offered therein.

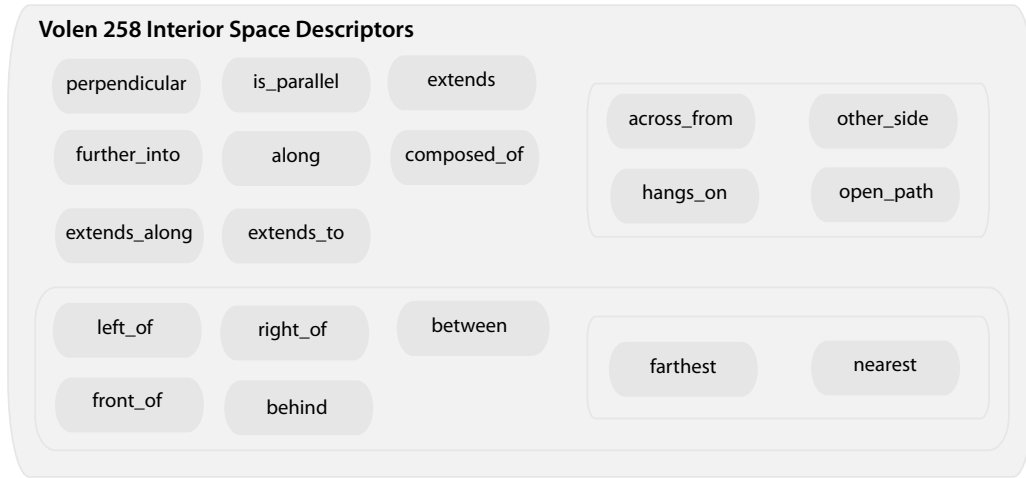


Fig. 2. Key Spatial Descriptors

The above described notion of structural forms and their corresponding behavioural and functional entailments is not confined to the domain of architectural design alone. In the chapter, we will also illustrate the utility of this line of thought to a completely different design domain, namely the creative design of media. Furthermore, outside of the design domain, we also illustrate their applicability for the domain of real-time emergency assistance.

Aim and Organization. The aim of this chapter is to:

- (a) pragmatically illustrate the manner in which spatio-linguistic conceptions occur within a range of spatial assistance systems involving human assistance, assurance and empowerment;
- (b) provide an abstraction and formalization mechanism that may be used as an interfacing mechanism between the spatio-linguistic conceptualization of humans, and their precise interpretations within a practical system;
- (c) with respect to our perspective on spatial information handling for a stated purpose, illustrate the nature, role and significance of spatial computing within practical spatial assistance systems

The chapter is organised as follows:

Section 2. *What is a Spatial Assistance System?*

This section lays-out our interpretation of a spatial assistance system. Although the discussion here is rather general, it forms a basis for the select domain elaborations that are introduced in Section 3 and built-up in the rest of the chapter.

Section 3. *The Spatio-Linguistic Markers within Spatial Assistance Systems: Select Case-Studies*

Here we focus on select application areas from the range introduced in our general discussion of spatial assistance in Section 2. The spatio-linguistic markers within the domains of architecture design, creative media design and real-time emergency assistance are presented, together with an overview of the assistance potentiality and problematic aspects in the domains under consideration.

Section 4. *Structural Form: Multi-Perspective Representational Semantics and Modal Abstraction*

This section develops the formal framework that is required to operationalize the abstractly identifiable notion of the structural form (also developed in this section). The crux of this section lies in the elaboration

tions on multi-perspective semantics and qualitative abstractions mechanisms in the context of structural forms.

Section 5. *Spatial Computing within Assistance Systems*

Here we consolidate the rest of the chapter by demonstrating the spatial computing, and the underlying reasoning patterns thereof, that may be realised with the formal model presented in the chapter. We attempt to emphasise the philosophy the underlies our take on spatial computing – its precise grounding by way of our concrete examples themselves being only a few select possible interpretations.

Finally, Section 6 includes a brief summary of the chapter, together with a discussion of broad perspectives and aspects not covered in the chapter in detail.

2. What is a Spatial Assistance System?

A Spatial Assistance System (SAS) is a computational manifestation of the spatial decision-making and other forms of analytical and creative abilities situated along a multi-dimensional and mutually interacting spectrum: on the one hand are those abilities that typically require extensive domain-specific training, knowledge, and expertise (e.g., an architect, a film cinematographer), whereas on the other are those abilities that merely require the natural intelligence that humans are equipped with by virtue of their everyday existence (e.g., way-finding tasks). Regardless of the precise domain of application, the crucial developmental aim of a spatial assistance system is to transfer the cognitive stress involved in a human analytical activity onto a system, by externalising and operationalising the decision-making processes involved therein. In essence, spatial assistance systems are basically instruments of human *assistance*, *assurance* and *empowerment* and they serve one or more of these functions depending on the precise area of their application.

Given the scope of this chapter, which is focussed on computational systems and frameworks for human-like spatial awareness capabilities, some instances of SASs include decision-support tools requiring specialized *Spatial Computing* capabilities, for instance, in the manner as defined for the domain of intelligent spatial design assistance [8]. As a broad range of examples, consider the following application areas where the aforesaid notion of spatial assistance may be clearly identified:

- ▷ *Spatial Design Assistance.* The domain of spatial design assistance encompasses all those areas where humans engage in a creative spatial design or planning activity of some form. As a key example, consider the case of architectural design assistance systems where a work-in-progress design of a building within the context of a Computer-Aided Architecture Design (CAAD) tool has to be reasoned about. Other scenarios include urban planning, tasks involving spatial conceptualisation and visual thinking about spatial structures, e.g., pre-production assistance in media design.
- ▷ *Real-Time Emergency Assistance.* These are systems that provide intelligent assistance for emergency scenarios such as fire-fighting, rescue and evacuation, and paramedic-support in emergency scenarios. This domain is characterised by the need to provide high-level strategic-planning assistance, e.g., in order to meet the immediate challenges of navigating and overcoming physical obstacles in an unfamiliar and hostile (e.g., low-visibility) environment.

- ▷ *Ambient Intelligence (AmI), Pervasive and Ubiquitous Computing (UbiComp)*. These include a broad range of technologically-driven systems involving the modelling of, for instance, action, change, interaction, situational context and the semantics of *space* and *place* within practical deployments in the real world. Some instances include, mobile and location-based services, systems of activity modelling, behaviour interpretation and analysis.
- ▷ *Indoor Navigation Assistance*. These are systems that provide specialised way-finding and navigation support mechanisms for built-up environments such as Malls, Exhibition Centres, Museums, Air-Ports, Train-Stations and other categories of built-up public spaces.
- ▷ *Ambient Assisted Living (AAL)*. These are a highly specialized class of practical systems aimed at serving an empowering and assuring function within private spaces such as residences and offices. Typically, these systems involve interactions between humans, robots and software systems.

Whereas there exist distinct categories of spatial assistance systems differing in the domain of application and the precise manner of intelligent assistance they provide, there are several fundamental similarities underlying the systemic and information-theoretic aspects of these systems. Primarily, the similarities pertain to the ontological, representational and computational foundations that underlie their practical design and implementation. Specifically, central to these categories of assistance systems is a common foundational basis consisting of representational modalities and computational capabilities:

- from a *representational viewpoint*, modalities for semantic modelling, multi-perspective representations, and qualitative spatial abstractions acquire a central significance
- from a *computational viewpoint* and closely connected to the representational modalities, computational techniques for conceptual and spatial reasoning define the essential character and nature of the (spatial) analytical and assistive capability that is implemented

In essence, one may identify several fundamental capabilities with respect to the spatial conceptualisation, modelling, and computing capabilities within the context of the range of systems identified herein. For instance, consider the case of spatial design assistance, and emergency and navigation assistance systems. The information and computational requirements for *spatial computing* in the context of an indoor *Structured Spatial Environment* (SSE) bears close relationships and similarities⁴ – several capabilities, e.g., by way of way-finding complexity analysis, (real-time) way-finding assistance, data analysis and artefactual simulation, virtual reality, natural human-computer interaction that may be operationalised within these systems are easily identifiable. Furthermore, the conceptualisation and representation of quantitative descriptions of real (i.e., already existing) or hypothetical (i.e., being designed) indoor spatial environments is also based on shared foundations. For the case of indoor or built-up environments, and for spatial assistance scenarios such as those aforementioned, it may be presumed that geometric model(s) of the environment under consideration are available, e.g., by way of accurate building and floor-plans (CAAD, design assistance), graph-based models (way-finding assistance), and CFD-based finite-element models (for structural analysis, cost estimation, phenomenal studies to simulate fire spread). These models may pertain to real spatial environments that have been built (e.g., a Museum), or they may pertain to an arbitrary environment that is undergoing initial conceptualisation, prototyping, and design.

Spatial computing (for spatial awareness), however it may be defined from a cognitive, ontological and computational viewpoint, does not differentiate between real and hypothetical environments. That is, different types of analytical capabilities that may be deemed to be within the purview of a particular interpretation of spatial awareness have to be based on high-level quantitative and qualitative perspectives that are grounded to a geometric model of an environment that may exist either in reality, or merely as a hypothetical construction within a system.

⁴These models of SSEs need to be grounded to industrial data representation standards designed for community-wide tool compliance and interoperability. Relevant remarks concerning this aspect may be found in Section 6.

3. The Spatio-Linguistic Markers within Spatial Assistance Systems: Select Case-Studies

This section directly builds on the overall premises established in Section 1 and our interpretation of spatial assistance systems described in Section 2. The aim of this section is to present a high-level, yet concrete examples of the nature of spatial assistance that is applicable within a select category of spatial assistance systems. The approach here is to illustrate the spatio-linguistic conceptions that accrue within the scope of our selected case-studies. These case-studies are then further elaborated on in the rest of the chapter.

3.1. Architecture Design Assistance

Spatial design in general, and architectural design in particular, as a problem-solving activity typically consist of the Conception – Modelling – Evaluation – Re-modelling cycle. Essentially, a designer in this case is considered to be an *agent of change*, who in the absence of any computational assistance, may be intuitively regarded as traversing a complex configuration space of possibilities, and selecting one course of action (guided by domain knowledge, expertise, cognitive capabilities, specialized requirements, aesthetic preferences and so forth) that produces a desired product or design. Since architectural design tasks are concerned with a spatial environment, formal representation and reasoning along conceptual and spatial dimensions is essential to ensure that the designed model satisfies key requirements that enable and facilitate its intended function.

A Design Task. As a use-case, consider the task of initial conception and design of a museum. A museum is an instance of a *structured spatial environment* that not only has a desired form and function, but is also constructed keeping in mind pre-determined aesthetic, cultural, psychological and other subjective parameters. Consider some of the descriptions that occur in the context of the design of the *Museu Calouste Gulbenkian* in Lisbon, Portugal.

