Constructing Hierarchical Representations of Indoor Spaces

Kai-Florian Richter
SFB/TR 8 Spatial Cognition
Universität Bremen
Germany

Stephan Winter
Department of Geomatics
University of Melbourne
Australia

Urs-Jakob Rüetschi
Zürich
Switzerland

Abstract

Indoor spaces pose many challenges for spatial information systems, amongst them appropriate spatial communication. Compared to typical outdoor spaces, indoor spaces are clustered, have a fragmented social structure, and diverse groups use the space in different ways, which results in different conceptualizations and communication needs. This paper presents a hierarchical representation of indoor spaces that accounts for different use roles. The hierarchization exploits structural, functional and organizational dimensions and allows for communicating different aspects of the space in a way tailored to the specific user groups.

1. Introduction

Human cognitive spatial representations and spatial communication are known to be hierarchic [13, 2]. Hierarchy can convey a sense of place and of orientation, and support wayfinding. Thus, we argue for a dependency between access to spatial hierarchies and successful communication. And yet the information provided by current services is known to fail in these qualities [7, 10].

Information technology is currently transforming the ways spatial information is generated and communicated. In indoor environments, relevant technologies concern intelligent building systems, ubiquitous mobile computing and positioning, and ad-hoc communication. These developments provide novel channels to convey even real-time spatial information, but they do not per se change the form of the spatial information. Wall screens and information terminals in malls still show traditional You-Are-Here maps, and location-based services on mobile devices still utilize map data, providing contextual noise instead of a hierarchic focus.

This paper studies requirements for providing hierarchic spatial information to users of indoor environments. Providing such information is challenging for at least three different dimensions have to be considered:

- Structural: compared to outdoor space, indoor space has many discontinuities, making it physically fragmented and clustered.
- Organizational: diverse organizational groups may share (or compete for) indoor space, making for a complex structure of ownership and access.
- Functional: other than urban street space with its main use of traveling, indoor space has many stationary uses. Furthermore, the use of indoor space depends on the roles and capabilities of users, i.e., different user groups may use (and conceptualize) an indoor environment differently.

For example, the room label in Figure 1 reveals a spatial (“[Room] 208”), organizational (“Civil and Environmental Engineering”) and functional (“office for academics”) structure.

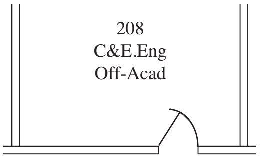

Figure 1. A room label in a floor plan.

A hierarchical representation of indoor space that accounts for the different dimensions is a pre-requisite to generate meaningful spatial information automatically. The hypothesis of this paper is that such a hierarchic representation can be formally described. This formal description can be used to communicate about indoor space in many ways, such as within hierarchic place descriptions (including a way for dealing with uncertainty in position estimation) or hierarchic route directions. The representation needs to capture all elements that are relevant for the different communication needs. In the following, we first present related work and then develop a hierarchical representation of indoor spaces that adheres to the demanded properties: spatial, functional, and organizational structure. The procedure starts from a finest granularity capturing containers, regions and links of scenes (Section 3.1), finds passages and weighs links (Section 3.2), and finally determines a joint hierarchy (Section 3.3).

2. Representation of Indoor Spaces

The observation that indoor spaces differ from urban street spaces is acknowledged in other approaches as well. In particular, movement in indoor space is richer than a linear network representation suggests.

Raubal [11] uses image schemata and affordances to model navigation through indoor spaces. The navigation process is modeled as a wayfinding graph capturing states of knowledge and locations of decision points and the transitions between them. His representation remains at one level of granularity. Lorenz *et al.* [8] decompose the spatial structure of indoor spaces into convex cells that are used to build a hierarchical graph representation of structure (e.g., dividing it into wings and floors). Rüetschi [12] introduces a distinction between *network space* and *scene space*. Network space is structured by the linear features that support navigation, such as street networks. Scene space, on the other hand, is determined by (a combination of) vista spaces that do not provide a clear, constraining navigation structure, but rather are open spaces allowing for far less constrained movement. Indoor environments frequently have a scene space structure. In the following, we will use, modify and formalize the latter approach.

