A Continuous-Based Model for the Analysis of Indoor Spaces

XIANG LI [1], CHRISTOPHE CLARAMUNT [2] AND CYRIL RAY [2]

[1] Key Lab of Geographical Information Science,
East China Normal University,
Shanghai 200062, China

[2] Naval Academy Research Institute,
Lanvéoc-Poulmic,
CC 600, 29240 Brest Cedex 9, France

INTRODUCTION

CONTINUOUS-BASED MODEL FOR INDOOR SPACES

From Large to Small Scale Environments

- People spend large parts of their lives in indoor spaces : office buildings, shopping center, airports…

- Emerging and continuing advances in ambient devices and systems and communications bring novel opportunities for indoor “geo-services”
  - Human way-finding and navigation in built environments
  - Evacuation routes for people stuck in a building during an emergency
  - Tracking suspicious moving objects in a building using video surveillance…

- Is there any need to reconsider current GIS models when considering indoor environments ?
  - Taking into account human cognition and behaviours in such environments
  - The way indoor spaces are constrained by architectural designs
  - Considering the role played by smart location-based devices
  - Taking into account the range of applications in indoor environments…

Research Issues and Objectives

- Modelling issues :
  - How to spatially represent an indoor space ? (discrete, continuous, symbolic)
  - How to transform/map an indoor physical space towards a spatial-based model ?
  - How to take into account the behaviour and positioning data of a moving object and an indoor-based model ?
  - How to apply the model of an indoor space to a given phenomena, either discrete or continuous ?

- Modelling approach
  - We retain a continuous and structural-based modelling approach allowing the integration of graph-based properties
  - Such an approach favours accurate indoor positioning, tracking and navigation and the modelling of continuous phenomena
  - The approach is illustrated by the diffusion of a gas leak

RELATED WORKS

MODELLING BACKGROUND

Modelling Indoor Spaces

- From physical to conceptual modelling : geometric → set-based → topological → semantic

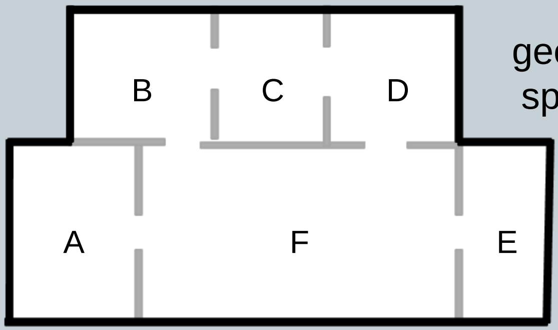
- Geometric spaces :
  - Representation mainly based on Euclidean geometry
  - Using by absolute or relative coordinate systems and transformation between them

- Symbolic spaces (spaces with qualitative description)
  - Set-based representation where space is described by spatial regions and relationships between them
  - Structural representation where topological relationships and structural properties are derived from a graph-based model
  - Semantic representation where space is considered as a set of objects and relationships between them

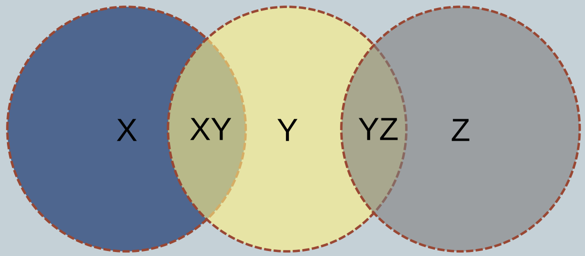
Modelling Indoor Spaces

Adapted from Li, 2008

Primal spaces

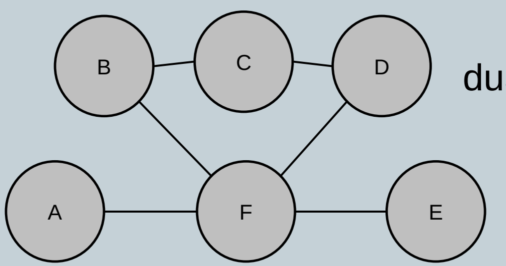


geometrical space (R^2)

