# A Qualitative Bigraph Model for Indoor Space

Lisa A. Walton and Michael Worboys

Department of Spatial Information Science and Engineering
University of Maine, Orono, ME USA
lisa.walton@spatial.maine.edu and worboys@spatial.maine.edu

**Abstract.** Formal models of indoor space for reasoning about navigation tasks should capture key static and dynamic properties and relationships between agents and indoor spaces. This paper presents a method for formally representing indoor environments, key *indoor events* that occur in them, and their effects on the topological properties and relationships between indoor spaces and mobile entities. Based on Milner's bigraphical models, our *indoor bigraphs* provide formal algebraic specifications that independently represent agent and place locality (e.g., building hierarchies) and connectivity (e.g., path based navigation graphs). We illustrate how the model supports the description of scenes and narratives with incomplete information, and provide a set of reaction rules dictating legal system transformations to support goal-directed navigation. Given a starting scene and a particular navigation task we can determine potential sequences of events satisfying a goal (e.g., if a building fire occurs, what actions can an agent take to reach an exit?).

**Keywords:** Bigraphs, Bigraphical Reactive Systems, Indoor Bigraphs, Indoor Events, Indoor Space, Indoor Navigation.

## 1 Introduction

Spatial information systems supporting indoor navigation require models of built space that transcend traditional 3D CAD or building information models (BIMs). Although BIMs support the representation of building elements in terms of their 3D geometric and non-geometric (functional) attributes and relationships [1], they do not typically provide support for modeling navigation tasks. Outdoor navigation systems usually incorporate 2.5D models of large scale geographic environments consisting of physically bounded 2D regions (e.g., building footprints and cities) with an extra half dimension attribute (e.g., elevation) which are overlaid by road networks. Mobile objects of interest (e.g., pedestrians or cars) are represented by points (or single icons) that move through the network or inside the flat regions. Outdoor systems, however, cannot typically support indoor navigation, which must take topological configurations such as building hierarchies into account. In addition, locality, often defined with absolute coordinates in outdoor environments, is more likely to be described in relative terms for both physical and functional spaces in indoor environments (e.g., John's office). Moreover, traditional approaches to modeling built spaces typically require quantitative (geometric) building and navigation data. Existing spatial models supporting indoor navigation often incorporate graph-based representations of architectural space, and some consider cognitive models of agent navigation behavior in indoor environments [2-5]. However, many of these do not formally capture connections between the network model for navigation and other, non-spatial relations that exist between indoor spaces and mobile objects or agents. Our approach constructs a qualitative model of indoor environments based on Milner's bigraphs [6], which provide a formal method for independently specifying connectivity and locality between nodes (places of interest). Milner's tight coupling of place and connectivity graphs combined with formal methods for modifying and composing bigraphs provide a novel and useful approach for representing and reasoning about indoor navigation.

This paper presents a qualitative framework for formally representing and reasoning about indoor environments to support indoor navigation tasks. It models agent actions and their effects on topological properties and relationships between indoor spaces and mobile objects and agents. Indoor bigraphs provide formal algebraic specifications of indoor environments that independently represent agent, object, and place locality (e.g., building hierarchies) and connectivity (e.g., path based navigation graphs). The framework is flexible enough to model and reason about indoor scenes with incomplete information. System configurations can be updated with more complete scene information or in response to an agent's dynamic behavior as they carry out goal-directed indoor navigation tasks. In the following sections we define bigraphs and show how to build indoor bigraphs using floor plans and contextual knowledge about indoor scenes. Finally, we describe modifying indoor bigraphs based on new contextual information or changes due to agent actions. The material presented here complements earlier work by the authors on cognitive representations of indoor space and spatial relations in bigraphs [7] using image schema such as CONTAINER and PATH, and section 5 includes examples of reaction rules (which model atomic agent actions) using image schema.

## 2 Bigraphs

Originally developed for the virtual world of communicating processes and information objects, bigraphs originate in process calculi for concurrent systems, especially the pi-calculus [8] and the calculus of mobile ambients [9] for modeling spatial configurations (e.g., networks with a dynamic topology). Ambients, represented as nodes in bigraphs, were originally defined as "bounded places where computation occurs" [10]. However, bigraphs nodes typically have a more general interpretation as bounded physical or virtual entities or regions that can contain or link to other entities and regions. In defining indoor bigraphs here we will not repeat Milner's formal definitions, instead we use his simpler visual descriptions that are tightly coupled with an underlying algebra that provides reaction rules for appropriate system transformations based on connection or location changes in spatial configurations.

A **bigraph G** is a pair of constituent independent graphs **G = < $G^P$, $G^L$ >** sharing a common set of nodes where *place graph* $G^P$ specifies containment relations and *link graph* $G^L$ specifies connectivity relations. Fig. 1 shows a bigraph and its constituent place and link graphs with nodes {A,B,C}and a single undirected hyperedge ABC.