"The current topographic conditions of the site, where the larger trees are located in an area that is more elevated than the whole northern rim of the plot, made it possible to install a huge underground floor in the already existing depression, whose covering creates a gentle artificial elevation that perspectively accentuates and enhances the whole architectural composition. The distribution of the construction volumes fundamentally followed a desire for horizontality, allowing one to read the continuity of the green space beyond the construction and in all directions."

"This sober, rational and markedly horizontal structure is distinctive for its laminar exterior, its modular repetition, austere design and the hard quality of the materials which shape it, concrete and glass."

"Seeking a balance between artificial and natural light, the initial solution settled on an overhead lighting system which was later abandoned and replaced by one which was more controlled in terms of its openings and its relationships between the interior and exterior in order to fit in the landscape between the patios and garden."

"The main matrix-like structure had long units and was spatially austere, linking public and private spaces while at the same time delineating the two inner patios of the Museum."

"In the internal spaces, it comes closer to the human scale with its comfortable, luminous and low ceilinged atriums that are gently linked by stairs seeking relations of surprise with the garden."

(Museum Gulbenkian, Lisbon. Architecture and Landscape (pages. 22, 23, 26, 27) [50])

Statutory Building Codes. In addition to high-level conceptions of the design, designers are confronted with mandatory regulations that enforce several structural constraints ranging in different levels of complexity:

"Steps of a staircase may not be connected directly to a door that opens in the direction of the steps. There has to be a landing between the staircase steps and the door. The length of this landing has to have at least the size of the door width"

(Staircase / Treppen (§35 (10), pg. 24. Bremen (Germany) Building code [18])

Design Guides. In addition to the statutory codes, one may also identify design requirements emanating from expert recommendations. For instance, the following (statutory and optional) set of requirements may be identified from the US Courts design guide [51], and Alexander's *pattern language* [2]:

"Courtroom areas used by the public must be accessible to people with disabilities. Private work areas, including the judge's bench and the courtroom deputy, law clerk, bailiff, and court reporter stations, must be adaptable to accessibility. While all judge's benches and courtroom personnel stations do not need to be immediately accessible, disabled judges and court personnel must be accommodated."

"The architecture of federal courthouses must promote respect for the tradition and purpose of the American judicial process. To this end, a courthouse facility must express solemnity, integrity, rigor, and fairness."

"All architectural elements must be proportional and arranged hierarchically to signify orderliness. The materials employed must be consistently applied, be natural and regional in origin, be durable, and invoke a sense of permanence."

"The height and location of the judge's bench expresses the role of the judge and facilitates control of the court [...]. Generally, the judge's bench should be elevated three or four steps (21-24 inches or 525-600 mm) above the courtroom wall."

"The entrance or entrance vestibule should be clearly visible and recognizable as such from the exterior of the building. The vestibule should be a minimum of 7 feet in depth and able to handle the flow of traffic at peak times."

"A duress alarm must be easily accessible and visible to all occupants."

(US Courts Design Guide 2007 [51])

"Place the main part of the kitchen counter on the south and southeast side of the kitchen, with big windows around it, so that sun can flood in and fill the kitchen with yellow light both morning and afternoon."

(A Pattern Language [2])

Environmental feature descriptions such as the ones aforementioned refer to abstract, high-level spatial design patterns that correspond to specific structures at a quantitative level. For instance, it is noticeable from the descriptions of the Museum that early design and conceptualisation involved high-level feature descriptions of the *structural form* of the environment. Spatial features such as *continuity*, *spaciousness*, *symmetry*,⁵ *modular repetition*, *elevation*, *relative positioning of entities*, *visibility relationships*, (*barrier-free*) *accessibility* may be easily identified. Section 4.2 will further illustrate the manner in which such high-level features may be modelled and reasoned about using the abstraction mechanisms that we propose in this chapter.

Contemporary professional design tools, and the precise quantitative modelling paradigm that they are based on, are inherently incapable of exploiting the correspondence between high-level descriptions of spatial concepts and features. Such tools simply lack the ability to exploit the expertise that a designer is equipped with, but is unable to communicate to the design tool explicitly in a manner that is consistent with its inherent human-centred conceptualization, i.e., *semantically* and *qualitatively* [8]. This chapter, in its remaining parts, illustrates the manner of formalization and computation that is needed to develop the assistance capability to solve design problems of this nature.

3.2. Creative Assistance in Media Design

We interpret *creative assistance in media production* as the capability of computational tools to augment the creative capabilities of experts and artists such as cinematographers, directors, script and screenplay writers, and story-boarding artists at several stages within the media design and creation process. Consider the domain of Film and Comic Book pre-production. Here, one may identify several forms of assistance at the production phase, e.g., virtual cinematography, story-boarding and scene visualization from scripts, automatic camera control in the animation domain. Some examples from domains of our active interest follow [7]:

⁵For example, one way to ensure a sense of 'justice' and 'fairness' within a court-room is to ensure a symmetric balance and equal access to (elements from) both sides of the courthouse.

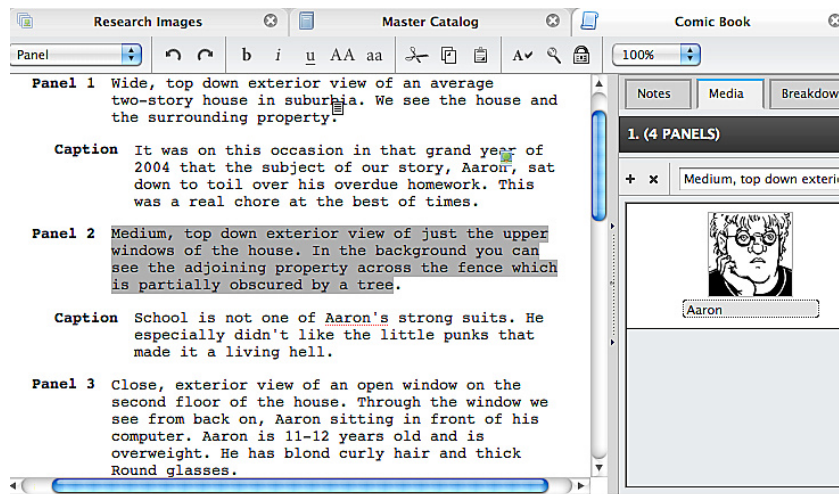


Fig. 3. CeltX: A (free) Media Pre-Production Software.

Scenario Description in Media Pre-Production. As an example, consider a typical creative design process between a script or screenplay writer, and story-boarding artist and cinematographer or director. The illustration in Fig. 3 is a snapshot from the freely available media pre-production software CeltX, which is designed from the viewpoint of a wide-range of design domains. It facilitates creation and organization of media projects like screenplays, films, videos, stageplays, audio plays, documentaries, machinima, comics, games and podcasts.⁶

The illustration of Fig. 3 corresponds to parts of a script and screenplay for a comic strip, as re-produced below:

- Scene:** Wide, top down exterior view of an average two-story house in suburbia. We see the house and the surrounding property.
- Scene:** Medium, top down exterior view of just the upper windows of the house. In the background you can see the adjoining property across the fence which is partially obscured by a tree.
- Scene:** Close, exterior view of an open window on the second floor of the house. Through the window we see from back on, Aaron is [...]
- Scene:** A wide panel that uses the lower half of the page. A close-up view of Aaron. He is staring directly ahead [...]

(The Mechanical Shakespeare; Text source: Comic Strip, CeltX Pre-production Software.)

As a basic level of assistance, the capability to automatically produce scenario visualizations based on the semantics of the spatial content present in the discourse material is useful. For instance, it is typical for cinematographers and set-designers to use the skills of story-boarding artists to start conceptualizing the precise manner and technical method of actually filming or animating a sequence. Consider the example story-boards included in Figures 4(a)⁷ and 4(b)⁸ – here, one may imagine the automatic production of such story-boards on the basis of the ‘*structural form*’ that is semantically interpreted and derived from the scenario description of the scene. The generation of these story-boards is connected to the much broader goal task of scenario and narrative completion, as explained below.

Scenario and Narrative Completion. In general, the field of automatic cinematography aims to derive a sequence of camera shots (i.e. the camera’s orientation to the actors, camera’s focus, and angle of view, etc.) from descriptions provided in a script [7, 20, 23, 33]. Most automatic cinematography involves using a knowledge-base of filming heuristics to control the perspective or placement of a camera based on

⁶CeltX. A Media Pre-Production Environment. www.celtx.com/

⁷Art credit: Wikimedia, Wikiversity. www.wikiversity.org/

⁸Art credit: Peter Rubin; Source: (Goldman et al. 2006)

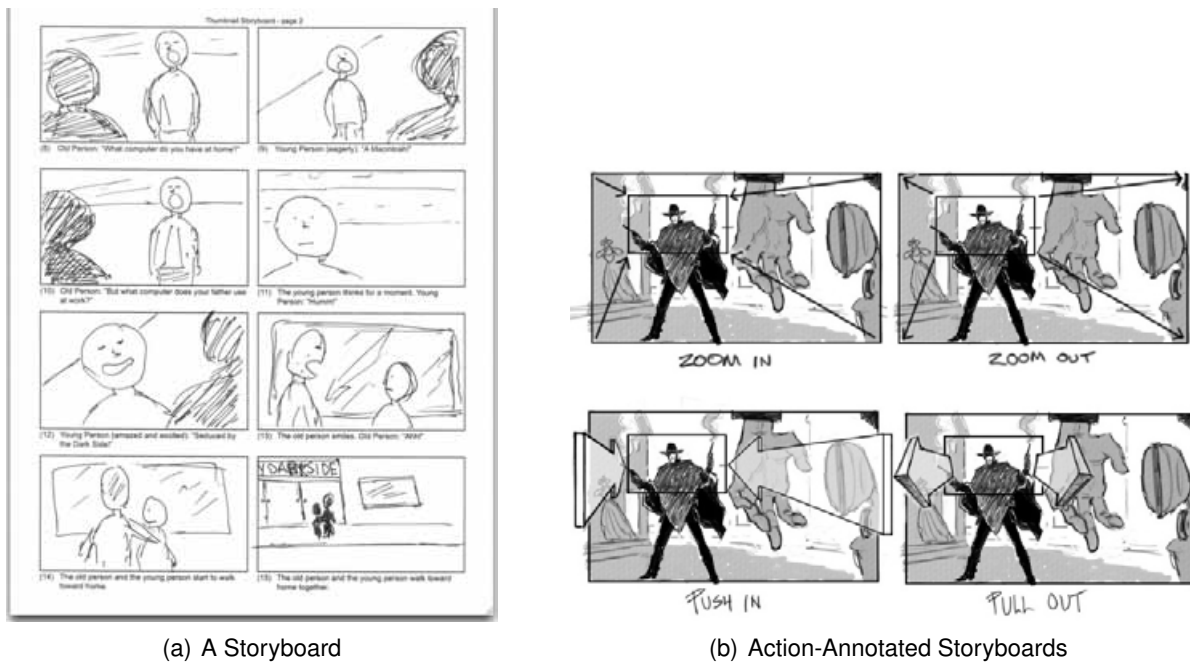


Fig. 4. Automatic Storyboarding



Fig. 5. 'Film Idioms' are heuristics for determining the relative positioning of actors and the camera within a scene

contextual cues of the scene. In this context, a film can be viewed as a hierarchy [33]; the top of the film hierarchy is the script, which consists of a sequence of time-ordered narrative descriptions [7], referred to as scenes. Each scene, in turn, provides contextual information, in the form of actions and events that can be used to derive a specific camera shot. The objective of each camera shot is to capture the sequence of events in a manner that is cinematically '*pleasing*', i.e., achieves a pre-determined aesthetic, dramatic or emotional effect.⁹

As an example, consider the simple, but common, scene in Fig. 5¹⁰ depicting a group of two actors. Within

⁹For elaborate studies on the theory, art and semiotics of narration, and the '*language games*' that underlie this domain, the collected works of Edward Branigan [16, 17] should be investigated.