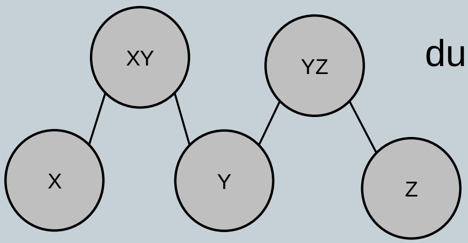


set-based space

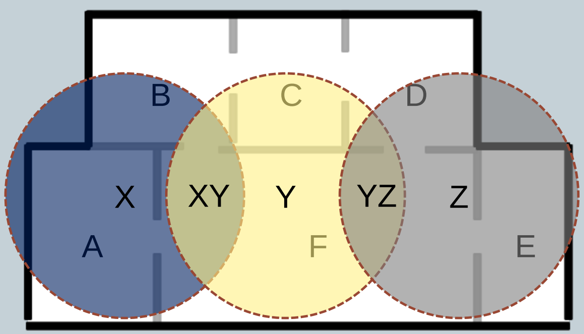
Dual spaces

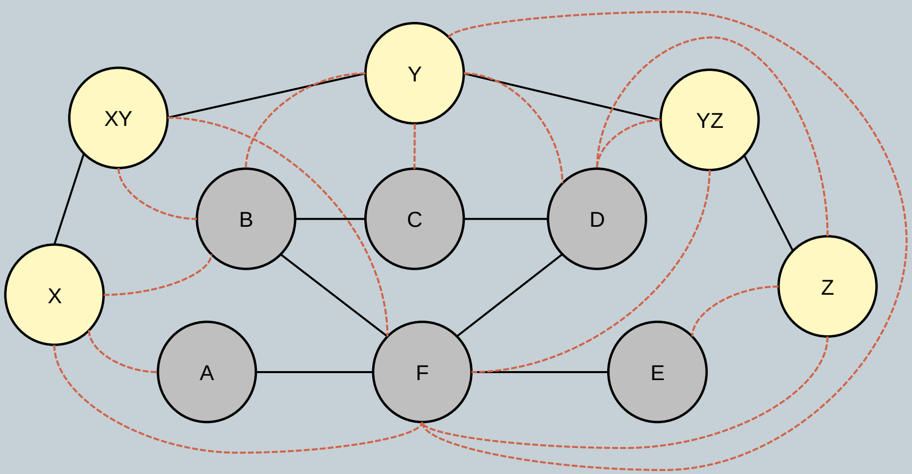


dual topological graph



dual topological graph





Symbolic Spaces vs. Geometric spaces

- Symbolic models of indoor space are often preferred over traditional geometric models because they are able to capture the semantics associated with indoor entities (Jensen *et al.*, 2009)

- Non-exhaustive advantages of symbolic models
  - Simple models generally based on graph models and theory
    - Nodes represent rooms, and edges connections, such as corridors and doors, between rooms
    - Nodes and edges obtained by division, adjacency and connectivity
  - Cells (nodes, edges, objects) define a location reference for indoor space
  - Ambient systems emerge with appropriate positioning systems (presence sensors vs. position sensors)
  - Geometry is approximated as each cell may have (or not) its own geometry
  - Topology is implicit as cell connections reflect the structure of space
  - Spatial relationship between cells and moving object can be established

Is Symbolic Representation Always Appropriate?

- Space syntax had been long applied to indoor environment (e.g. Kim *et al.*, 2008)
  - Well defined from a spatial modelling point of view, and with operators long identified by graph theories
  - Local operators evaluate the connectivity of a given room, while global operators measure the role played by a given room in the whole network

- The assumption of this modelling approach is that there might have a correlation between structural patterns that emerge from layout and the way moving objects (phenomenon) evolve through spaces...

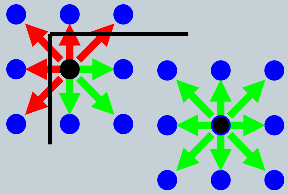
- ..., but
  - There is a lack of continuity and geometrical measures of space or time that encompass another class of properties (such as “continuous” events)
  - People’s behaviours are often non deterministic processes that cannot always be approximated by a structural representation of space

Towards a Finer Modeling Approach

- Usual node-edge representation is structural and reveals the main spatial structure of a built environment

- While such a model can represent topological relationships, It fails to retain the whole semantics of complicated indoor spaces
  - For example, is a single point enough to represent a room with a large area or an irregular shape?

- Alternative solutions considering indoor spaces at a lower level of granularity should be considered (Ray *et al.*, 2009)
  - A fine “cell-based” modelling approach is based on an occupancy grid that reflects the main geometrical properties
  - Each cell/node is connected to its neighbours that represents connectivity and displacement opportunities



INDOOR MODELLING

NODE-EDGE GRAPH WITHIN OCCUPANCY GRID

Modelling Background

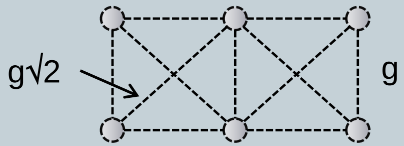
- From an occupancy grid as initially introduced in mobile robotics and artificial intelligence
- Where an occupancy grid is a regular matrix consisting of equally-sized cells
- In such approach, the surrounding environment of a mobile robot is represented by the occupancy grid
  - Movement opportunities and/or probabilities can be estimated
  - E.g., an high probability of displacement is given to cells relatively connected, while a low probability to cells surrounded by obstacles
- Simplicity and metric embeddedness are two advantages of the occupancy grid approach