2.1. Indoor Space as Scenes

Building on Raubal's work [11], Rüetschi [12] models scene spaces using image schemata [5]. The basic constituents of this spatial representation are: CONTAINER, an area that is surrounded by (built) borders, such as a room in a building; REGION, an area that is perceived as a unit while not being completely surrounded by physical borders, such as a square; GATEWAY, representing a physical link that is clearly perceived when moved through, such as a door; ULINK, a link that connects two spaces and has no obvious physical manifestation, such as the transition between a platform and a directly adjacent square. AGGREGATES are groupings on higher levels, however Rüetschi is not explicit about how aggregates are derived.

A hierarchization of scene space starts with containers and regions at the finest level of granularity. Starting the modeling of a hierarchy at the level of containers and regions corresponds to the level of detail where environmental space—the coarser levels in a hierarchy—reverts to vista space, and hence, where spatial information needs to change drastically. People's conceptualization of places does not stop at this level of granularity. For example, a coffee booth in a train station hall can be conceptualized and communicated as a place of its own within the container of the hall ("Let us meet at the coffee booth"). The decision to cut off places at a clearly defined level of granularity is a critical one. We argue that the modeled subset of an infinite set of possible places is sufficient to *generate* wayfinding information (but not to interpret human expressions).

While [12] studied wayfinding, our interest is in the cognitive conceptualization of indoor spaces. We claim that conceptualization is correlated with experience of an environment, and experience depends on the perspective of the person (role/user group, capabilities). Accordingly, indoor spaces can be hierarchically organized along different dimensions that emphasize the different perceptions. This builds on work by Gaiser [1]. Taking an analysis of typical user groups and tasks as a starting point, he suggested a grouping of an indoor space's elements according to their functional role and spatial nearness. The dimensions of indoor spaces used are:

- Structural: this level represents the structural organization of an indoor environment, i.e., how it is spatially organized and the accessibility of different areas (e.g., different floors in a university building, or gate areas at an airport).
- Functional: this level captures different functions of the structural elements, such as offices, labs, and server rooms at universities, or ticket counters, check-in counters and duty-free shops at airports.
- Organizational: on this level, different organizational units are captured, such as research groups, departments, and schools at universities, or different airlines and airport proper facilities at an international airport.

Indoor spaces can be hierarchized using each dimension individually. However, to achieve a hierarchization that is suitable for the communication needs addressed in the introduction, individual dimensions need to be combined in sensible ways. The dimensions do not need to be orthogonal, i.e., there may be correlations between them. For example, architects designing built environments have specific functions of indoor spaces in mind, so their structure will reflect these aspired functions. Because of this relationship the emerging hierarchies can be expected to behave nicely most of the times, in the sense that they are coherent representations of an environment in all three dimensions.

2.2. User Groups and Roles

For functional and organizational hierarchization the different elements of an environment need to take different roles depending on the user group at hand. Roles reflect that the conceptualization and communication of how rooms, for example, are used is largely depending on how the space is experienced by a human. The physical entity *room* may have different functional or organizational *roles* for different people. These roles can be modeled as properties of the entity in the DOLCE ontology [9] and depend on the context. Functional and organizational aspects have separate ontologies. This way, different domain ontologies can be used, depending on the user group at hand. Note that the general principles underlying the hierarchization do not change when using different ontologies.

3. Constructing Hierarchical Representations of Indoor Space

Based on the chosen ontologies, i.e., the user groups and their tasks, different hierarchies may emerge (Section 2). Independent of this, the general process of constructing hierarchical representations of indoor spaces comprises the following three steps:

1. Generating the base structural representation.
2. Setting the weights for links.
3. Hierarchization.

3.1. Base Structural Representation

First, the base structural representation consisting of the elements introduced in [12] is constructed. This representation reflects the structure of the indoor space on the finest level of granularity considered here (Section 2). The constituting elements (e.g., rooms, corridors, and doors in a building) are identified, and the elements are assigned their functional and organizational classification according to the chosen domain ontologies.