¹⁰Stills credit: '*Mesrine: L'instinct de mort*' (2008), France. Director: Jean-Francois Richet. www.mesrinemovie.com/

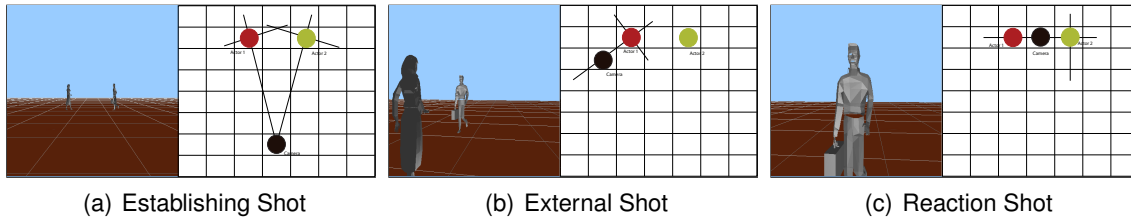


Fig. 6. Minimal Structural Form of Film Idioms Modelled using Ternary Orientation Relationships. Virtual Cinematography: 2 Avatars and 1 Virtual Camera; animation shows perspective of the dark / black circle, which is a virtual camera.

this scenario, the context of each scene is based on the current state of each actor with regards to their participation in the conversation, i.e. *talking*, *listening*, or *reacting*. Below is a sample script that involves two actors, Kendra and Annika, engaged in a conversation. In the example, contextual cues are provided as key words that indicate the current state of each actor, i.e. “Kendra starts to *talk*” and “Annika *reacts* with astonishment” and so forth, whereas from the screenplay writer’s perspective, the manner in which the scene has been conceptualised is based on heuristics guiding the placement of the actors and entities in relation to the location of the camera:

Act: Kendra and Annika

[[Establishing-shot](#)] – Kendra and Annika

Kendra starts talking to Annika – [*“dialogue”*]

[[Cut: mid-shot](#)] – Annika reacts anxiously to Kendra

Kendra continues talking to Annika

[[Cut: Close-up](#)] Annika responds to Kendra – [*“astonishment”*]

End.

(A Sample Narrative)

As the scenes progress the states of each actor change as the conversation develops. From this information, it is the job of the (automatic) cinematographer to decide on an appropriate sequence of camera shots to properly depict the conversation. The result of this process is similar to the storyboard found in Fig. 5, or the virtualization depicted in Fig. 6, which shows the perspective of the camera throughout the key moments of the scene. Because this scenario is so common in film, cinematic patterns have emerged that define heuristics to capture this particular type of situation, referred to by cinematographers as a *film idiom* [3]. These idioms have been defined for many typical cinematic situations, such as groups of actors in a conversation, or an action sequence. For instance, the ‘spatial structure’ associated with a film idiom may be formalised using qualitative spatial abstraction in a manner depicted in Fig. 6. In general, a film idiom can be seen as a set of declarative rules that specify a mapping between the use of camera shots to a situational context. We formally build-up on these aspects in the sections to follow, and in Section 5, illustrate the nature of spatio-temporal computation that is necessary to perform reasoning (e.g., scenario consistency, scene interpolation, spatio-temporal abduction) in this particular domain of interest.

3.3. Real-Time Emergency Assistance

The domain of emergency rescue work is characterised by urgent, safety-critical decision making based on very limited and vague information that is dynamic, volatile and possibly erroneous. These challenges exist at a range of abstraction levels, from the high-level strategic planning of firefighting captains to the

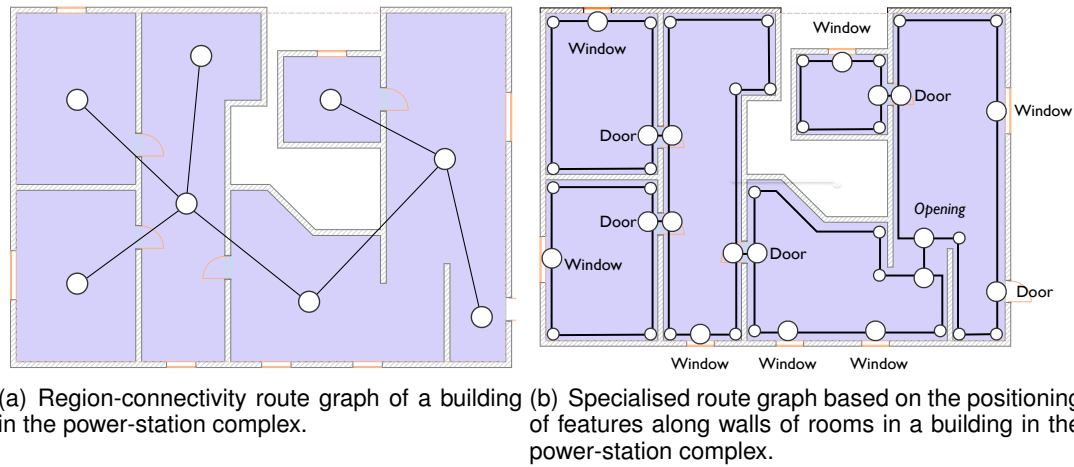


Fig. 7. Specialised route graphs provide a more effective modality that supports firefighters' current approaches to navigation compared to the standard definition of route graphs (floor-plan adapted from the ground floor of the Stockholm Fire Department training facility in the Agesta training centre, as cited in [40, 41]).

immediate challenges of navigating and overcoming physical obstacles in extremely hostile, noisy and low-visibility environments faced by firefighters. Navigation requires a combination of spatial modalities; in particular, the standard definition of route graphs as being defined based on the connectivity of regions is effective at the geographic level, but is too general for providing the spatial references and directions needed by firefighters as they navigate through a burning building with zero-visibility. Instead, a more specialised definition of route graphs is required that is modelled on the spatial language that firefighters use when communicating and navigating through hazardous indoor environments.

For example, consider the scenario that a caller has notified the fire service of a potential fire at a local power station; the following communication between the fire captain (FC) and the command centre operator (CCO) takes place.¹¹

FC: <"[...] we are heading for Nuevo-hotel">
CCO: <"okay [...] behind Nuevo-hotel along the cycle way there is an electricity-house, says the caller, and there is smoke [...]">
FC: <"[...] what company or address did you say?">
 :
 :
CCO: <"no .. along the cycle way behind Nuevo-hotel, there is some .. a large .. an electricity-house .. with smoke coming out [...]">
Foreman: "drive to the backside, ...when you pass the OceanStore"
Driver: "okay"
 :
 :
Foreman: "[...] we should drive behind the apartments ... on the backside"
FC: "yeah, there is that ... that entrance gate"
 :
 :
FC: "if there is ground current you should not take any big steps"

(communication recorded during ethnographic studies conducted by Landgren [39])

Spatial assistance tools can greatly assist rescue workers by integrating vague qualitative spatial knowledge with geometric CAAD-based city maps and building floorplans. Intelligent tools can help to resolve any conflicting information, assist in the maintenance of spatial information, and suggest the most

¹¹Quotations in angled parentheses represent radio communication.

plausible incident description (e.g. by annotating a building floorplan with symbols that represent the approximate location of firefighters, fires, smoke plumes, and so on); visualisations of this incident model could also be automatically communicated to any relevant parties. For example, consider two firefighters navigating through one of the buildings at the power station site in search of victims; the following communication takes place:

FFA: "you are in the kitchen, I am in the reference room"
:
:
FFB: "[...] we're standing by the door where we came in .. so now we can put the right hand on the wall here"
:
:
FFA: "do you feel a wall on the right side?"
FFB: "yeah, I've had contact with the wall the whole time there was a shoe shelf on the right side so"
:
:
FFA: "here is another door"
:
:
FFB: <"[...] we've gone into the reference room again, so now we're going into the second door on the left side">
FC: <"ah, you went into door two I heard, over">
:
:
FFA: "[...] ok .. then we have one room left in the first room, there was a door, we haven't been in there"
:
:
FFA: <"[...] we went straight on the first door on the left side and searched it">
FC: <"eh, can you repeat, over">
FFA: <"[...] we took the left hand on the wall and [...] went into the first room">
:
:
FFA: "[...] we should lead them to the kitchen [...]"
:
:
FFA: "[...] I've reached a doorway on the left side and we are going in there and we're holding the right hand on the wall [...] and see if we find the fire-extinguisher, over"

(communication recorded during firefighter training exercise by Lindgren et al. [40, 41])

The firefighters' sense of orientation depends heavily on reference features such as doors, walls, corners, and large pieces of furniture. As illustrated in Figure 7(a) the standard route graph does not provide the type of information that a firefighter needs when navigating through a building. A more effective, domain-specific route graph is defined by the arrangement of salient features such as doors and windows along room walls, as illustrated in Figure 7(b).

The chapter by Gally et al. (in this book) focuses on devices that provide navigation assistance for blind pedestrians. Within this context, the task we present for first response emergency rescuers can be characterized as requiring global navigation assistance via either visual or non-visual interfaces in a low-to-zero visibility environment; as a contrast to the chapter by Gally et al., we focus on assistance through a visual interface.¹² For example, consider the environment from a firefighter's perspective as they enter the building, as illustrated in Figure 8. A navigation assistance system is mounted on each of the firefighter's helmets with a small transparent display on the mask. The mask display lists the features of the room that are useful for orientation, ordered using the specialised route graph in Figure 7(b). The standard route graph can be used when the firefighters can move freely through the room, although when visibility is significantly reduced, the specialised route graph is more effective for navigation, as the firefighters need to rely on walls for orientation.

¹²In contrast to pedestrian navigation, relatively fine-grained localization required for indoor navigation can be achieved using a combination of dead reckoning strategies [44].