Modelling Principles

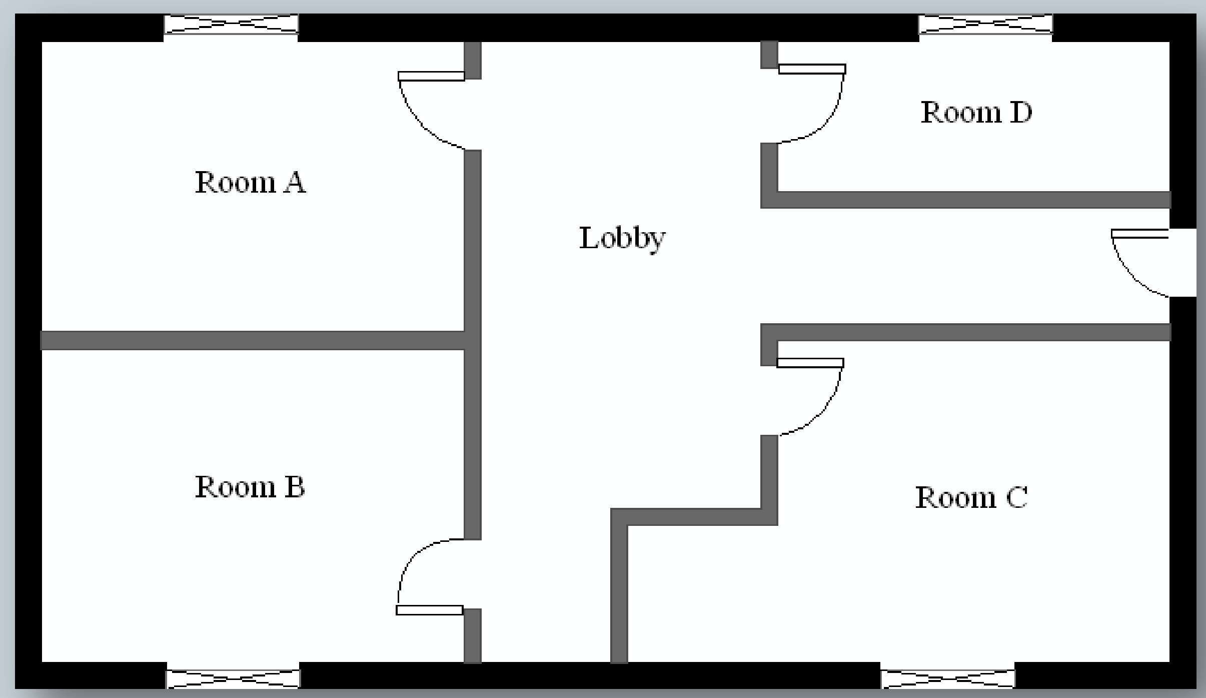
- Indoor modelling based on :
  - A node-edge graph that covers all the indoor space
  - Where nodes represent cells within an occupancy grid, and connections between cells are materialized by edges
  - Where impedance values are given to each edge depending of the application of interest
- Modelling properties
  - The graph-based model retain displacement opportunities from a continuous point of view
  - Structural properties can be encapsulated within the graph-based representation
  - The geometrical properties are implicitly represented by the continuous layout of the graph and reflect the shapes of the rooms considered

Modelling Principles

- A built environment is modelled as a two dimensional space of extent S materialized as a continuous space of cellular units
- The continuous representation covering S is parameterized by a level of granularity g that generates a grid graph of step g
- The grid graph includes additional diagonal edges so that each node is connected to 8 neighbours
- Nodes and edges are labelled according to their memberships to a given cellular unit such as a room or a connecting space
  - Each node has one and only one membership value as a node is contained by one and only one cellular unit
  - Membership value of an edge is multi-valued when this edge intersects several cellular units



Modelling Illustration

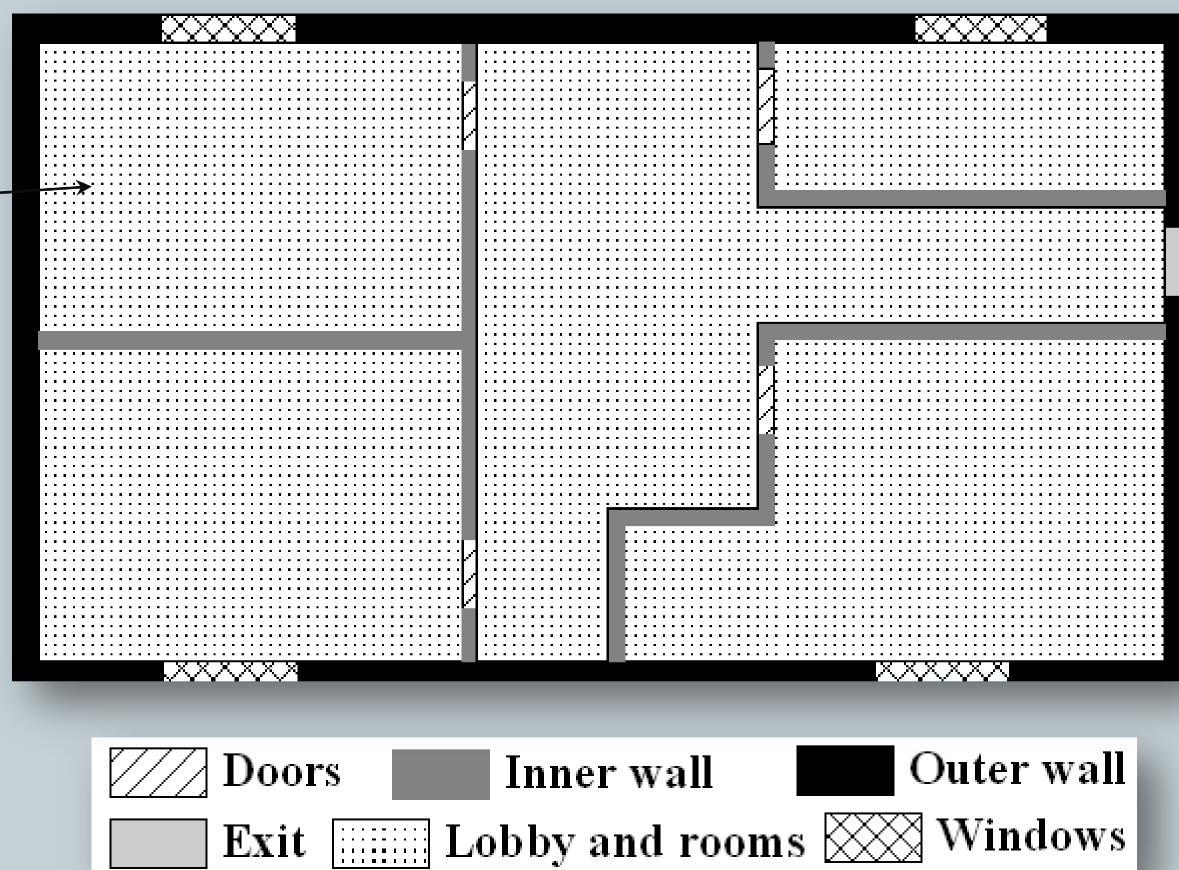


A floor plan

Cellular Units

- Each cellular unit contains nodes regularly placed (every *g*). Nodes are labelled according to their memberships to a cellular unit