3.2. Link Weights

Links are elements of an environment that connect other elements. Rüetschi [12] distinguishes between GATEWAYS and ULINKS, both afford and facilitate passage between CONTAINER and REGION elements. In indoor scenes gateways are typically doors, and ULINKS perceptual and conceptual boundaries without a physical realization. Beyond the classification of [12], it must be noted that many containers serve the sole purpose of offering passage and hardly constitute a place in their own right; corridors and gangways are prominent examples. The hierarchization process proposed in this paper needs to distinguish such passages from 'ordinary' containers, so we introduce the PASSAGE as a special purpose CONTAINER that serves as a link.

Depending on user role and perspective (spatial, functional or organizational), some links are cognitively more significant or prominent than others. This can be handled by assigning different link weights. The weighting reflects on which levels of the hierarchy a link is still present (compare connecting two rooms with connecting two wings in a building). A sufficient parameter for this purpose is the impedance of the link. Passable doors and openings have no spatial extent, and hence, an impedance of zero. Locked doors have infinite impedance, and doors passable from one side (e.g., emergency exits) have a directed impedance. Passages, on the other hand, have impedance proportional to their travel costs. A lift has costs in form of waiting times, and stairs and corridors have costs in form of travel time or energy consumption.

Also different user groups—groups with different abilities or preferences—may apply different impedances. For example, stairs have infinite impedance for people sitting in a wheelchair. Also, going upstairs may have different impedance than going downstairs. In general, vertical movement costs more than horizontal movement. The mental costs of moving between levels are significant [3].

A scene connectivity graph enables assignment of impedance measures to links. There are two main advantages of an explicit representation: 1) other than, for example, by using adjacency matrices, links are directly represented in the hierarchies (see below) and, thus, can be directly addressed when using this representation for communication about a space; 2) instead of assigning weights to the spaces themselves, assigning impedance values to the links on the one hand directly reflects the effort it takes to get from one place to another, and on the other hand reflects the conceptual relevance of that link. Besides impedance, literature on network theory (e.g., [6]) and space syntax (e.g., [4]) provides alternative measures based on centrality and accessibility of spaces. However, a critical review of the cognitive relevance of impedance and the other measures is left for future work.

3.3. Hierarchization

In general, an algorithm that automatically constructs a hierarchization of indoor spaces works as follows. First, a distance function is needed, which may combine individual distance functions for the structural, functional, and organizational dimension. The algorithm is iterative. In each step the globally minimal distance between two elements of the current hierarchy level is determined. This is achieved by a pairwise comparison of elements. It can be expected that often several pairs of elements have an identical distance on a given hierarchy level. All subsets of elements whose mutual distance is this minimal distance are combined to form a new element in the next higher hierarchy level. With mutual distance we refer to cases where, for example, element A and C have a distance greater than the minimal one, but both have the minimal distance to element B and, thus, are joined via this element B to form an abstracted element $\{A, B, C\}$. When all new elements have been formed, distances are updated using the new elements. This, then, reflects the distances as they are on the next hierarchy level. These steps are repeated until there is only one element left in the hierarchy, which is the root element. This process results in a tree.

The construction of hierarchies is essentially determined by a distance function, which can be formulated within and across each of the three dimensions. Hierarchization based on only one dimension is easy to achieve; it just accounts for the distance of elements within this dimension. For example, for structural hierarchization the key concept is connectivity of elements, which can be covered by topological distance. Linking the structural dimension with either the functional or the organizational dimension results in a refinement of a purely functional or organizational hierarchy, in that initially on the lower levels of the hierarchy smaller clusters of identical function or organizational classification emerge that are spatially closely connected. Combining all three dimensions results in more complex distance functions. In combining dimensions order matters.

4. An Example

This section illustrates the hierarchization process presented above by an example using one level of a building of the University of Melbourne. Figure 2 shows a floor plan of this level (Level 2 of Engineering Block B), Figure 3 the corresponding base structural representation. In the following, we assume a user who is faculty or postgraduate student in one of the departments located in this building.