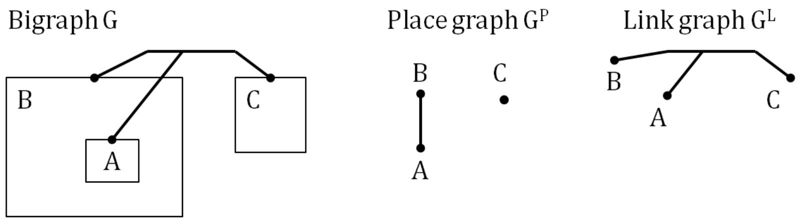


**Fig. 1**. Bigraph G with place graph (downward directed) and link graph (undirected)

Containment relations in bigraphs are visualized by letting nodes contain other nodes and connectivity relations by hyperedges joining two or more nodes. Bigraph visualizations need not maintain region shapes, relative node positions, or relative node sizes. Other spatial relationships between regions such as overlap, meet, or equals are not expressible as place relations in basic bigraphs.

**Place graphs** are forests of trees showing only containment relations between places (e.g., in Fig. 1 $G^P$ has two trees). In general, a place is a *node*, a *root* (outer context) or a *site* (inner context). Here, contexts are not actual nodes (bounded regions or entities), but rather *open placings* for partially known scene information that can be filled in later via bigraph composition (see section 4). For example, in indoor bigraphs (see next section) a root might represent the unknown environment outside a building and a site a collection of unknown objects in a room. Staying with the simple example, if we knew B and C were set in the same (but unknown) outer environment, and that B and C had unknown content, we could model that as follows (Fig. 2):

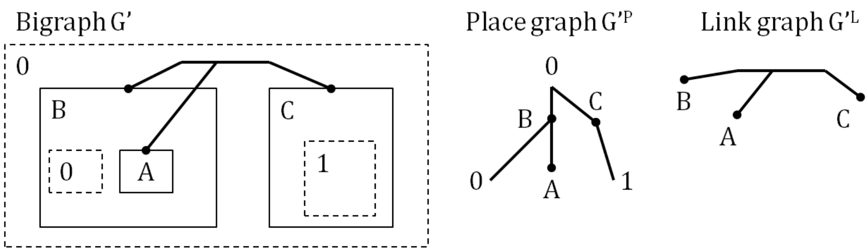


**Fig. 2.** Adding a root and sites to bigraph G

By convention [6], roots and sites are both labeled with integers beginning at 0. Note that when additional open placings are added the link graph remains unchanged.

**Link graphs** are hypergraphs, generalizations of graphs in which an edge may join any number of nodes. A *link* is a hyperedge connecting *nodes*, *inner names*, or *outer names*, where names are *open linkings* that support additional connectivity. Open linkings, like open placings, support the addition of context via bigraph composition. The bigraph and link graphs above both contain a single undirected hyperedge ABC.

# 3 Indoor Bigraphs

Indoor bigraphs to support navigation tasks must represent place and accessibility relations between people, objects, and spaces based on environmental features (e.g., doors may be locked), and agent capabilities (e.g., agent may not have appropriate keys or an agent may not be able to use stairs). Indoor *bigraph nodes* represent spatio-temporally bounded entities including rooms, people, and mobile small-scale objects such as keys. Fig. 3 describes an initial indoor scene with a first floor plan and an agent in the reception area (RA) who has a key to room 102.

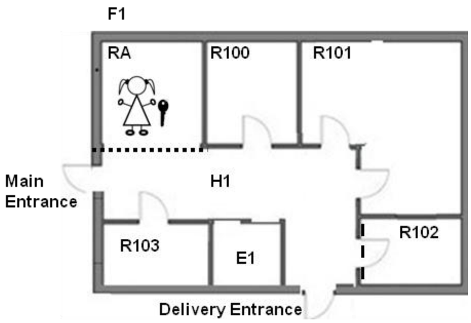


**Fig. 3.** First floor plan and agent and key initial locations

The bigraph for this scene will have ten nodes {F1, RA, R100, R101, R102, R103, E1, H1, A, K102}. The agent A, the key K102, and six spaces (the floor itself (F1), rooms 100-103, and the elevator E1) are completely physically bounded, and the hallway (H1) and reception area (RA) share a fiat boundary. Note that there are doors to the outside, and that the elevator presumably can access at least one other floor. Fig. 4 shows the **place graph $F1^P$** for this scene as a tree with root 0 (outer context where the exits lead to), nodes, and one site 0 (unknown context in room 102).