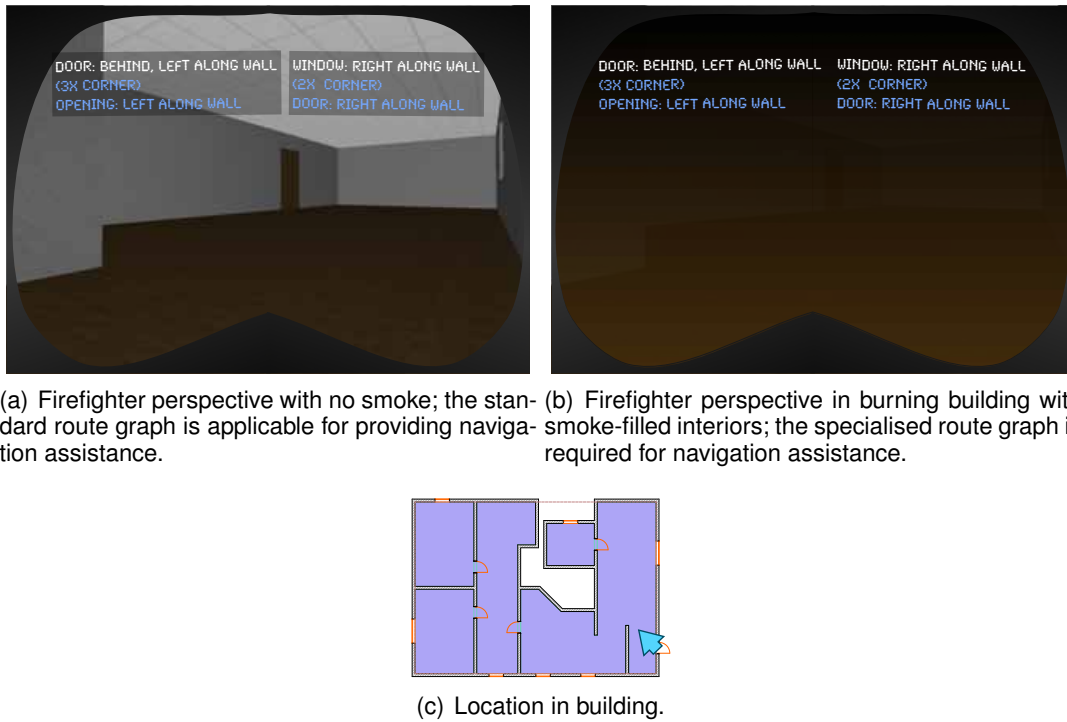


Fig. 8. Navigation assistance as firefighters enter the burning building.

The role of (assistive) spatial computing is to augment the firefighter's sense of the surrounding space and enhance their comprehension of the environment, for example, by informing them about local reference objects and their relative qualitative spatial relationships. Effective information technology tools can assist in strategising about search routes within the building, taking into account temperature sensor readings, fire spread models based on the known characteristics of the incident floorplans of the building, and so on.

4. Structural Form: Multi-Perspective Representational Semantics and Modal Abstraction

Having exemplified the spatio-linguistic markers that are identifiable as a point of human and spatial assistance system interaction in Section 3, the aim in this section is to elaborate on the internalisation mechanisms of the respective linguistic markers within the system. The section situates itself in the context of the range of spatial assistance systems introduced in Section 3.

4.1. Formalizing Spatial Structure

Reconsider the range of spatial assistance systems introduced so far in Sections 3.1–3.3 by way of the architecture design assistance, creative media design assistance, and the real-time emergency assistance domains. In each of these domains, a human stakeholder is involved in the spatio-linguistic conceptualisation and its communication with a system using some human-computer interaction modality. In essence, there exists some human-centered conceptualisation of the spatial structure of a real or hypothetical environment, scene or more abstractly, a *structural form*.

The following abstract notion of the *structural form* of an environment is identifiable:

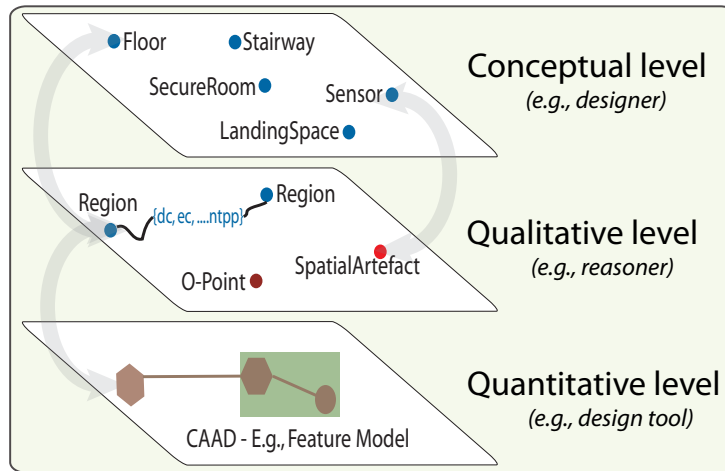


Fig. 9. Multi-Perspective Representational Semantics

The *structural form* of an environment is an abstraction mechanism generally corresponding to the layout, shape, relative arrangement, composition at the commonsense level, of spatial entities, artefacts, and anything else — abstract or real — that may be geometrically modelled, interpreted or derived within a system. The only conceivable premise underlying this notion is that it should be possible to communicate the conception of the structural form using one or more spatio-linguistic modalities – e.g., spatial prepositions, path and pattern descriptions, region and point-based abstractions – that may be wholly or partially grounded to an underlying physical structure either in metric space, or in an abstract qualitative space.

For instance, the structural form may be minimally interpreted as a constraint network that determines the relative qualitative spatial relationships between the real and artefactual entities (Section 4.3; Fig. 10) contained within a design. A *scene description matrix*, i.e., a two dimensional table characterising the spatial relationship of each entity with every other entity in the model, could be the minimal basis of qualitatively abstracting an indoor spatial model. Indeed, from a formal modelling viewpoint, the qualitative model would be based on a semantics that is not only possibly cognitively and linguistically grounded, but also confirms to the formal relational semantics of a spatial logic [1].

The above-stated notion of structural form based on a complete scene model is indeed minimal, and several possibilities exist for further refinement. For instance, as opposed to a complete scene description that characterizes the spatial relationship of an entity with every other entity, one may resort to a hierarchical model that exploits the natural order of organisation in the physical environment. Similarly, hierarchies may be generated not only based on physical structure, but also on the basis of semantic organisation. Further, it is also useful to be able to characterize *spatial patterns* such as circularity, extends_along, further_into, open_path, composed_of etc that were identified in the context of the Volven 258 scenario illustrated in Fig. 1 in Section 1.

4.2. Multi-Perspective Semantics, and Representational Modularity

Given the interpretation of structural form, an abstraction such as a Room or ArchitecturalEntity may be identified semantically by its placement within an ontological hierarchy and its relationships with other conceptual categories. This is what a designer must deal with during the initial design conceptualization phase. However, when these notions are transferred to a tool (e.g., a CAAD or a media pre-production tool), the same concepts acquire a new perspective. In the case of the CAAD tool, the designer must deal with points, line-segments, polygons and other geometric primitives available within the feature hierarchy of the design tool, which, albeit necessary, are in conflict with the mental image and qualitative conceptualisation of the designer. Likewise, a Floor at the designer's conceptual level is abstracted as a Region at the qualitative level of a reasoner and as a ClosedPolygon within the geometric perspective of the design

tool, thereby preserving the geometry at the quantitative level of a CAAD-based feature model (Fig. 9). Multi-perspective representational semantics enables a knowledge-based system to make inferences about the conceptual design and its geometric interpretation within a CAAD model in a unified manner. On the representational front, the concept of multi-perspective semantics may be readily translated to representational modularity, as identified within the ontology / knowledge engineering and conceptual modelling disciplines [49].

4.3. Multi-Modal Abstractions

This abstract view of spatial structure can be grounded to reality via the medium of modalities, namely, semantic, qualitative and other forms of (graph-theoretic) abstractions that serve as an interface between the spatio-linguistic conceptualisation of structural forms, and their concrete interpretation within a spatial assistance system. The following abstractions may be identified:

▷ *Spatial Artefacts*. Semantic descriptions of designs and their requirements acquire real significance when the spatial and functional constraints are among strictly spatial entities as well as abstract *spatial artefacts*. For instance, although it is possible to model the spatial layout of an environment at a fine-grained level, it is not possible to model *spatial artefacts* such as the *range space* of a sensory device (e.g., camera, motion sensor, view-point of an agent), which is not strictly a spatial entity in the form of having a material existence, but needs to be treated as such nevertheless. In general, architectural working designs only contain physical entities. Therefore, it becomes impossible for a designer to model constraints involving spatial artefacts at the design level. For instance, consider the following constraint: '*the motion-sensor should be placed such that the door connecting room A and room B is always within the sensor's range space*'. The following spatial artefacts may be identified:¹³

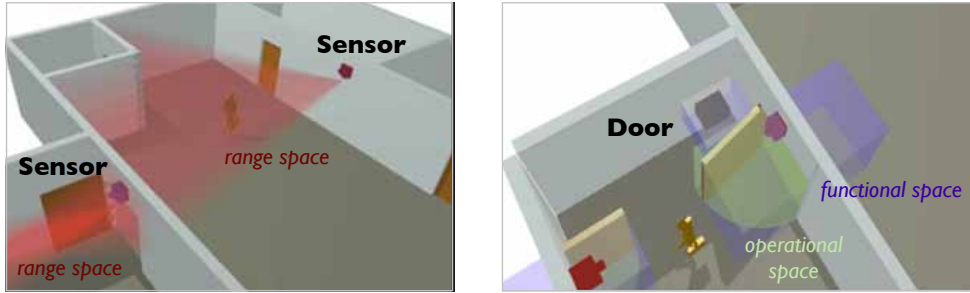
- A1. the *operational space* denotes the region of space that an object requires to perform its intrinsic function that characterizes its utility or purpose
- A2. the *functional space* of an object denotes the region of space within which an agent must be located to manipulate or physically interact with a given object
- A3. the *range space* denotes the region of space that lies within the scope of a sensory device such as a motion or temperature sensor, or any other entity capable of visual perception. Range space may be further classified into other categories, such as *observational space* (e.g., to model the concept of the *isovist*¹⁴)

▷ *QvGraphs*. We propose Qualitatively Annotated Visibility Graphs (QvGraphs) as an extension to the concept of a *Visibility Graph* [22, 42]. In computational geometry, a visibility graph of a polygonal scene shows the intervisibility relations between a set of points (indicating locations, obstacles, and so on) in a scene, as geometrically constituted within the Euclidean plane. Specifically, visibility graph vertices correspond to point locations and edges represent a visible connection between them. QvGraphs extend visibility graphs by deriving and annotating the *visibility link* with (potentially disjunctive) knowledge about spatial relationships pertaining to one or more spatial domains such as topology, orientation, and distance. Figure 11(a) illustrates an example of a visibility graph of a museum lobby. The direction of the edges indicates the direction of the binary qualitative relations; for example, the ReceptionDesk is *right_of* the LobbyEntrance, indicated by the direction of the edge in the QvGraph, although the visible relation in this example is symmetric.

