Indoor cartography

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ARTICLE HISTORY

Compiled April 26, 2019

ABSTRACT

This review paper explores at a high conceptual level cartography's potential role in the emerging field of indoor mapping. It introduces an interdisciplinary literature on foundational theories, approaches, and applications of indoor maps driven by advancements in indoor positioning systems and an accompanying desire to exploit those capabilities through maps. The review concludes that cartography, with its rich heritage in the mapping arts and sciences, can make important contributions as technologies, needs, and theories converge to make sophisticated indoor mapping a reality. This paper includes discussions of issues, challenges, and prospects for indoor maps along with examples of possible new applications.

KEYWORDS

Indoor mapping, indoor cartography, 3D mapping, 3D models, standards

1. Introduction

Cartography has been defined as the "science, art, and technology of making, using, and studying maps" (Robinson, Sale, & Morrison, 1978; Rystedt et al., 2003). In turn, a map has been defined as "a depiction of all or part of the earth or other geographic phenomenon as a set of symbols and at a scale whose representative fraction is less than 1:1" (Clarke, 1995, 2003). The use of the term "other geographic phenomenon" and the limiting scale of 1:1 clearly encompasses a role within cartography for indoor mapping.

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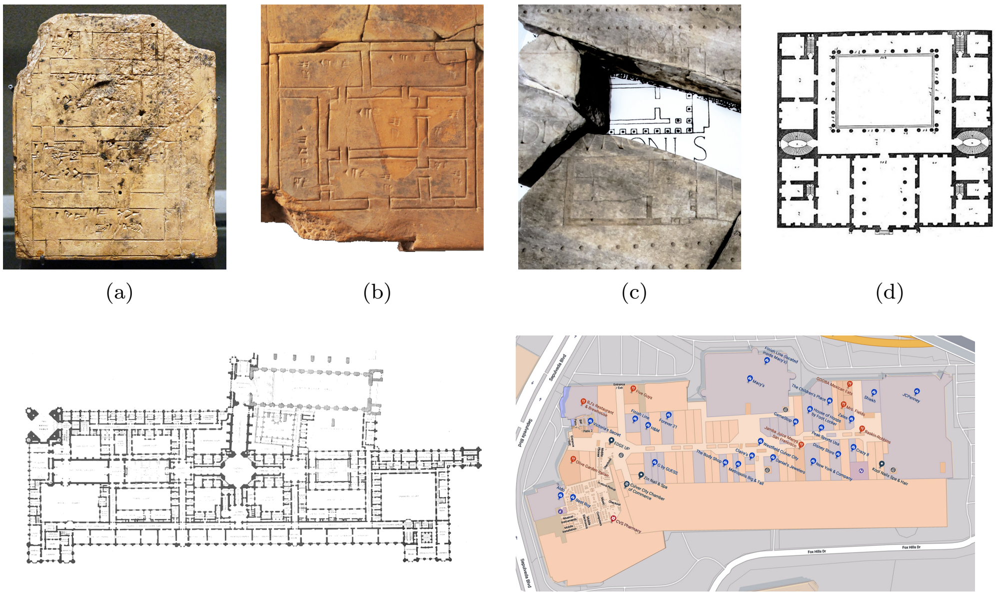
Indeed, maps of interior spaces, from floor plans to evacuation charts, have populated cartography's history for at least 5,000 years, as illustrated in Fig. 1 (Abrahami, 2016; Chen, 2018a). Indoor maps continue to provide valuable spatial information for all types of indoor spaces such as train stations, underground railway systems, airports, office buildings, and cruise ships. Many even have their own cartographic symbols, such as the "You Are Here" markers (Montello, 2010), and application-specific designs, such as for autonomous vehicle navigation (González-Baños & Latombe, 2002). From the most ancient to modern versions, nearly all of these maps have a common limitation: they take the form of two-dimensional line drawings due to the limits of 2D media (Fig. 1). However, recent advancements in remote sensing, computation, ubiquitous networking, geospatial positioning, and digital visualization now make it possible to expand indoor mapping to all three dimensions (Zlatanova & Isikdag, 2017; Zlatanova, Sithole, Nakagawa, & Zhu, 2013). The goal of this paper is to explore at a high conceptual level cartography's potential contributions to advanced digital mapping of indoor spaces as this capability matures and becomes ingrained into mainstream society.