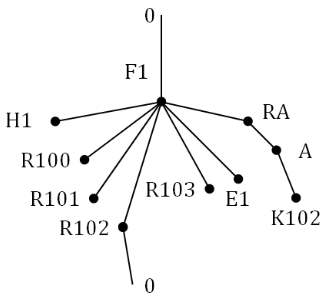


**Fig. 4.** Place graph $F1^P$ for the first floor scene

Although the elevator probably leads to a different place than the building exits, we defer representing that partial information to a later section when we have more building information. While there are many ways to represent a locked room scenario in a bigraph [7], here we have chosen to represent the agent-key relation as a place relation (i.e., the key is *in* the possession of the agent), and the key-lock relation as a link.

*Indoor Accessibility Graphs*

Most floor plans can be discretized to obtain an adjacency or accessibility graph [3]. For many indoor navigation tasks accessibility is sufficient to determine if an agent can navigate between places. Fig. 5 shows a discretization of the first floor scene.

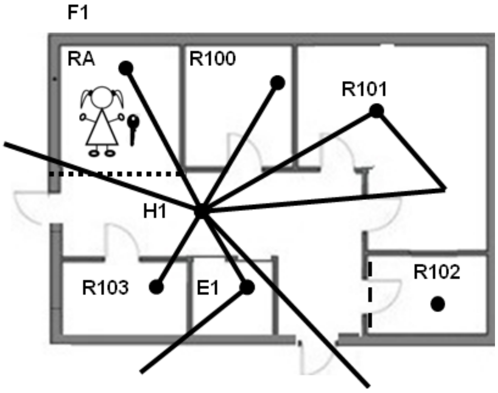


**Fig. 5**. Accessibility graph for the first floor

Rooms with two doors (e.g., R101) require two edges. Edges to unknown areas (the outdoors and other building floors) are open. R102 is locked (inaccessible) from the rest of the floor. Combining the accessibility graph and the single dotted edge key-lock graph yields the **link graph $F1^L$** in Fig. 6.

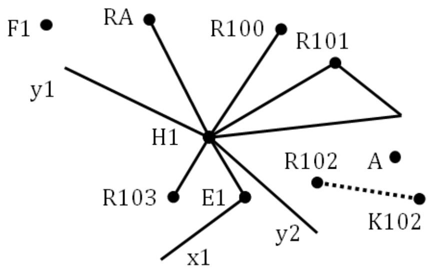


**Fig. 6.** Link Graph $F1^L$ for the first floor

The first floor (F1) and agent (A) nodes are in the link graph, but have no link relations. Open links to unknown areas are labeled with outer names y1, y2 (to the outdoors) and inner name x1 (to another floor). Combining the link and place graphs yields the bigraph in Fig. 7. Note that the elevator node has been moved to the top of the diagram for readability since topological configurations need not be preserved in bigraph representations. Node types are visualized using solid bordered squares to represent spaces, triangles for agents, and circles for mobile objects such as keys. Open placings (roots and sites) are represented as regions with dashed lines.