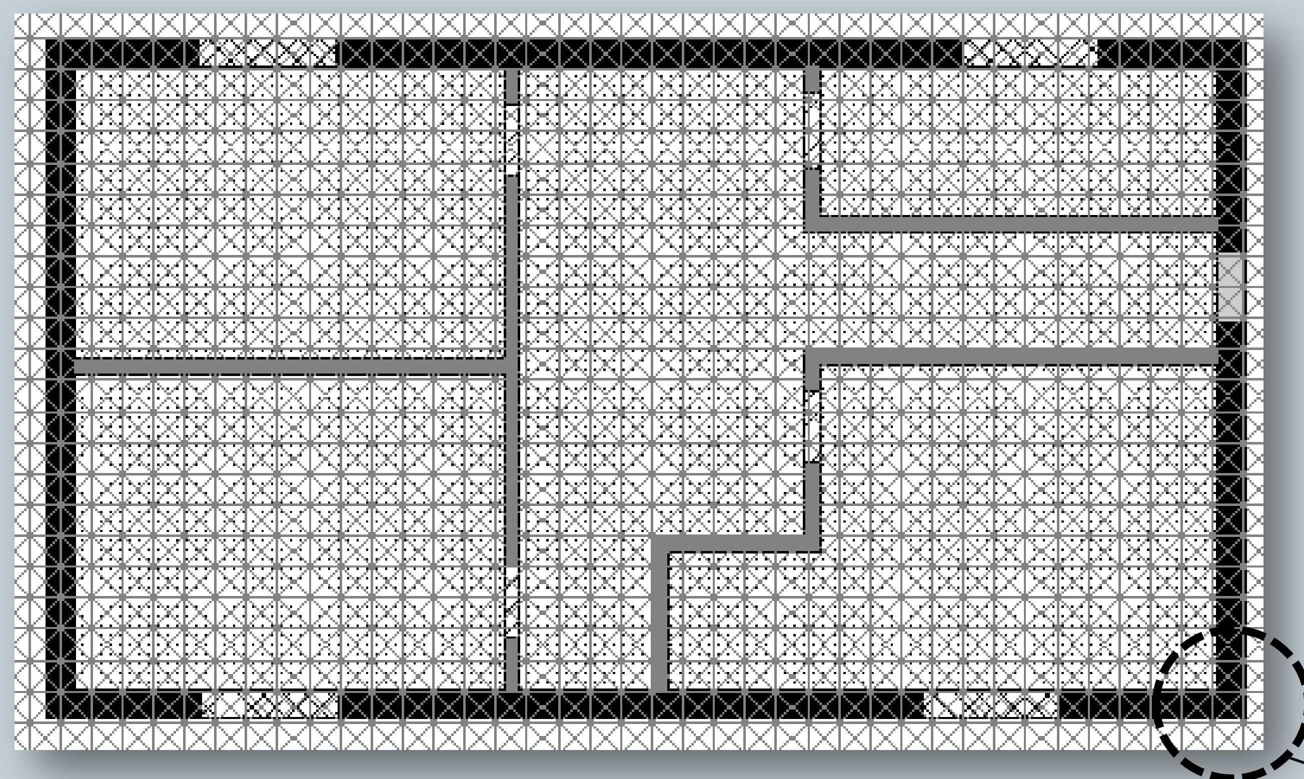
cellular unit



The grid granularity *g* can be adapted according to the considered application

Grid Graph

- Edge impedance (v) allows modelling of different constraints associated to studied phenomena



Overlap of a grid graph and labeled cellular units

Impedance values might be correlated with g. They are closely related to studied application

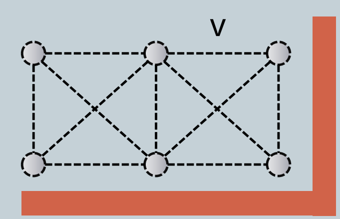
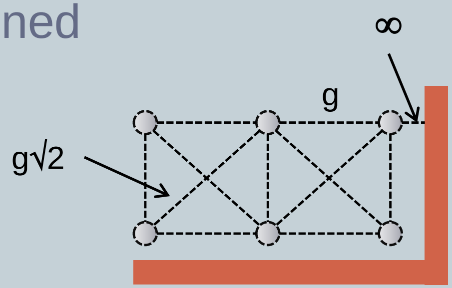
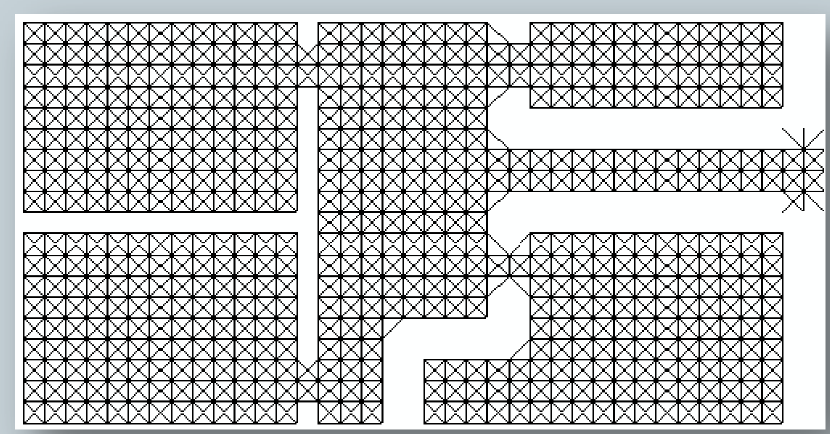