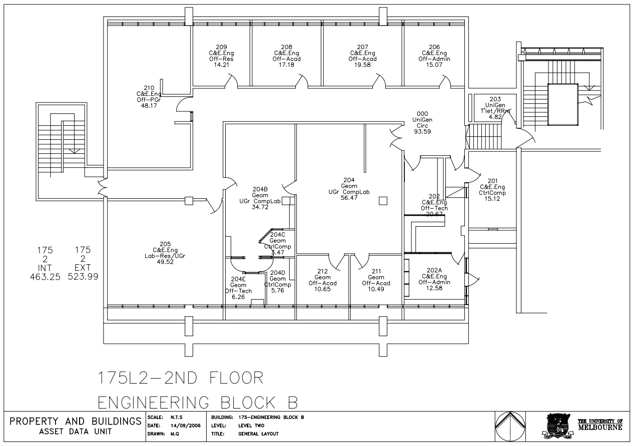

Figure 2. The chosen indoor space.

Next, passages are identified and weights are assigned to all links. Weighting imposes an order on these links. Thus, integer values are sufficient to represent cost values. In the example, the corridor (labeled "000"), the staircase landing and the stairs serve as passages. The corridor and staircase landing are assigned 0 as weight, i.e., do not increase the impedance. All doors that connect two rooms, i.e., two CONTAINERS or a CONTAINER with a PASSAGE, are assigned 1. The stairs between the staircase landing and corridor "000" are assigned a weight of 2 as they have a higher impedance than a door; the door connecting the two PASSAGES of corridor stairs and staircase landing has a weight of 3. The staircase gets a weight of 4, reflecting both the higher energy consumption of climbing and the cognitive effort of switching floors.

Finally, hierarchization is performed using a distance function that reflects the discussion of Section 3.3. It combines all three dimensions to construct hierarchies that capture organizational-functional groupings within parts of the indoor space and a structural grouping of these parts. Note that this only reflects one kind of hierarchization, especially suited for the communication tasks outlined in the introduction; others are possible as well to suit other user groups or tasks.

Algorithm 1 lists the distance function used in the example. The variables d_s, d_o and d_f are structural, organizational and functional distance, respectively. The threshold value $struct\_depth$ determines the structural distance between elements where a switch in dominance from an organizational-functional to a structural dimension happens (e.g., where wings are joined to form levels). In each step, only spatially disjoint elements are considered ($d_s \geq 1$), which may have the same function ($d_f \geq 0$) or belong to the same organizational unit ($d_o \geq 0$). The algorithm first groups elements that are functionally and organizationally equal and have a structural distance of 1, and then increments this distance up to $struct\_depth$. In this version of the algorithm, first functional distance is increased, then organizational distance. Finally, all elements with a structural distance greater than $struct\_depth$ are grouped in order of increasing distance. That way, we achieve a local grouping based on functional and organizational aspects, with a dominance of the organizational dimension (i.e., it is the stronger separation criterion).

The emerging hierarchy reflects that for the addressed user group of people associated to a specific department rooms belonging to this department typically are more relevant and are seen to belong together. Such users separate between "our" rooms and "their" rooms. This holds especially between departments, but also within the department by separating offices for faculty and lab room for students, for instance. For other users, for example IT specialists, a hierarchization that predominantly focuses on function, i.e.,

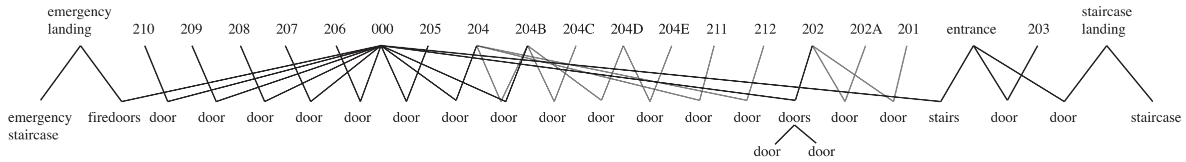

Figure 3. The base structural representation of the floor plan depicted in Fig. 2