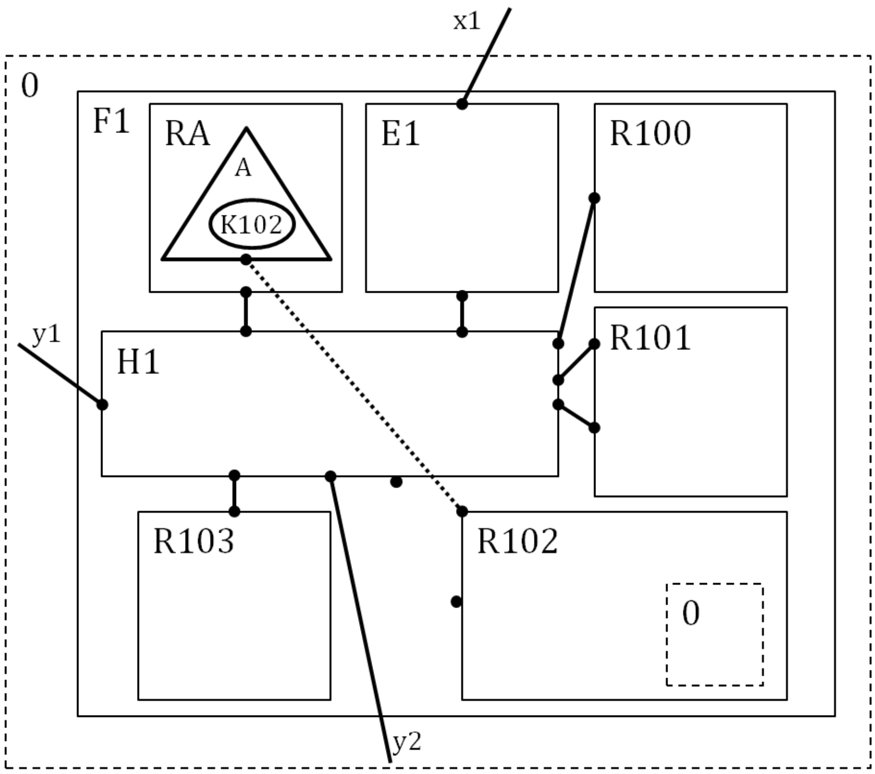


**Fig. 7.** Bigraph F1: <{0}, {x1}> → < {0}, {y1, y2}>

Each node has a fixed number of *ports* indicating the number of links (of any type) that are permitted, and any port can be connected to 0 or 1 edge. Here, the agent and first floor have no ports. Rooms 100, 103, and the RA each have 1 port, whereas room 101 with two exits, the elevator, and lockable room 102 each have 2 ports. The hallway has 9 ports. Edge types are visualized with solid lines for accessibility relations and dotted lines for key-lock relations. Indoor bigraph closed edges connect exactly 2 ports, and open linkings (inner and outer names) connect to 1 port.

Each bigraph has a mapping between *interfaces*, or minimal specifications of the portions of a particular bigraph that support additional openings for more containment or linking information. Bigraph F1 above has site set {0} and inner name set {x1} that map to root set {0} and outer name set {y1,y2}. Ports, including open ports such as those on the hallway and R102, are not included in the interface.

### 3.1 Indoor Bigraph Typology

For the domain of indoor navigation the typology of places (nodes) and edges is very important. So, for each specific indoor environment at a minimum the following bigraph node types must be defined:

- $A = \{a_1,\ldots,a_i\}$ is a finite set of agents
- $P = \{p_1,\ldots,p_j\}$ is a finite set of places an agent can be in
- $K = \{k_1,\ldots,k_k\}$ is a finite set of keys where $k_i$ unlocks place $p_i$

The set of bigraph nodes is $N = A \cup P \cup K$. Edge types are defined as follows:

- AEdges = $\{(p1,p2) \mid p1,p2 \in P\}$ is a finite set of edges representing accessibility relations in the link graph
- KEdges = $\{(k,p) \mid k \in K, p \in P\}$ is a finite set of edges representing key-lock relations in the link graph
- PEdges = $\{(p1,p2) \mid p1,p2 \in P\}$ is a finite set of edges representing containment relations in the place graph

The set of bigraph edges is E = AEdges $\cup$ KEdges. PEdges in bigraph diagrams are represented as actual region containment not with an edge. Note that for indoor bigraphs all edges are between just two nodes, although the general bigraph model allows hyperedges. Typically, nodes sets will also be partitioned according to how many ports (possible link connections) each type of node can support.

The bigraph example above is a temporal snapshot of an incomplete indoor environment. While floor plans are usually static, agent locations and the lock state of doors (and hence access links) can change over time. In the following sections we first show how to add context via bigraph composition and next how to make changes to indoor environments (e.g., people moving around) by applying reaction rules to change system configurations. Bigraphs can be modified using:

- *Composition* to add missing context (e.g., create outdoor-indoor bigraphs or combine partial building plans)
- *Reaction rules* to change the system state (e.g., person unlocks a room)

## 4 Bigraph Integration

### 4.1 Bigraph Composition

Given two bigraphs with matching interfaces, composition is used to add additional context. For example, outdoor spaces containing buildings and road networks can be integrated with indoor spaces. Suppose building B1 is accessible from two parking lots which access the city road network. Fig.8 specifies an outdoor scene including a footprint for the building containing the first floor.

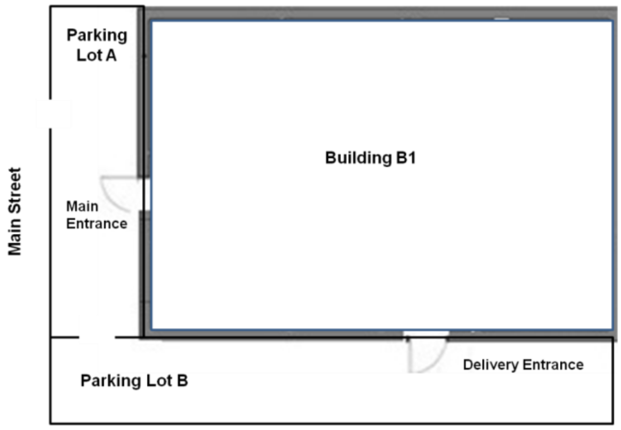


**Fig. 8.** Outdoor Map

*Resolving Outer Names and Roots*

Suppose that we know that the entrances from the parking lots lead to the 1st floor hallway, represented as open links (outer names) y1 and y2 in the 1st floor bigraph. In addition, we know there are two floors in the building, the first of which is inside root 0 in the original bigraph. Adding sites 0 and 1 (placeholders for the 1st and 2nd floors) we define a *host bigraph* H which can be composed with the original bigraph to provide outside context. Fig. 9 shows an outdoor bigraph H with appropriate interfaces.