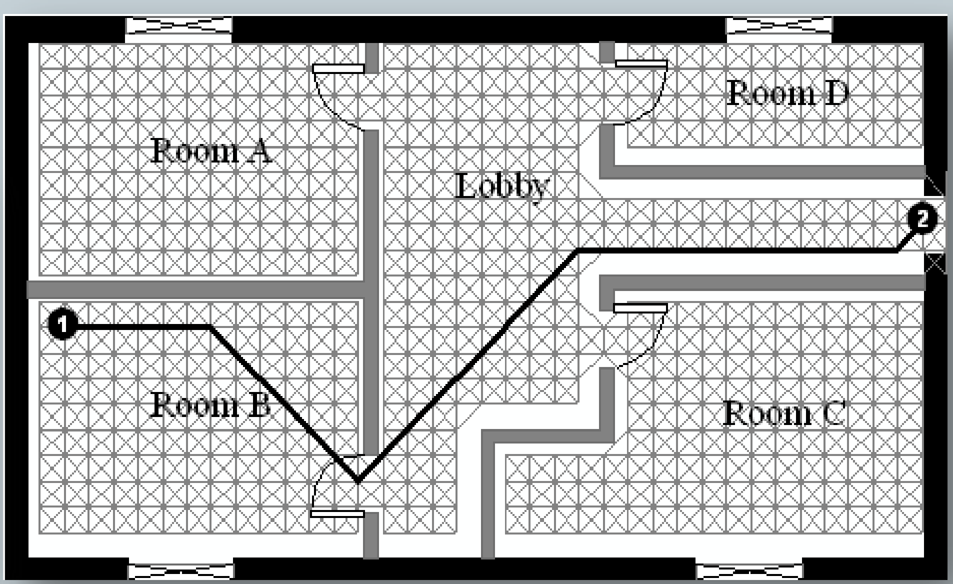
Illustration for Moving Objects

- The model allows finding accurate shortest path between two points
  - Impedances are based on graph granularity g and assigned according to cellular unit membership
  - Doors opened





Free space represented by a grid graph



Shortest path between ❶ and ❷

CASE STUDY

MAPPING GAS LEAK IN AN INDOOR SPACE

Objective and Assumptions

- Objective : to map the diffusion of a gas leak in an indoor space
- Some assumptions :
  - The source of the gas leak is located in a given room of an indoor space
  - The impedance of each edge equals the time it takes gas to diffuse along the edge
  - The diffusing speed is denoted as *s* in the free space considered, let *T* be *g/s*
- Example of edge impedance values for gas diffusion in an indoor space

Description	Edge length	Impedance
Edges are completely within free space: room, lobby, opened door, opened window, or opened exit	*g*	*T*
	g.√2	T.√2
Edges are completely within or intersect less occupied space: closed door, closed window, closed exit, or inner wall	*g*	40.*T*
	g.√2	40.T.√2
Edges are completely within or intersect more occupied space: outer wall	*g*	*Infinity*
	g.√2	*Infinity*

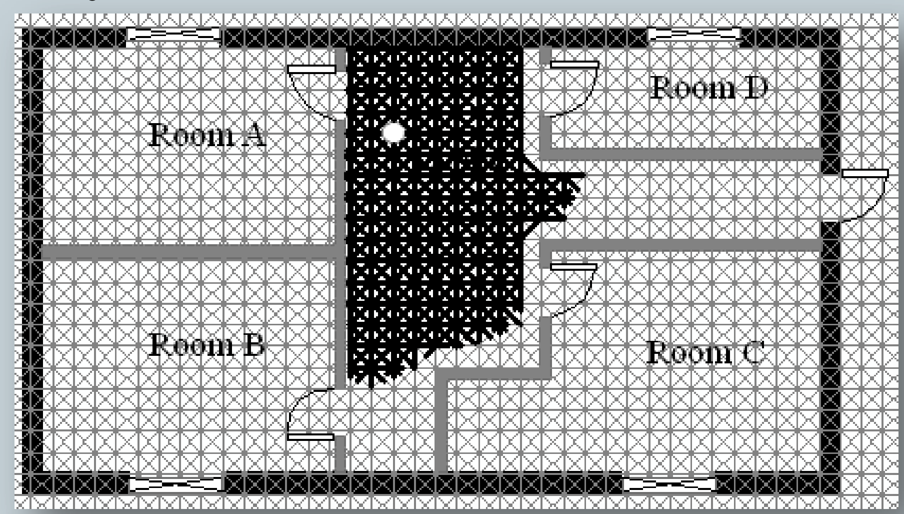
Algorithm Principles

- The diffusion algorithm figures out the evolution of nodes and edges covered by gas diffusion