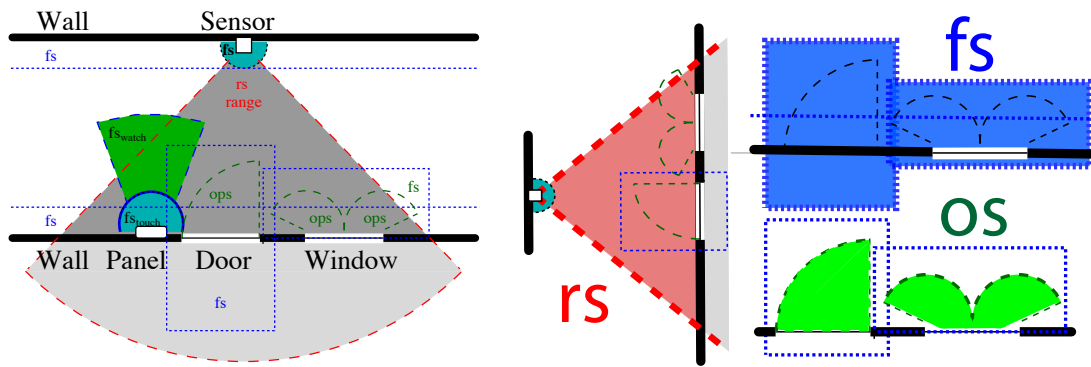
▷ *Spatial Sequence Graphs*. In natural language, it is common to refer to a sequence of objects, where the objects are ordered along some path through the environment. Consider the following expressions:

¹³Formal definitions of spatial artefacts may be found in [10].

¹⁴An isovist is the set of all points visible from a given vantage point in space and with respect to an environment [5].



(a) Implicit artefacts within a design.



(b) Floor plan perspective of the Implicit artefacts within a design.

(c) Range space (rs), Functional space (fs), Operational space (os)

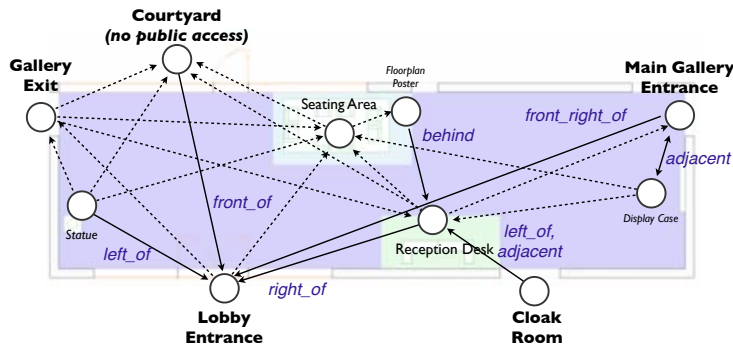
Fig. 10. Spatial artefacts are entities, which unlike regular spatial objects, do not have a physical manifestation in reality (or within a design), but need to be treated as such for all practical / reasoning purposes.

- Numerous paintings are mounted along the wall.
- The Far East art section is down the room after the Oriental-Islamic and Armenian rooms.
- Rivets have been placed evenly along the edge of the column.
- Further into the room is a group of partitions.

In each of these examples a virtual *path* has been implicitly defined, and the objects have been partially or totally ordered along this path. The paths typically follow the shape of some reference object such as a wall, beam, table surface edge, and so on. Moreover, the path is *directed* giving meaning to the terms *before* and *after*; one example is by specifying the start of the path to be the object that is nearest to the person referring to the sequence of objects. Note also that paths may be a simple cycle consisting of a single loop involving all objects (i.e. a circuit), for example, art pieces positioned along the complete perimeter of a gallery room.

This notion is formalised as a *spatial sequence model* where vertices represent objects and directed edges represent the object ordering. Edges are optionally annotated with any useful additional qualitative spatial relations between the ordered objects. Figure 12(a) illustrates an example of two spatial sequence models in one of the Museu Gulbenkian gallery rooms.

▷ *Route Graphs.* A route graph, as defined in [53], corresponds to a cognitively and linguistically motivated spatial representation of an environment that focuses on qualitatively capturing different routes an agent can use for navigation [53]. The derivation of such navigational knowledge for the case of built-up spaces is an important facility provided by our data access framework. The standard definition of route graphs is based on the connectivity of spaces (rooms for example), such that an agent can move freely from one space to another without necessarily passing through an intermediate space. For example, Figure 13



(a) Partially annotated QvGraph of the lobby. The user has specified that orientation and topological relations are relevant for this QvGraph (the qualitative annotations on the dashed edges have been omitted for clarity).



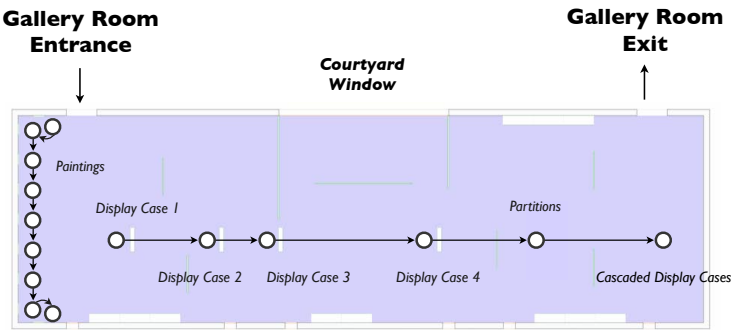
(b) The Real Environment: Lobby Area

Fig. 11. Lobby Area at Museum Gulbenkian – QvGraph Analyses

illustrates the route graph (from the perspective of art gallery visitors) of the entire Gulbenkian floorplan, and Figure 14 illustrates the route graph of the Gulbenkian lobby.

There is a strong connection between properties of structural layout (such as regularity), floorplan complexity, and properties of navigability that a building design affords (i.e. separate from other means of navigation such as signage) [4, 45, 46, 47, 52]. Route graph analysis can greatly assist in tasks such as building design and navigation when the route graph is derived from the appropriate structural properties according to the particular application domain. That is, domain-specific specialisations of connectivity are required to model movement in different applications. Moreover, these heterogeneous route graphs must be integrated in a manner that corresponds to a person's local and more global, topological comprehension of an environment [32].

▷ *Flow Vectors*. The topological information represented in route graphs is often not rich enough (or at least does not make the necessary region distinctions) to specify certain qualitatively significant movement patterns of people and objects, such as modelling airflow in a relatively confined room connected to the building ventilation system [36]. In particular, it is likely that the regions in a space that are qualitatively significant for specifying movement patterns are not qualitatively significant in general, and those regions will not have been distinguished a-priori. Thus, movement patterns cannot be sufficiently expressed using route graphs without first introducing new approaches for partitioning a room into regions that are only relevant for adequately modelling some particular movement phenomenon such as airflow. Rather than introducing numerous specialised region distinctions, these distinctions can be implicitly embedded in the definition of a new type of model called the *flow vector graph*.



(a) Two spatial sequence models



(b) The Real Environment

Fig. 12. Oriental-Islamic and Armenian Gallery Rooms at Museum Gulbenkian – Spatial Sequence Graph Analyses

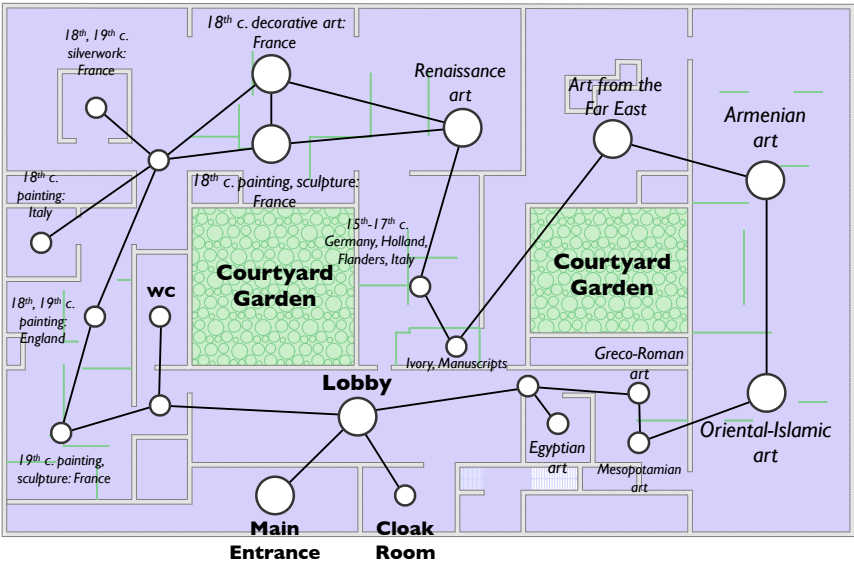


Fig. 13. Route graph of the Gulbenkian floorplan from the perspective of visitors.

Flow vector graphs are derived by directly focusing on the physical movement patterns of agents and objects rather than on the a-priori definition of connectedness of the spaces that the agents and objects are moving through. In contrast to route graphs, flow vectors are effective for modelling object movement patterns using rules that specify expected object behaviour, in a manner that is independent of the qualitative regions that have been defined beforehand. Flow vector graphs are thus closely tied to the underlying

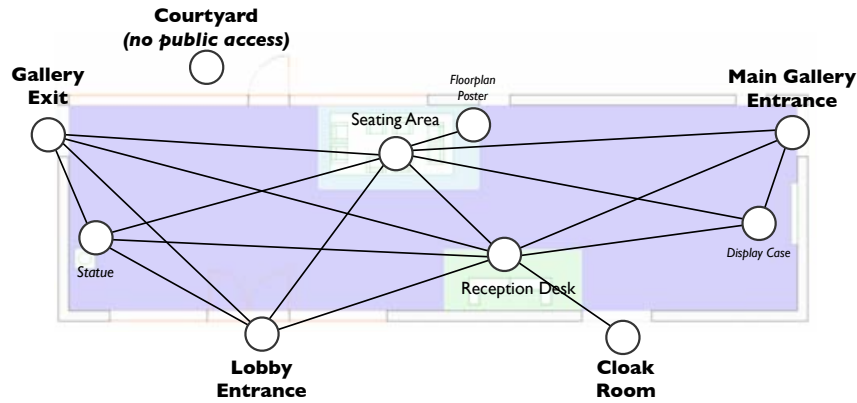


Fig. 14. Route graph of the Gulbenkian lobby from the perspective of visitors.