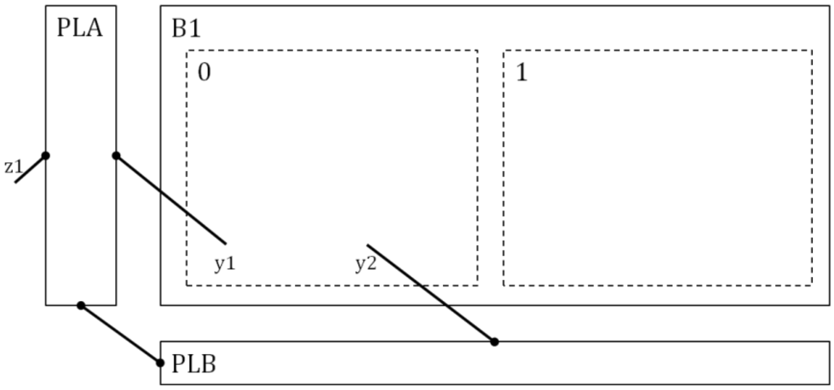


**Fig. 9.** Outdoor bigraph H: $<\{0,1\}, \{y1, y2\}> \rightarrow <\{\},\{z1\}>$

Fig. 10 shows the composition of the 1st floor bigraph F1 and the outdoor bigraph H. It joins root 0 in F1 with site 0 in H causing both to disappear, and joins the open links y1 and y2 replacing them with two closed edges between the hallway and parking lots. All nodes in the original bigraph, site 0 (from F1, a placeholder for the contents of R102), and site 1 (from H, the placeholder for the 2nd floor) are left unchanged, as are open links z1 (an outer name indicating access to the outdoor road network) and x1 (an inner name indicating access via the elevator to the 2nd floor).

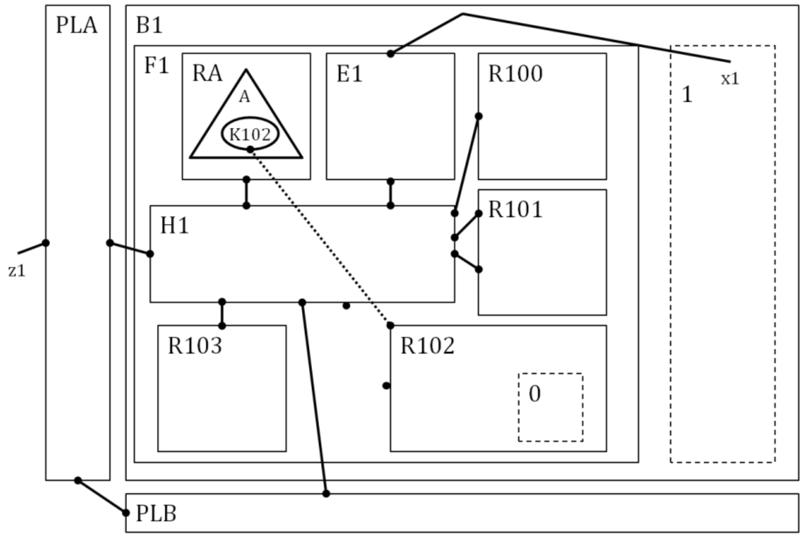


**Fig. 10.** Outdoor-Indoor bigraph F1 o H: <{0,1}, {x1}> → <{},{z1}>

*Resolving Inner Names and Sites*

Suppose that the 2nd floor plan looks much like the 1st, except that there are no external exits and there is a bathroom in the upper left corner. Because we need to combine this bigraph with the rest of the building bigraph, we place the nodes inside a root 1 and include an open link (here an outer name) x2 from elevator E2 (Fig. 11).

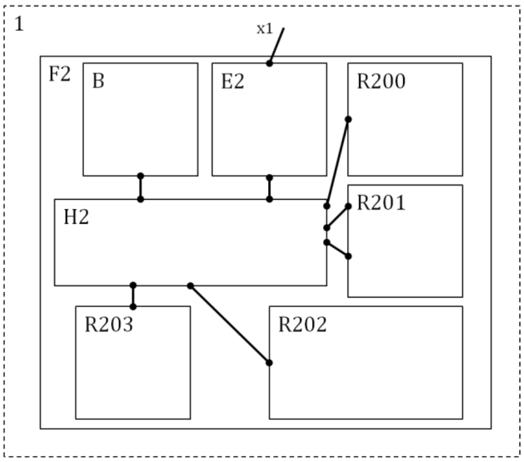


**Fig. 11.** 2nd floor bigraph F2: <{},{}> → <{1},{x1}>

Composing the outdoor-indoor bigraph and F2 joins the building bigraph site 1 with F2's root 1, and inner and outer names x1 (Fig. 12).