IT vs non-IT rooms, may be more adequate. Such a hierarchy can be achieved by adapting the distance function or the order of dimensions of Algorithm 1 accordingly.

```
$d_o \leftarrow 0$
while not grouped and $d_o <=$ maximal organizational distance do
    $d_f \leftarrow 0$
    while not grouped and $d_f <=$ maximal functional distance do
        $d_s \leftarrow 1$
        while not grouped and $d_s <=$ struct_depth do
            forall elements with identical mutual distance do
                if org_dist = $d_o$ and funct_dist = $d_f$ and struct_dist = $d_s$ then
                    Group elements
                else
                    $d_s \leftarrow d_s + 1$
        $d_f \leftarrow d_f + 1$
    $d_o \leftarrow d_o + 1$
if not grouped then
    while not grouped and $d_s <=$ maximal structural distance do
        forall elements with identical mutual distance do
            if struct_dist = $d_s$ then
                Group elements
            else
                $d_s \leftarrow d_s + 1$
```

Algorithm 1: The distance function for constructing a hierarchization with a local organizational-functional hierarchy and a global structural hierarchy.

Figure 4 shows the hierarchy that results from the distance function of Algorithm 1. Similar hierarchies emerge for the other floors of the building, which, in the end, would be combined to form a hierarchical representation of Engineering Block B. Since the example uses only one floor, only on the two topmost levels of the hierarchy the structural dimension determines grouping. Taking the building as a whole the superimposition of a global structural hierarchy would become more obvious; however for reasons of space it cannot be shown here. The labels can be derived automatically by using the concepts of the functional and organizational ontology that describe the distance of the elements on this level. "Geomatics" labels, for example, refer to all elements belonging to Geomatics; they have an organizational distance of 0. They can have any functional distance since Geomatics has rooms of diverse function. "Civ. Eng. Students" are all elements used by students (function) that belong to Civil Engineering (organization). At the finest level of granularity we find the containers forming the base structural conceptualization of scene space (Figure 3). These containers are connected via links. By attaching the links again the strict hierarchy (a tree) is broken up to reflect the actual structure of the environment (a lattice). The base structure allows for path search, while the tree structure is conceptually and algorithmically simpler for communicating these paths.

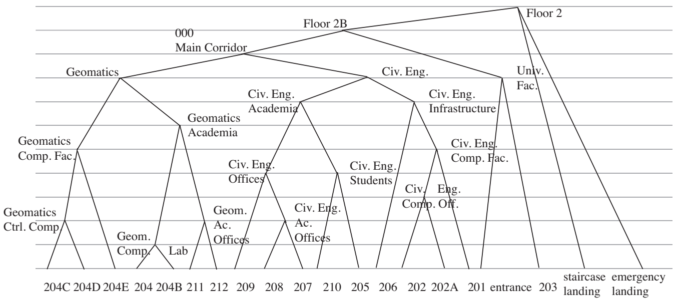

Figure 4. A structural hierarchy imposed on a local functional-organizational one.

This hierarchy now can be used to address elements of the represented environment in spatial communication. For instance, for new students the Geomatics computing labs can be referred to using an expression such as "the Geomatics computing labs are on Floor B2, next to the offices of Geomatics faculty." Likewise, if the current positioning signal does not allow for a precise localization of a user, the hierarchy can be used to communicate a meaningful location by stepping levels up in the hierarchy. For someone visiting the Civil Engineering department, this may mean to use "you are at Civil Engineering offices" instead of "you are at Room 208," for instance. Finally, to guide users who want to visit the Civil Engineering lab in Room 205, upon entering the second level they may receive instructions such as "Turn right, enter Floor B2, then get over the stairs. Pass Civil Engineering offices and turn left at the postgraduate lab to find Room 205." Such instructions require linking the hierarchy to the physical layout of the floor plan again (see [8] for one way of doing this).

5. Conclusions and Future Work

This paper argues for a hierarchical representation of indoor spaces that accounts for three different dimensions, namely structural, functional, and organizational aspects of the spaces. The approach combines and extends previous work on hierarchic representations [12, 1]. It is able to capture conceptualizations of such spaces of different user groups and information needed for different tasks. Most importantly, an algorithm for automatically constructing such hierarchic representations has been presented and has been illustrated using a floor of a university building as an example. The proposed hierarchization is well suited for different kinds of communication about indoor spaces.