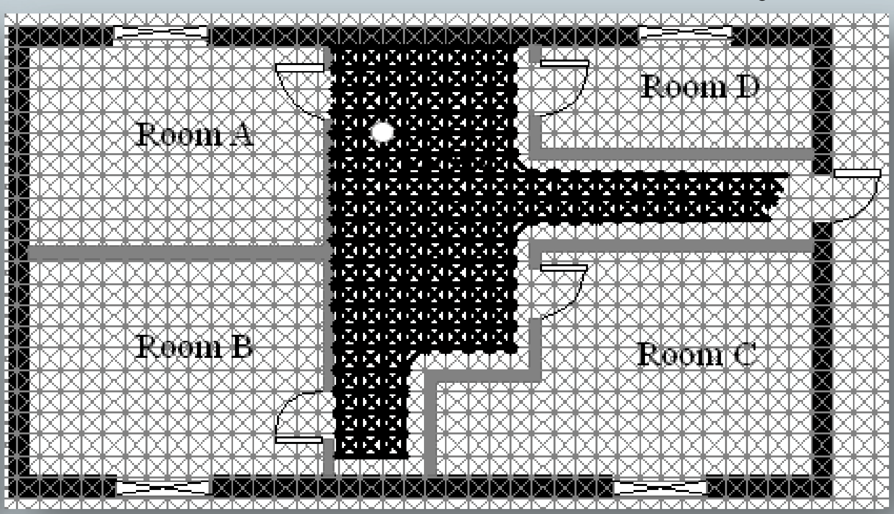
- Algorithm Principles
  - Let n_0 denote the node representing the source of gas leak, and t_0 the starting time of leak
  - For a given time instant t_0+mT, where m is a real number
    - Find all nodes whose shortest paths to n_0 are less than mT in terms of cost (i.e., diffusing time)
    - Check each edge through examining its two associated nodes and figure out those covered by gas during the interval from t_0 to t_0+mT
    - If not the whole but a part of an edge is covered by the phenomenon, only the covered part is considered