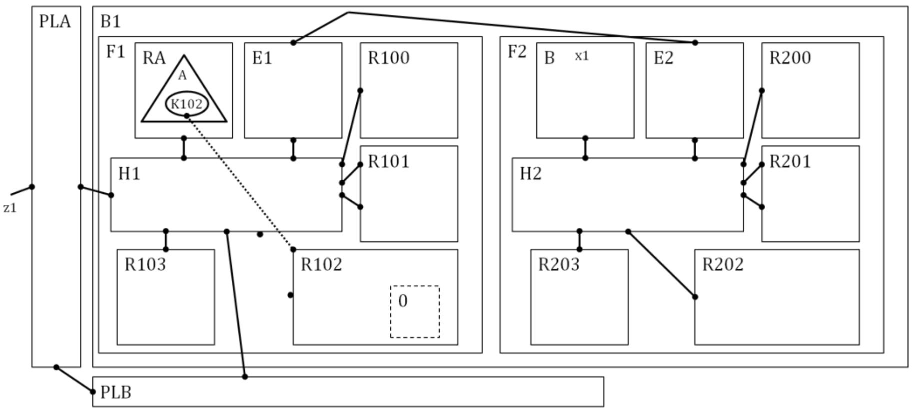


**Fig. 12.** Multistory indoor-outdoor bigraph F2 o F1 o H: <{0},{}> → <{},{z1}>

Inner name x1 from the indoor-outdoor bigraph is joined with outer name x1 from F2 to form a new closed edge (access link) between elevator nodes, and site 1 in the indoor-outdoor bigraph has joined with root 1 in F2. Note that the nodes and closed links are left unchanged after bigraph composition.

## 5 Representing Change in Bigraphs

Bigraphs can be modified by the application of reaction rules, which specify legal changes to linking and place relations. A reaction rule consists of a pair of bigraph parts consisting of a *redex* (pattern to be changed) and *reactum* (resulting pattern). Most domains modeled with bigraphs require one or more reaction rules that support changing basic locality or linking relations. For indoor bigraphs agent actions such as going *into* or *out of* or *locking/unlocking* a place are modeled with rules. The choice of appropriate reaction rules that change a single placing or link relation based on spatial *image schemas* was explored in earlier work [7]. Here we provide a representative sample of reaction rules (associated with the CONTAINER and LINK schema respectively) for modifying indoor bigraphs in response to agent actions.

*INTO Rule*

An agent with a key may move into any place accessible from her current location, whether or not the rooms have additional content (Fig. 13). Open links on the nodes indicate that other links are permissible parts of the pattern to be matched. This rule is self-inverse, and no link relations are changed by applying it.

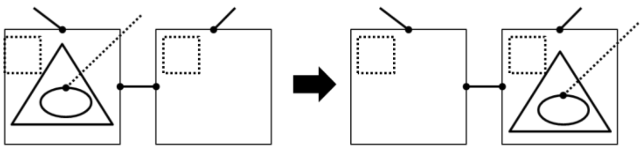

**Fig. 13.** INTO Rule: INTO(a,p) is the action of a ∈ Agents moving into p ∈ Places

*LINK (UNLOCK) Rule*

Because we have modeled the relationship between a key and the room it unlocks as a link we require an access LINK rule (corresponding to an UNLOCK action) which creates an access link between places after a door is unlocked (Fig. 14). An inverse UNLINK (LOCK) rule is also usually required to make a place inaccessible [7]. No place relations are changed when applying this rule.

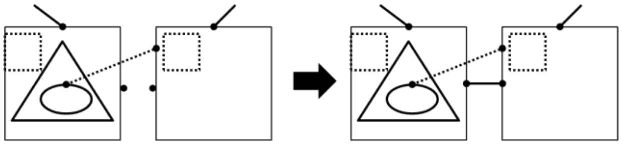

**Fig. 14.** LINK Rule: ALINK(p1,p2) is the action of p1 linking to p2 where p1,p2 ∈ Places

There are many rule variants. For example, with more specific agent and place types the INTO rule for stairways can be restricted to only allow agents that can use stairs to enter stairways. Therefore, a well-typed agent that can't use stairs wouldn't be sent into stairways because that action couldn't be modeled in the formal system.