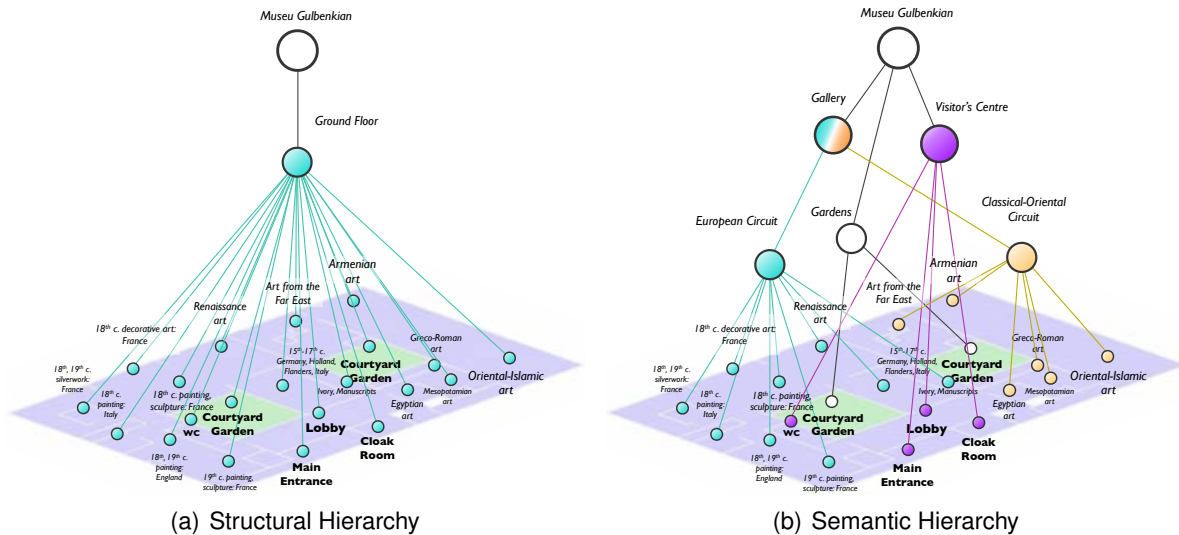


Fig. 15. Hierarchical models of the Gulbenkian Museum.

geometry of spaces, and the geometry and semantics of objects contained within those spaces (that is, rules for deriving flow vector graphs can specify different movement patterns depending on whether an object is a *statue* or a *chair*). As with route graphs, flow vector graphs typically either specify movement between different spaces within a building, or specify local movement within a space (such as a room).¹⁵

▷ *Hierarchical Models.* The data access framework provides access to a *hierarchical* and *multi-domain* model of space that is suited to solving representation and reasoning problems that arise within the context spatial assistance systems. From the viewpoint of hierarchization, the aim of this work is to develop an organization of qualitative spatial information that splits the related entities into independent subsets and allows for solving spatial reasoning tasks at an adequate level of granularity. The resulting hierarchical representation should support the same reasoning and design tasks that would be possible with a flat qualitative representation but do so in more efficient and intuitive way.

Hierarchisation of buildings is defined based on spatial containment and spatial aggregation, such that a higher-level feature contains or consists of the lower-level features in the hierarchy. These hierarchical models can be based on either structural or semantic relationships. Structural containment refers to the

¹⁵Flow-vector graphs are further elaborated on with an example in Section 5.3; also see Fig. 18.

strictly physical aggregation and containment of the components of a building; for example, a building is composed of floors (or storeys), each floor is composed of spaces (such as rooms and corridors), where each space contains features such as furniture, windows and so on. Figures 15 illustrates the structural and semantic hierarchical models for a section of the Gulbenkian museum. Semantic containment is based on the logical grouping of building components regardless of the physical relationship between those spaces. For example, two different art gallery rooms may be located on separate floors (or in completely different sections of the building), but are logically grouped together as belonging to the same art era. Another example is the set of components that are associated with *utilities* at the highest abstraction level such as water, heating, electricity, or the ventilation system, each of which, in turn, consists of utility-specific components distributed throughout the building such as air vents, ventilation shafts, terminals for controlling airflow, and so on.

5. Spatial Computing within Assistance Systems

In Section 3, we presented the spatio-linguistic conceptualisations that occur within the range of the select application domains, namely, the architecture and media pre-production design domains, and the real-time emergency assistance scenario. Section 4 introduced the key notion of the 'structural form' that accrues as an abstraction mechanism for the formalism of spatial structure. Here, the focus was on the multi-perspective, qualitative, and multi-modal characterisations that constitute one model for our notion of structural form. In this section, we now turn to some instances of the types of spatial computing tasks that may be achieved with the abstraction and formalisation mechanisms illustrated so far: Section 5.1 attempts to take stock of the paradigmatic underpinnings and fundamental problems within the scope of spatial computing. Sections 5.2–5.4 provide concrete examples grounded to the application domains introduced in the chapter.

5.1. Spatial Computing: Guiding Principles and Fundamental Problems

The kinds of fundamental reasoning tasks that may be identified within the purview of spatial computing span a wide spectrum, e.g., including reasoning patterns such as spatial property projection, spatial simulation, spatial planning (e.g., for configuration problems), explanation with spatial information (i.e., causal explanation, hypothetical reasoning) to name a few. Both within and beyond the range of domains identified in this chapter, these are reasoning problems that involve an inherent interaction between space, actions, events, and spatial change in the backdrop of domain-specific knowledge and commonsense knowledge about the world [6].

Our notion 'spatial computing' has at least two semantic interpretations: (1) it refers to computing spatial relations, and (2) it refers to using spatial structures to do the computing. When we use the notion 'spatial computing', we actually refer to both meanings simultaneously, i.e. we use spatial structures to compute spatial relations. For instance, a simple and well-known example of spatial computing heavily used in architecture is constructive geometry: here we use a flat sheet of paper, an architect's plan, as a spatial structure that is made to correspond in certain aspects to the spatial structure of the floor of a building. In particular, angles on the plan are identical to the corresponding angles of the building. Distances typically intentionally are not chosen to be identical, to make it easier to handle the plan and to obtain a good overview of the depicted structure; however, the ratios of corresponding distances and the ratios of corresponding areas are identical.

The important aspect of the architect's representation of the floor layout of the building is that many correspondences 'automatically' are generated by their plan without requiring any computing time: in the moment the architect has correctly drawn the lines for parts of the layout, the corresponding angles, the corresponding ratios between line segments, the corresponding areas, and all other spatial correspondences

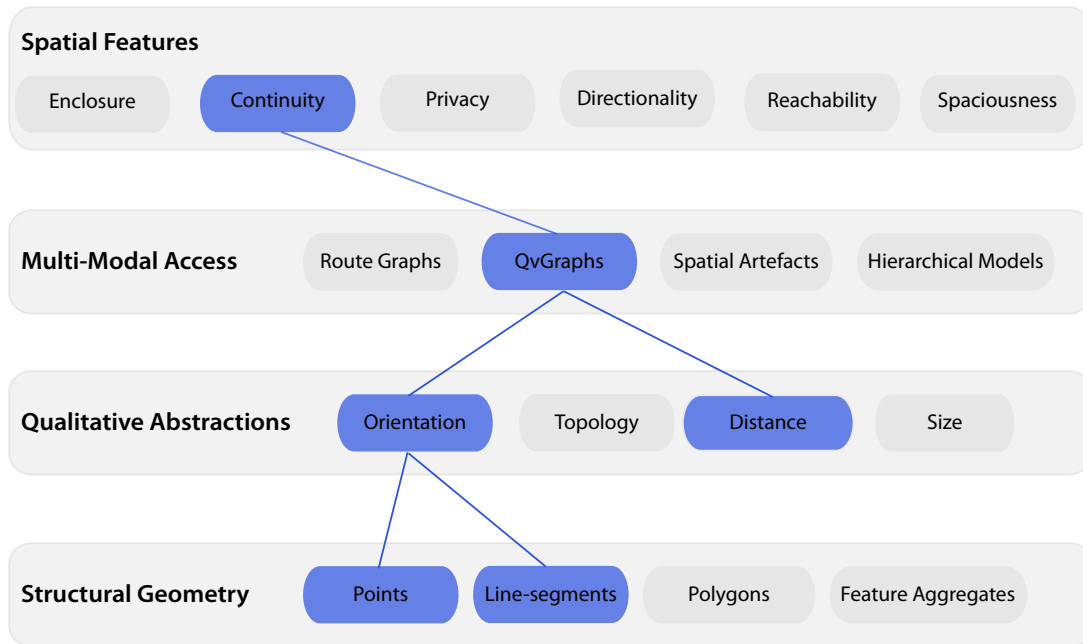


Fig. 16. Spatial Qualities within the Architecture Design Assistance Domain as Viewed Through Multi-Modal Lenses

are established. In other words, the architect's plan is an extremely powerful 'computer'.¹⁶ The computing power of the architect's plan comes at a cost, though: you can't automatically do all the things that a regular computer can do; it is specialized at computing spatial relations.

5.2. The Behaviour and Function in Spatial Structure, as Viewed Through Multi-Modal Lenses

The illustration in Fig. 16 is an elaboration of the concept of multi-perspective semantics from Section 4.2: the top-most component comprises spatial features that may be identified at an initial design conception stage. For instance, it may be desired that a certain (set of) spatial structure(s) or its components may be desired to fulfill one or more of the qualities exemplified in Fig. 16.

As one goes lower down the abstraction hierarchy of Fig. 16, one moves close to the quantitative perspective of the design tool, which is where the precise geometry of a spatial structure resides. The basic idea is short, and simple: high-level spatial features and qualities that exist within the conceptualisation of a human (e.g., designer, creative artist) correspond to a one or more spatial structures at a lower-level of abstraction. Some examples from the domain of architecture follow:

▷ *Privacy (Security).* A typical design requirement may entail that certain parts of the environment may or may not be visible or readily accessible. For instance, it may be desired that the WashRoom is as isolated as possible from other work-areas, and that it may not be within the reach of sensing apparatus

¹⁶A rather disconnected, but interesting analogue may be identified here in the context of the ISO 216 Standardisation of paper sizes: all ISO paper sizes in the *A*, *B* and *C* series have the same aspect ratio of $1 : \sqrt{2}$. If a sheet with this ratio is divided into two equal halves parallel to its shortest sides, then the halves will again have the same ratio. The practical advantages of this are many, but most importantly, in automatic scaling (e.g., A3-to-A4 on copiers) without compromising layout, paper or space wastage, and estimation (e.g., postal and publisher estimates, organisation and binding ease for libraries) etc. All this is achieved by just one structural constraint, which in some sense, is similar to our semantic characterisation of spatial structure being a rather powerful computer in itself.