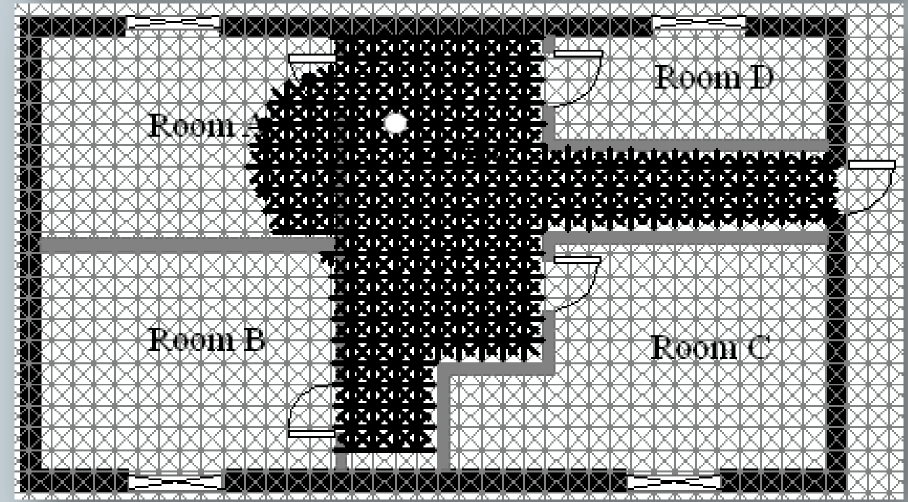
Mapping Gas Leak in an Indoor Space

$t = t_0 + 10T$



$t = t_0 + 20T$





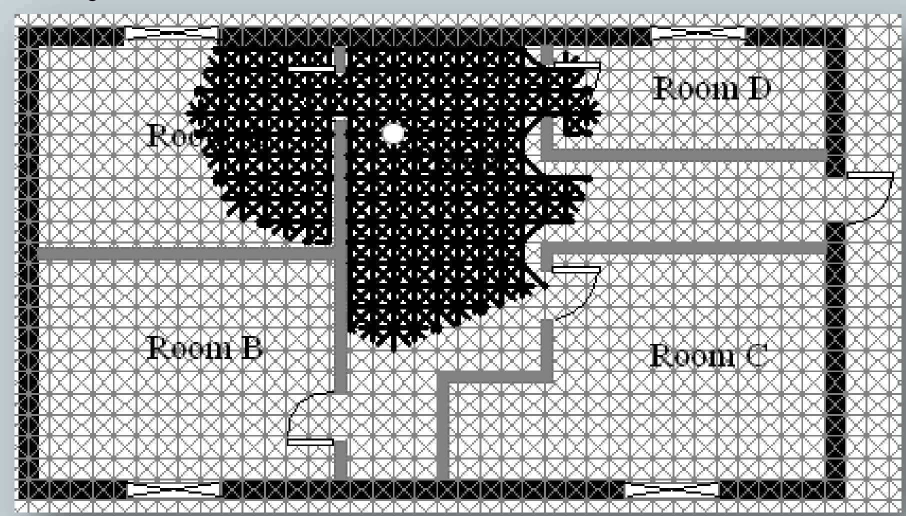
$t = t_0 + 45T$

Gas leak when all doors are closed

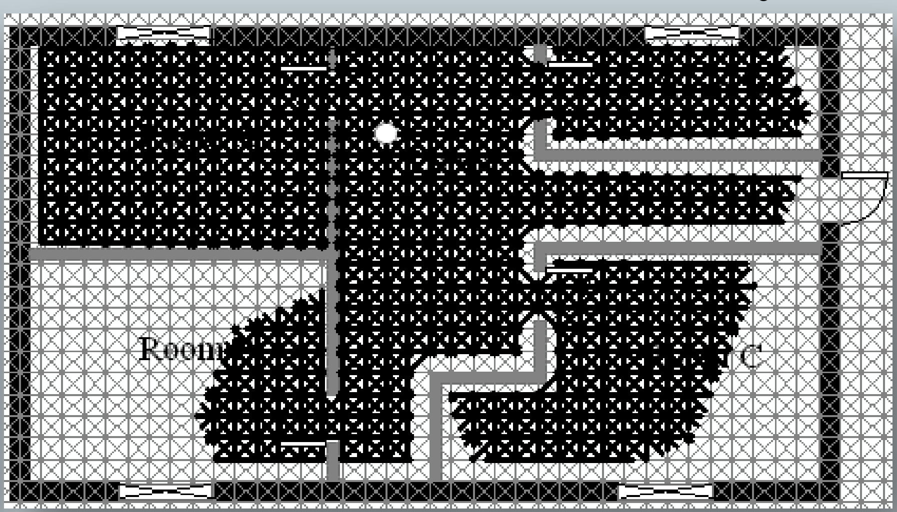
- ○ Starting point of the phenomenon

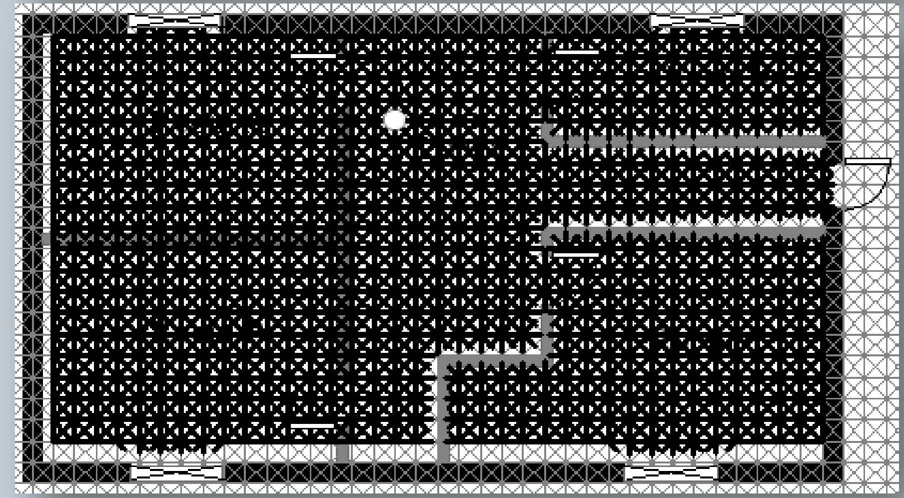
Mapping Gas Leak in an Indoor Space

$t=t_0+10T$



$t=t_0+20T$





$t=t_0+45T$

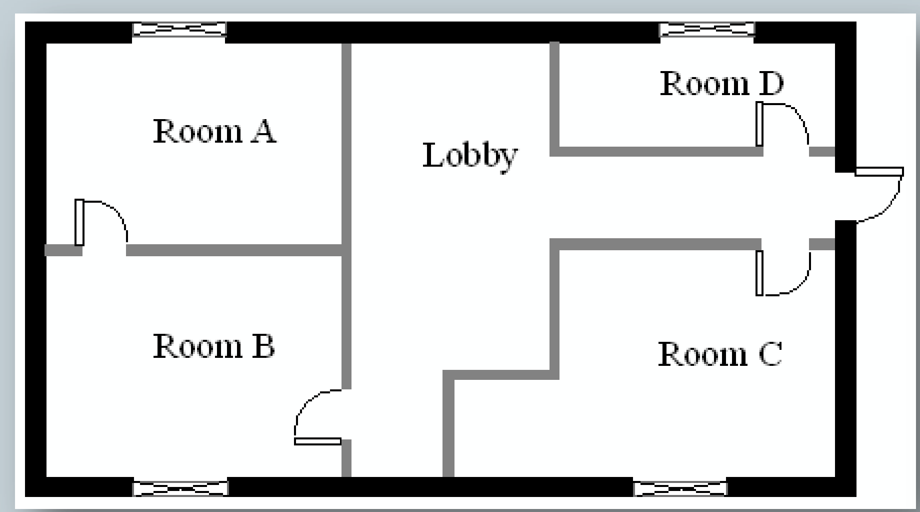
Gas leak when all doors are opened

○ Starting point of the phenomenon

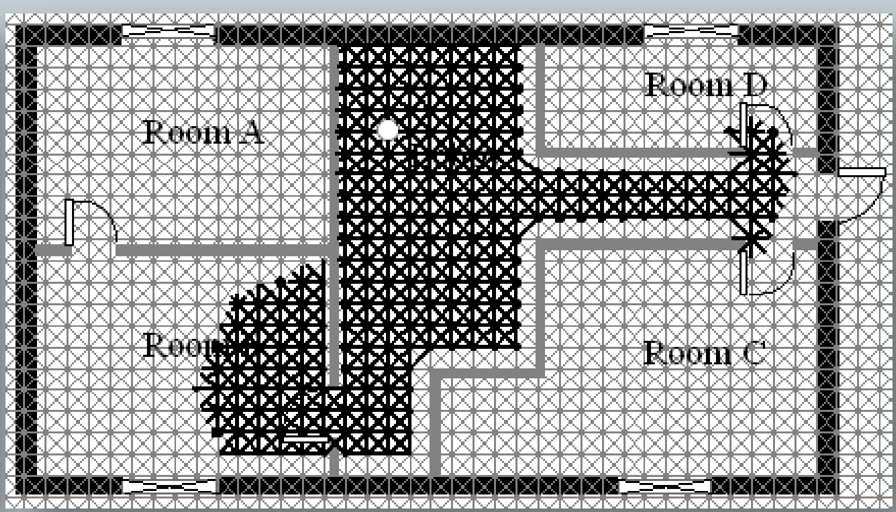
Mapping Gas Leak in an Indoor Space

- Beyond the evaluation of existing structural configurations face to phenomenon…
- … another objective can be to identify "best" structural configuration(s)

What if doors' locations are changed ?