### 5.1 Indoor Navigation

Combining bigraphs with a set of reaction rules yields a *bigraphical reactive system* (BRS), in which indoor navigation can be modeled by modifying bigraphs (temporal snapshots of indoor environments) by the sequential application of appropriate rules. For example, suppose the agent with a key in the reception area from Fig. 7 wishes to access locked room 102. We do not need information about the 2nd floor or the out-doors to model these actions. The first step is applying the INTO rule, resulting in a new bigraph showing the agent has moved from RA into the hallway (Fig. 15).

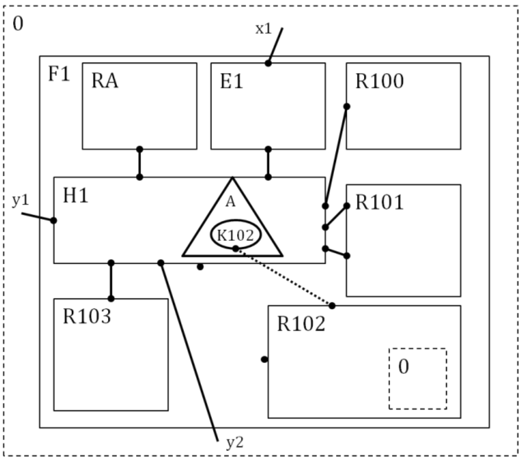


**Fig. 15 .** F1 after applying the INTO rule

Next, use the LINK (UNLOCK) rule to change the link relation between the hallway and RM102 by connecting the open ports to make the room accessible (Fig. 16):

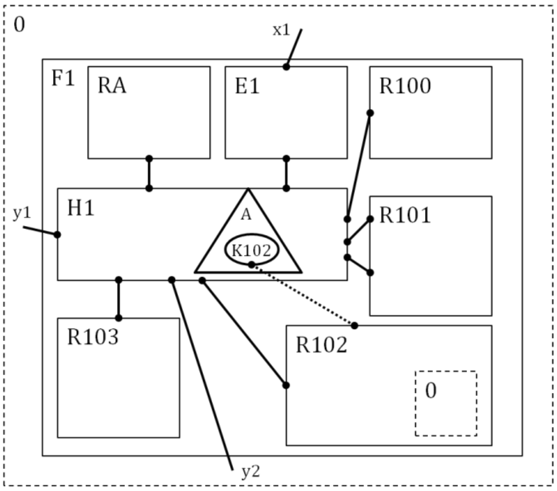


**Fig. 16.** Indoor scene after applying UNLOCK rule

Finally, use the INTO rule again to model the agent entering RM102 (Fig. 17).

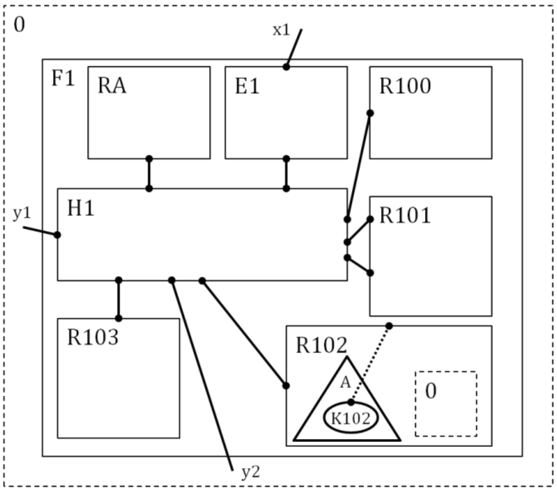


**Fig. 17.** Agent reaches her destination

By defining key indoor events (corresponding to atomic agent actions) and modeling them as reaction rules we can construct sequences that model dynamic agent behaviors to modify indoor environments. Given an agent's starting situation and a particular navigation task we can determine potential sequences of events that would lead to satisfying her goal (e.g., how can she reach the nearest bathroom?). This can be done even when there is incomplete information about the environment, such as not knowing where the building exits lead when the tasks involve actions on just one floor.

## 6 Conclusion and Future Work

This paper describes a qualitative framework for formally representing and reasoning about indoor environments to support indoor navigation tasks. Our primary goal was to demonstrate that indoor bigraphical models are appropriate formalization and visualization tools for indoor environments that support reasoning about the effects of indoor events (precipitated by agent actions) on key indoor environmental elements.

Indoor bigraphs provide formal algebraic specifications of indoor environments that independently represent agent and place locality (e.g., building hierarchies) and connectivity (e.g., path based navigation graphs). Our examples illustrate that indoor bigraphs can be constructed from building floor plans with some additional scene information (e.g., agent and mobile object locations). Further, we demonstrated that scenes with partial information (e.g., incomplete building plans) could be modeled in a way that supported adding additional context, including outdoor contexts, suggesting a new approach to integrating outdoor and indoor navigation systems.