One task for future work is the extension and improvement of the algorithmic realization of the hierarchization process. This comprises automatically constructing the base structural representation, setting weights for the links, and determining passages as discussed above. Link weights need to reflect the (physical or conceptual) relevance of a link. In the example given above, they have been set manually. As it is sufficient to have an ordering on the links, the challenge in doing this automatically is not assigning the weights, but determining how many different levels of weights are needed and which link belongs to which level. Furthermore, the algorithm needs to be tested for a number of different environments in order to test its robustness and to identify further challenges. Along this line, the threshold value for switching from a functional-organizational to a structural dominance in hierarchization may need to be adapted for different environments. It can be expected that approaches to automatically determining passages can also be used to automatically set this threshold value.

Generating human-like expressions is possible with the places provided by our hierarchic model, although it provides only a subset of the infinite number of places in human conceptualizations of an environment. Accordingly, a second task, the one of understanding human expressions, is more challenging. This task would require to deal with synonyms, especially common names replacing authoritative names, relative references instead of absolute ones ("the shop behind Toni's Pizzeria"), categorical references instead of individual ones ("at the pizzeria", or "at a pizzeria"), and references to places of granularity smaller than containers.

Acknowledgments

Support by the German Science Foundation (DFG) and Group of Eight / DAAD Australia Germany Joint Research Co-operation Scheme is acknowledged. The reproduction of the plan in Figure 2 is with permission of the Property and Buildings Asset Data Unit, University of Melbourne.

References

[1] V. A. Gaiser. *Improving Spatial Awareness in an Indoor Environment with Wireless Positioning Technology*. Master thesis, The University of Melbourne, 2008.

[2] S. C. Hirtle and J. Jonides. Evidence of hierarchies in cognitive maps. *Memory and Cognition*, 13(3):208–217, 1985.

[3] C. Hölscher, T. Meilinger, G. Vrachliotis, M. Brösamle, and M. Knauff. Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, 26(4):284–299, 2006.

[4] B. Jiang, C. Claramunt, and M. Batty. Geometric accessibility and geographic information: Extending desktop GIS to space syntax. *Computers, Environment and Urban Systems*, 23(2):127–146, 1999.

[5] M. Johnson. *The Body in the Mind. The Bodily Basis of Meaning, Imagination, and Reason*. University of Chicago, Chicago, IL, 1987.

[6] D. Koschützki, K. A. Lehmann, L. Peeters, S. Richter, D. Tenfelde-Podehl, and O. Zlotowski. Centrality indices. In U. Brandes and T. Erlebach, editors, *Network Analysis*, volume 3418 of *Lecture Notes in Computer Science*, pages 16–61. Springer, Berlin, 2005.

[7] M. Levine. You-Are-Here Maps. Psychological considerations. *Environment and Behaviour*, 14:221–237, 1982.

[8] B. Lorenz, H.-J. Ohlbach, and E.-P. Stoffel. A hybrid spatial model for representing indoor environments. In J. D. Carswell and T. Tezuka, editors, *Web and Wireless Geographical Information Systems*, volume 4295 of *Lecture Notes in Computer Science*, pages 102–112. Springer, Berlin.

[9] C. Masolo, L. Vieu, E. Bottazzi, C. Catenacci, R. Ferrario, A. Gangemi, and N. Guarino. Social roles and their descriptions. In D. Dubois, C. Welty, and M. Williams, editors, *Proceedings of the Ninth International Conference on the Principles of Knowledge Representation and Reasoning (KR2004)*, pages 267–277, Whistler, Canada, 2004.

[10] D. R. Montello. You are where? The function and frustration of you-are-here (YAH) maps. In A. Klippel and S. C. Hirtle, editors, *Workshop on You-Are-Here Maps in conjunction with Spatial Cognition 2008*, pages 21–27, Freiburg, Germany, 2008. SFB/TR8.

[11] M. Raubal and M. Worboys. A formal model of the process of wayfinding in built environments. In C. Freksa and D. M. Mark, editors, *Spatial Information Theory*, volume 1661 of *Lecture Notes in Computer Science*, pages 381–399, Berlin, 1999. Springer.

[12] U.-J. Rüetschi. *Wayfinding in Scene Space—Modelling Transfers in Public Transport*. Phd thesis, University of Zurich, 2007.

[13] B. Shanon. Where Questions, 1979.