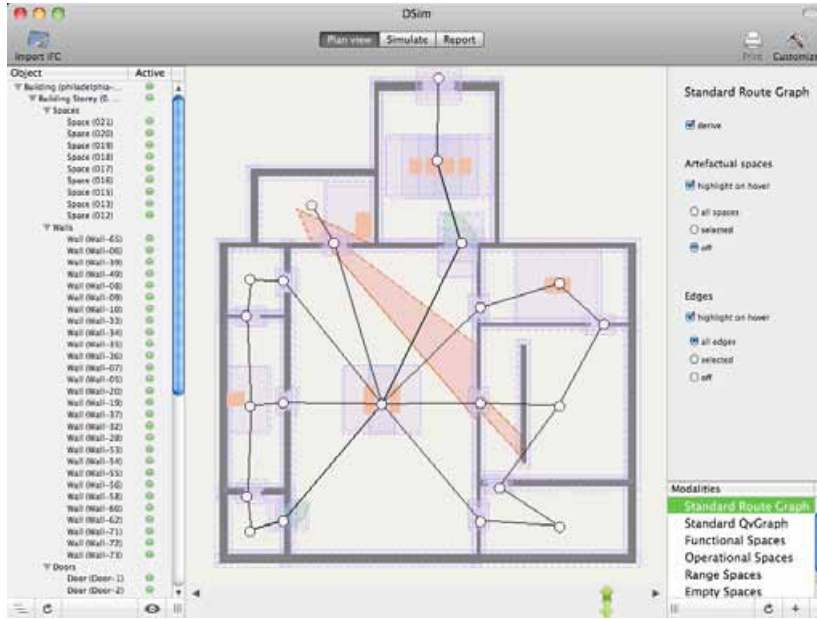


Fig. 17. DSim – A Design Assistance System (prototype; 01.01.2011)

such as in-house cameras. As an example, such a constraint may be directly encoded at a higher-level of abstraction within a rule-based programming mode (also see Fig. 17):¹⁷

```
secure_by(Door, Sensor) :-
    structural_geometry(Door, SGeom),
    operational_space(SGeom, OpSpace),
    range_space(Sensor, RgSpace),
    topology(OpSpace, RgSpace, inside).
```

The example constraint utilizes the spatial abstractions that were introduced in Section 4.3 by way of the *spatial artefacts*: i.e., the requirement of visibility or invisibility is formulated in terms of a topological constraint between two spatial artefacts, namely, the *range space* (of a sensor), and the *operational space* (of the door). Note the manner in which even a simple rule such as this utilizes concepts and data-structures from three different perspectives: the quantitative geometry coming from the CAAD model, the qualitative abstractions by way of spatial artefacts and topological relationships (e.g., *inside*), and the conceptual level of the designer, consisting of elements such as Doors and Sensors.

▷ *Continuity*. Continuity among a set of entities or locations may be, for instance, identified as mutual visibility among the entities and locations under consideration. In addition to mutual-visibility as an interpretation of continuity, one may expect additional constraints involving relative and absolute positional constraints among the entities. Additionally, one may further refine the notion by the inclusion of distance constraints, e.g., “*X should not only be visible from Y, it should also not be too far away...*”. At a lower-level of abstraction, the notion of continuity therefore translates to a set of visibility, orientational and distance constraints over a spatial structure, which is precisely the perspective offered by the modality of a QvGraph (see Fig. 11(a); Section 4.3).

▷ *Spaciousness*. One may interpret a high-level spatial feature such as *spaciousness* as denoting the sense of volume and openness felt by an occupant, i.e., spaciousness too may be interpreted as being

¹⁷Indeed, such as rule-based model would technically rely on the underlying representational framework that has been discussed herein. Precise details are not relevant for this chapter, but it may be noted that we realise such rule specifications within the Constraint Logic Programming framework [13]. Also refer to the concluding discussions on this topic in Section 6.

related to the notions of visibility and the arrangement of objects within a room [25, 26]. For instance a spacious environment can have many objects around the perimeter of the room, but critically must have no large objects, or very few, in the central region of the room. Centrally located objects can occlude mutual visibility of large portions of a room, and objects positioned on walking paths can create a sense of clutter [35].

Our objective in the above examples pertaining to spatial features has been to illustrate the usability of our multi-perspective and multi-modal abstractions as an interface between structural form, and the behaviour and function that it entails. The detailed examples, from an implementation viewpoint, for spatial features such as continuity and spaciousness are rather involved, and have therefore been omitted for the ongoing discussion.

5.3. Expected Navigation and Movement Patterns Through Art Exhibition Spaces

The manner in which a museum space is navigated by a visitor will have a direct impact on their experience of the exhibits [54]. Moreover, structural features of the layout often dictate, to a greater or lesser degree depending on the agenda of the visitor, how the space is explored, and in turn, affects the degree of exposure that particular exhibition pieces are afforded. For example, Melton presented these ideas in a seminal article [43] after conducting a number of studies on movement patterns of museum visitors.

Consider the situation where an art director of the Gulbenkian museum is planning to hold a temporary exhibit. The art director needs to make decisions about the placement of the temporary pieces to get the desired effect; for example the art director may want to

- elicit a sense of impact and boldness with the new pieces, or alternatively, introduce them in a subtle way
- maximise the exposure (i.e. maximise the average viewing duration at the cost of the presence of the permanent exhibits), or alternatively, strike a balance between the prominence of the new exhibits and the permanent works

The SAS with spatial modalities can be used to predict the expected movement patterns of visitors and thus assist in the art director's task of placing the new exhibits to evoke the desired impression in the visitors. Modelling the principles of movement patterns presented by the architecture research community requires combinations of spatial modalities.

At a global level, as people move between different spaces within museum they tend to establish a primary set of paths referred to collectively as the *skeleton* [38] of the environment in their comprehension of the space. Using this skeleton as a reference, visitors explore more localised collections of gallery rooms. Kuipers proposes that the skeleton that emerges as a person explores an environment tends to consist of "major" paths and locations that have a relatively high degree of topological connectivity to other paths and locations (i.e. boundary relations). Wineman and Peponis [54] link the notion of a skeleton to research on the movement of visitors in museums such as Choi [19]; they emphasise the role of *accessibility* and *visibility* between spaces in characterising major, integrated paths that form the skeleton [54]. By analysing combinations of spatial modalities, in particular, route graphs (for analysing topological connectivity), QvGraphs (for analysing semantically annotated isovists), and semantic hierarchical models (for analysing the distribution of collections throughout the museum), an architect can build up a picture of the accessibility and visibility afforded by the museum layout, and thus make reasonable predictions about visitor movement patterns (e.g. by automatically deriving a skeleton according to connectivity and visibility metrics). Moreover, researchers have investigated structural characteristics that influence the relative duration of occupancy of a space; for example, Choi's studies [19] lead to the following principle (as expressed succinctly in [54]):

Principle 1: "Visitors stop more often in spaces that have greater visual connections to other spaces; they also stop in spaces that are visually connected to [spaces on the skeleton]"

Spaces in which visitors are likely to occupy for relatively longer periods can be identified by analysing route graphs and derived skeletons in conjunction with QvGraphs. Thus, the art director can use the spatial modalities to determine the expected global movement patterns of visitors through the museum, and then decide where to place the new exhibits according to their desired aims. For example, by placing new exhibits in areas of high visitor traffic, the art director can ensure high exposure and conjure a sense of impact surrounding the new pieces.

At a local level, people move through a gallery room based on the layout of exhibits and the shape of the gallery room. Spatial assistance systems can employ key spatial modalities to model these movement patterns. We will consider a number of principles that have been proposed in the architecture research community for visitor movement behaviour and model these using as a vector flow graph. Bitgood [15] has compiled a collection of principles that govern visitor movement within a gallery room based on well known architecture research. For example:

Principle 2: "Visitors tend to turn in the direction of the closest visible exhibit, all other factors being equal [...]"

This indicates that *distance* plays a role in exhibit selection. This can be used to divide exhibits into those that are either near or far from a given visitor location based on a threshold shortest-path distance through the route graph, where near exhibits have priority over far exhibits. Exhibits that are near are considered to be in the same equivalence class with respect to distance, and thus the following principles can then take effect in determining further selection.

Wineman and Peponis have proposed a collection of principles that govern visitor movement in very open-plan gallery spaces [54] (i.e. where the visitor is not explicitly guided along a restricted set of paths):

Principle 3: "the more accessible an exhibit element is from all other exhibit elements, the more likely it is to be visited. This provides the [...] hierarchy of the likelihood that an exhibit will be perceived in spatially guided movement."

Accessibility refers to how "*easy*" it is to navigate to an exhibit from other locations in the room. Using the route graph where each node corresponds to an exhibit, accessibility of a given exhibit can be measured by the graph theoretic centrality value (many possible centrality metrics can be experimented with e.g. the degree, betweenness, and closeness). Thus, if a visitor is presented with a selection of exhibits, all other factors being considered equal, they will tend to choose the most accessible exhibit.

Bitgood [14] has proposed a precedence ordering on the decisions that museum visitors make, again based on a number of well known architecture studies (typically taking place in North American or Western European museums).

Principle 4: "[...] visitors exit a gallery by the first open door they encounter"

If a visitor is near an exit door, then they will take it.

Principle 5: "[...] people tend to walk in the same direction. Thus, if a visitor enters a gallery along the left-hand wall, [they] continue walking along this wall"

This introduces a notion of visitor trajectories, such that the direction of the path defined by the previously visited exhibit e_1 and the current exhibit e_2 will influence the decision for the next exhibit e_3 .

Figure 18 illustrates the application of these principles in generating a flow vector graph of the expected visitor movement pattern. We can observe that the central display cases dominate the paintings on the right-hand side of the entrance as visitors enter the gallery room due to proximity and accessibility (Principles 2 and 3). As the visitor travels down the gallery room, they are expected to exclusively take the left-hand path; this is because a movement trajectory is established (Principle 5) by the regularly placed display cabinets (each providing a natural "*next location*" due to proximity and accessibility, i.e. Principles 2 and 3). As soon as the exit becomes visible the visitors leave the room (Principle 4), ignoring the cascading display cabinets along the back wall. Using this predicted movement pattern, the art director can decide whether to place new temporary exhibits along the expected path, or perhaps position them in a more subtle position such as the courtyard window, or near the paintings at the entrance.

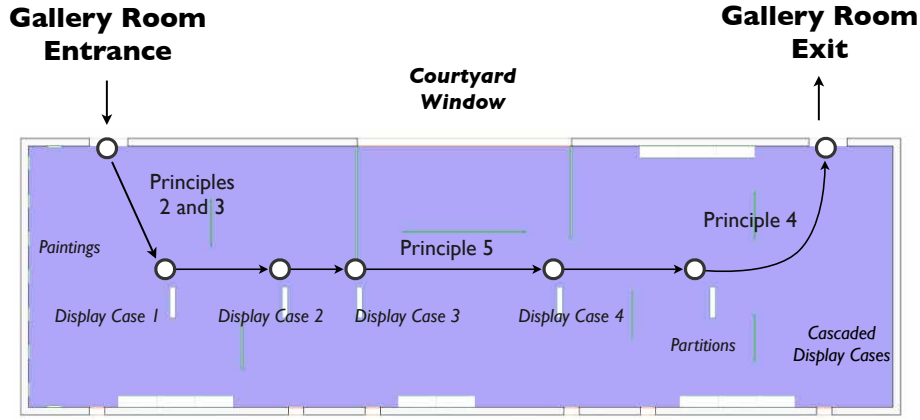


Fig. 18. Expected visitor movement pattern through the Oriental-Islamic and Armenian gallery rooms.