In related work the authors have developed constructions that provide explicit bigraph types for representing complex two-dimensional spatial configurations [11], and defined preliminary ontologies for indoor and hybrid outdoor-indoor spaces for built environments based on a typology of the space and the entities it contains [12].

This paper extends the authors' previous work on using image schemas to model spatial relations and agent actions in bigraphs [7]. To improve our representation of agent behaviors in indoor environments we also plan to incorporate *affordances* into the framework. Affordances describe objectively measurable actions an agent can take in an environment given their current capabilities [13]. Reaction rules in the original ambient calculus were established based on context-dependant abilities of certain ambients (processes) to perform actions [9]. Similarly, modeling affordances in indoor bigraphs should help to refine reaction rules and improve reasoning procedures in goal directed navigation task planning.

Future work will include the integration into the framework of an indoor *event calculus* [14] to provide a logic-based formalism for representing the *effects* of indoor events on indoor relationships. Currently, the effects of agent actions on indoor relationships are modeled with reaction rules (e.g., when an agent enters a room it has the effect of changing their location). By defining appropriate *effect axioms* in the calculus corresponding to the rules, we will be able to automatically generate time indexed *narratives* about indoor navigation tasks as sequences of events and their consequences in indoor environments. This will support forward reasoning (e.g., what sequence of actions can an agent take to reach a particular place from their current location?) and backwards (explanatory) reasoning (e.g., given that an agent is in a particular place now, how could they have gotten there from some previously known location?). Automated reasoning about indoor navigation using qualitative formal models has the potential to improve many kinds of spatial information systems such as providing decision support for visitors to large building complexes or analytic support for security personnel using alert systems to reconstruct possible security breaches involving unauthorized access to restricted areas or materials.

## 7 References


1. Howell, I., Batcheler, B.: Building Information Modeling Two Years Later – Huge Potential, Some Success and Several Limitations. The Laiserin Letter. (2005)
2. Franz, G., Mallot, H.,Wiener, J.: Graph-based Models of Space in Architecture and Cognitive Science - a Comparative Analysis. In Leong, Y-T. & Lasker, G.E. (eds), Proceedings of the 17th International Conference on Systems Research, Informatics and Cybernetics: 30-38 (2005)
3. Lee, J., Kwan, and M. P.: A Combinatorial Data Model for Representing Topological Relationships between 3-D Geographic Entities, International Journal of Geographical Information Sciences, 19 (10), p. 1039-1056 (2005)
4. Lorenz, B., Ohlbach, H.J., Stoffel, E.-P., Rosner, M.: Towards a Semantic Spatial Model for Pedestrian Indoor Navigation. In: LNCS - Advances in Conceptual Modeling – Foundations and Applications, Volume 4802/2007, Springer, Berlin, Germany (2007)
5. Richter, K-F, Winter, S., Rüetschi, U-J.: Constructing Hierarchical Representations of Indoor Spaces. Pp. 686–691 in Mobile Data Management, IEEE International Conference on, vol. 0. Los Alamitos, CA, USA: IEEE Computer Society (2009)
6. Milner, R.: The Space and Motion of Communicating Agents. Cambridge University Press (2009)
7. Walton, L., Worboys, M.: An Algebraic Approach to Image Schemas for Geographic Space. In Proceedings of the 9th International Conference on Spatial Information Theory (COSIT), France, September 2009. pp. 357-370, Lecture Notes in Computer Science, Vol. 5756, ISBN 978-3-642-03831-0, Springer (2009)
8. Milner, R.: Communicating and mobile systems: the π-calculus. Cambridge, New York, Cambridge University Press (1999)
9. Cardelli, L., Gordon,A.: Mobile Ambients. In Theoretical Computer Science, Special Issue on Coordination, D. Le Mtayer Editor. Vol 240/1. pp 177-213 (2000)
10. Cardelli, L.: Abstractions for Mobile Computation. In Secure Internet Programming: Security Issues for Mobile and Distributed Objects. Jan Vitek and Christian Jensen, Editors. Springer Lecture Notes in Computer Science, Vol. 1603, pp. 51-94 (1999)
11. Worboys, M.: Using Bigraphs to model topological graphs embedded in orientable surfaces. Journal of Theoretical Computer Science (2010) (Submitted)
12. Walton, L., Worboys, M: Indoor Spatial Theory. Technical report presented at the ISA project meeting held at the 2010 International Workshop on Indoor Spatial Awareness. Taipei, Taiwan (2010)
13. Gibson, J. :The Theory of Affordances. Perceiving, Acting, and Knowing. R. Shaw and J. Bransford (1977)
14. Kowalski, R.A., Sergot, M.J.: A Logic-Based Calculus of Events, New Generation Computing, vol 4, pp. 67–95 (1986)