Another configuration with all **doors opened**



Result at $t=t_0+20T$

Centrality Measures

- Similarly to space syntax studies (at structural level), various measures of the centrality (e.g. degree centrality, betweenness, closeness, eigenvector centrality) can be applied to such fine-grain indoor models

- Betweenness is a representative centrality measure applied to graphs (Bonacich, 1987)
  - Denotes the number of time a given node appears in shortest paths between the other nodes of the graph
  - The most central a node is, the most important its centrality role in the structure of the whole graph (i.e., indoor space)

$$C_B(n_a) = \sum_{a \neq j \neq i} \frac{\sigma_{ij}(n_a)}{\sigma_{ij}}$$

number of the shortest paths between nodes n_i and n_j that n_a lies on

betweenness of a node n_a

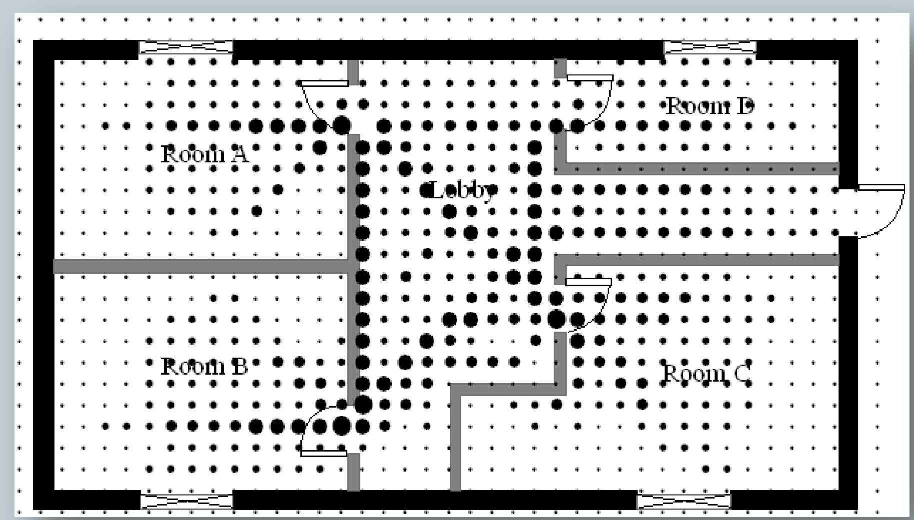
number of the shortest paths between nodes n_i and n_j

Results of Centrality Measures

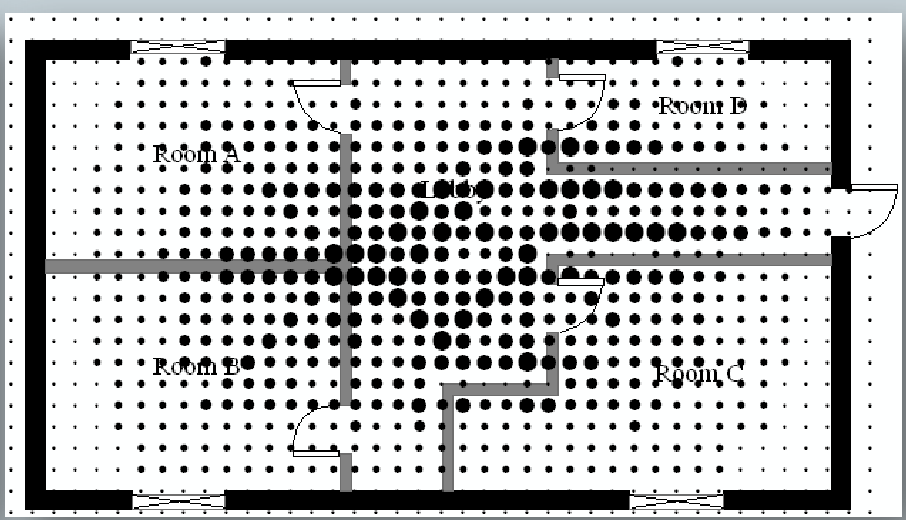
- Betweenness values are classified in five categories (black circles)

nodes with high betweenness values are located in the central area

nodes located in the lobby or around doors play a specific role in the spatial layout



All doors are opened



All doors are closed

- Interest : study the impact of different distribution layouts with respect to a given phenomenon

CONCLUSION

CONTINUOUS-BASED MODEL FOR INDOOR SPACES

Conclusion

- Built environment and indoor spaces represent a novel domain of GIS applications
- Early developments have been often successful in defining spatial representations of built environments such as structural-based models, cognitive and quantitative models
- The concept of space as considered in indoor environments deserves complementary spatial modelling approaches adapted to the specific continuous properties of built environments

Conclusion

- The proposed model is a continuous-based representation of a built environment
  - An occupancy grid is considered as the reference modelling concept
  - An interest of this approach is that the coverage of the emerging graph allows
    - A study of the spatial diffusion of a given phenomenon of interest
    - The application of structural measures that reveal some emerging structural properties of the represented space
- The approach thus keeps a continuous representation of space, while still embedding structural properties at a lower level of granularity
- Future efforts will be made to
  - Extend the modelling approach to 3D environments
  - Apply these modelling concepts to real-time positioning, tracking and navigation of pedestrian

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