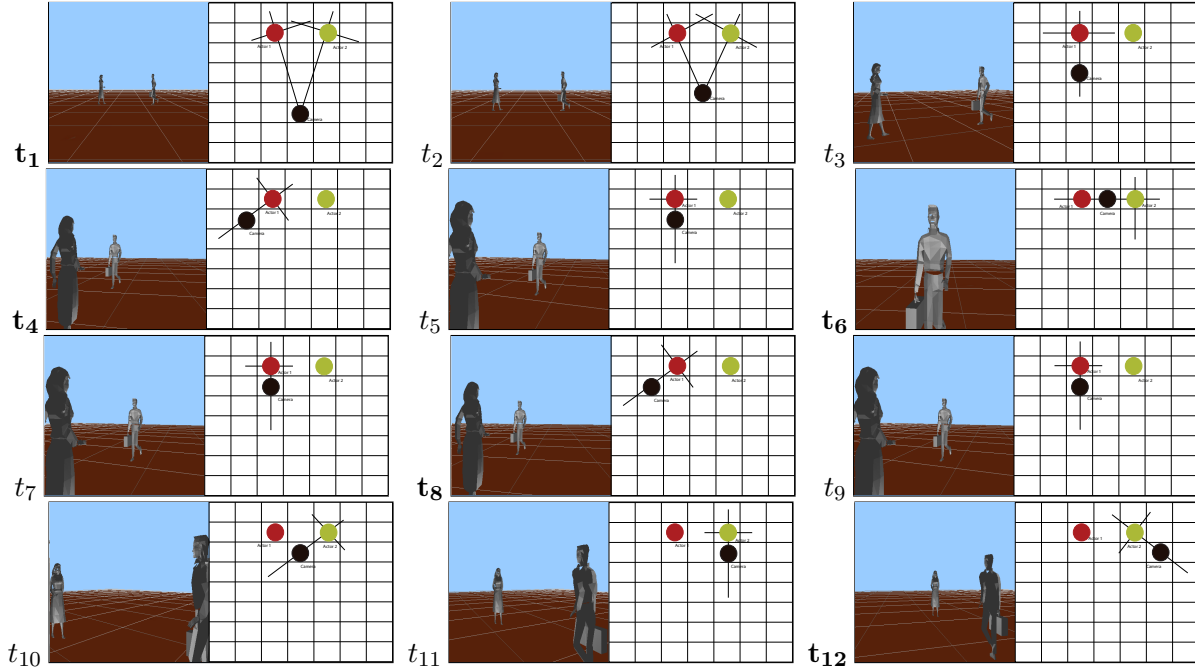


Fig. 19. Scenario and Narrative Completion by Abduction. Source [7].

5.4. Scenario and Narrative Completion by Spatio-Temporal Abduction

Re-consider the illustration in Fig. 6 for the domain of automatic cinematography that was introduced in Section 3.2: the world consists of three point-abstracted entities— 2 *avatars* and 1 virtual *camera*.¹⁸ Suppose that container space is modelled as a discrete grid world together with relative orientation relationships among the entities as per the partitioning scheme of the Single-Cross Calculus [28]. For this discussion, further suppose that the *camera* is the only entity that is able to move, i.e., change location from one grid-cell to another.

For a scenario such as this, spatio-temporal abduction serves as a basis of *scenario and narrative completion*, and for this particular example, the derivation of ideal *camera placements* as a side-effect of the abduction process. Figure 19 consists of a *narrative* (completion) from time-points t_1 to t_{12} , denoting

¹⁸The third entity in the simulation is a virtual camera that records the other two entities in the scene, and hence is not visible within the 3D illustration of Fig. 6.

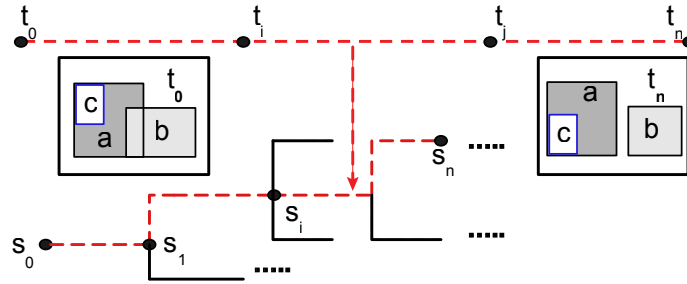


Fig. 20. Branching / Hypothetical Situation Space

an *abduced* evolution of the system, as represented the sequence of qualitative state descriptions for *two* stationery and *one* moving entity. For clarity, images from a 3D simulation are included together with the relational illustrations for each of the time-points. From an initial narrative description consisting of information about only some of the time-points,¹⁹ the narrative completion has been abduced on the basis of available *camera actions* – *pan*, *zoom*, *move* – and pre-specified knowledge or heuristics, referred to as *film idioms*, about desired camera placements, e.g., *establishing shot*, *external shot*, *mid-shot*, *close-up* and so forth. In this example, the resulting narrative is usable by a virtual reality or an automatic cinematography system to generate automatic visualizations for a script.

With respect to the automatic cinematography example, it is easy to intuitively infer the general structure of causal explanation (by abduction) within spatial information. Consider the illustration in Fig. 20 for a hypothetical (e.g., branching) situation space that characterizes the complete evolution of a system. In Fig. 20 – the situation-based history $\langle s_0, s_1, \dots, s_n \rangle$ represents one path, corresponding to an actual time-line $\langle t_0, t_1, \dots, t_n \rangle$, within the overall branching-tree structured situation space. Given incomplete narrative descriptions, e.g., corresponding to only some ordered time-points (such as in Fig. 19) in terms of high-level spatial (e.g., topological, orientation) and occurrence information, the objective of causal explanation is to derive one or more paths from the branching situation space, that could best-fit the available narrative information. Of course, the completions that bridge the narrative by interpolating the missing spatial and action/event information have to be consistent with domain-specific and domain-independent rules (e.g., pertaining to dynamics).

A formalisation of the above stated problem of scenario and narrative completion by spatio-temporal abduction in the Event Calculus may be consulted in [7]. The motivations and broad research questions underlying the approach may be referred to in [6].

6. Summary and Discussion of Chapter

This chapter focussed on the spatial informatics concerned with the conceptual, formal, and computational aspects of ‘space’ within a select range of spatial assistance systems. Specifically, we focus on:

1. identification of the nature of human-centred spatio-linguistic conceptions that occur within a specific class of application domains
2. development of a formal framework that may be used as an interfacing mechanism between the spatio-linguistic conceptualization of humans and its qualitative abstraction as per our interpretation of structural form

¹⁹These are, for instance, (implicitly) available from linguistic descriptions about *acts* and *scenes* within a drama or film script. Here, the progression of the script can be thought of as an imaginary evolution of the system.

3. enabling fundamental reasoning patterns, as identifiable with respect to a particular philosophy of general spatial computing within systems that creatively, or constructively, assist, assure and empower humans

Whereas the above were illustrated in the context of diverse application scenarios, the discussions focussed on the domain of architecture design assistance in particular. This is because spatial design as a problem-solving activity involves rich, real-world problem characterisations and solutions: the domain also enables concrete specification and illustration of problems and their solutions. The other two domains, involving creative media design, and real-time emergency assistance were chosen because in addition to being practically relevant, they offered significant breadth in order to illustrate the generality and transferability of the basic ideas concerning structural forms, multi-perspective and multi-modal abstractions, and the computational problems addressed in the chapter.

Further Pointers to Literature

Much has been left out of the chapter: a precise definition and formalisation of structural form – each constituent component thereof – and a formal treatment of the computational aspects concerning checking for functional design consistency using rule-based specifications has been omitted. For example, rule-based specifications, which we have implemented within the Constraint Logic Programming (CLP) framework [34], present their own set of fundamental challenges involving the realisation of a 'spatial semantics' such that rules may refer to spatial entities and relationships [13] – CLP is indeed not pre-equipped to understand the semantics of spatial relations such as inside, front-of (just like Prolog does not know anything about the semantics of 'likes' in the predicate 'likes(john, mary)'). We have left out the details of these issues from the chapter.²⁰ Similarly, an elaboration of the rather contrived notion of (logic-based) spatio-temporal abduction has not been included. Spatio-temporal abduction, which can be implemented [7] using the Event Calculus formalism [37], has only been described with respect to the computational structure that it acquires; much more may be elaborated on in this regard, e.g., with respect to its precise formalisation, the integration of the semantics of a qualitative spatial calculus within the event calculus, and the general applicability of spatio-temporal abduction in domains outside of the one discussed here (e.g., activity abduction in smart environments, geospatial dynamics). For the interested reader, these aspects, and the general agenda that underlies and inspires this line of research may be consulted in [6, 8, 9].

Finally, although we presented the concept of multi-perspective semantics and multiple modalities in sufficient detail, the industrial underpinnings and relevance of this work were not presented in the chapter: at a practical level, we have developed a multi-perspective, multi-modal spatial data access framework [48] designed to serve the informational and computational requirements of architectural design assistance systems that are intended to provide intelligent spatial decision-support and analytical capabilities. The framework focuses on multi-perspective semantics, qualitative and artefactual spatial abstractions, and industrial conformance and interoperability within the context of industry tools and standards: in this context, we ensure interoperability with commercial tools concerned with the creation, manipulation and management of environmental data by utilising the stipulations of the Building Information Model (BIM) [24] and the Industry Foundation Classes (IFC) [29]. The framework also aims at providing qualitative and cognitively adequate representational mechanisms, and the formal interpretation of the structural form of indoor spaces that are not directly provided by conventional CAAD-based or quantitative models of space.

More broadly, the ontological aspects concerning modular specifications, described only briefly in the chapter, are part of a broader initiative for the development of industrially relevant ontological specifications of indoor spatial environments. Here, the objective is to develop an *Indoor Space Data Representation Ontology* that encompasses industrial data models such as the IFC, and also integrates our perspective

²⁰Details are available in [13].

toward the conceptual representation of the structural form of an environment, and functional requirement constraints occurring thereof. Future research in this direction aims to contribute toward integration with broader standardisation initiatives, and provide industrially-driven case-studies, within international initiatives such as Applied Ontology (IOAO),²¹ and ISO-Space.²² More specifically, exemplary prototypes are also in progress as a part of the design assistance tool *DSim* [11] that is being designed to offer reasoning, simulation, and visualization capabilities.

Acknowledgements

We gratefully acknowledge the funding and support of the German Research Foundation (DFG), www.dfg.de/ – the work described in this paper has been conducted as part of the DFG funded SFB/TR 8 Spatial Cognition project [DesignSpace], www.sfbtr8.spatial-cognition.de/designspace.html.

All images from the *Museum Calouste Gulbenkian* (Lisbon, Portugal) have been taken as a part of a regular, paid Museum visit, with due permission from the Museum management. Corresponding designs and floor-plan constructions are our interpretations of the original Museum design; errors and omissions therein are also of our own making.

²¹IOAO. www.iaoa.org/

²²ISO-Space. <http://iso-space.org/>

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