(a) (b) (c) (d)

(e) (f)

Figure 1. Indoor maps from ancient to modern times: (a) Girsu, ca. 3000 BC; (b) Ur, ca. 2100 BC; (c) Rome, ca. 210; (d) Italy, 1570; (e) Palace of Westminster, London, ca. 1845; and (f) Westfield Culver City, Google Maps, 2018. Image credits: (a) Marie-Lan Nguyen, Wikimedia Commons, CC-BY 2.5; (b) Staatliche Museen zu Berlin–Vorderasiatisches Museum, CC BY-NC-SA 3.0 DE; (c) Sailko, CC BY-SA 3.0; (d) and (e) Wikimedia, public domain; and (f) used with permission from Google.

2. Indoor positioning systems: a catalyst for indoor mapping research

Indoor positioning system (IPS) technology stands out as perhaps the most significant catalyst for the development of advanced indoor maps, since the realization of ubiquitous navigation requires the integration of seamless indoor-outdoor positioning with seamless indoor-outdoor maps. In the outdoor world, the advent of global navigation satellite systems (GNSS) revolutionized global positioning and catalyzed the rapid development of automated outdoor mapping systems, even though digital mapping and various other forms of radio-based positioning systems already existed. However, the solid surfaces that form indoor environments—such as roofs, walls, and earth—interfere with GNSS signals, rendering GNSS-based systems ill-suited for indoor use.

While researchers have proposed numerous approaches to IPS (Mautz, 2012; L. Zhu, Yang, Wu, & Liu, 2014), none have yet emerged as the new universal "indoor GPS" offering affordability, ease-of-deployment, and high accuracy in three dimensions. A low-adoption rate of current solutions that have relatively coarse resolution has likely discouraged profit-driven companies from investing in the development of indoor maps beyond the time-tested 2D floor plan. However, the eventual adoption of a universal high-accuracy IPS will drive a growing demand for more sophisticated indoor maps that will in turn catalyze 3D indoor mapping research.

Liu, Darabi, Banerjee, and Liu (2007), Mainetti, Patrono, and Sergi (2014), Koyuncu and Yang (2010), and Hossain and Soh (2015) reviewed a host of possible IPSs to include those that use specialized equipment versus existing off-the-shelf technologies; various localization signals, such as sonar, radio, visible and non-visible light, and microwaves; and techniques that can exploit those signals, such as WiFi, infrared sensors, radio frequency identification, and Bluetooth. Despite this rich selection of options, none offers the degree of accuracy required for precise indoor mapping, say to the decimeter, along with affordability and ease-of-deployment, although very expensive high-accuracy systems do exist for specialized applications.

Nonetheless, high accuracy indoor *remote sensing* capabilities already exist (Dardari, Closas, & Djuri, 2015; Hossain & Soh, 2015) and continue to be the focus of intense research (Ali, Hur, & Park, 2019; Lashkari, Rezazadeh, Farahbakhsh, & Sandrasegaran, 2019), e.g., indoor autonomous vehicles. It appears likely that highly accurate and sophisticated indoor maps will continue to experience limited development within the confines of the research community until a universal IPS drives a widespread need and accompanying growth for those maps.

3. Exploring the cartography of indoor spaces

Since their early days, cartography and geographic information science (GISc or GIScience) have had a singular focus on outdoor topographic and digital mapping with little attention paid to the indoors. With outdoor maps, a building may be symbolized as a solid rectangle on a coarse-scale map or an outline of the footprint on a detailed map, while underground features, such as mines and transit systems, are represented only by their entrances. Move indoors, however, and the map—if it even exists at all—takes the form of a simple floor plan or cryptic blueprint, oftentimes with unknown reliability. With advancements in indoor positioning, autonomous vehicles, and miniaturized mixed reality systems calling for more sophisticated indoor maps, cartography—with its rich heritage in map making—has much to contribute to this growing field. For instance, point clouds and mesh models of indoor spaces are often incorrectly presented by non-cartographers as “maps” when they more closely resemble raw data containing minimal semantic information. Cartographic best practices can help transform this data into useful maps using symbolization, generalization, scale, and even projection (e.g., indoor-outdoor coordinate integration) in line with traditional forms of outdoor maps, e.g., physical, thematic, and topological.

Having a consistent body of concepts and terminology can help provide greater clarity and focus in the development of indoor maps. As a starting point, we define *indoor cartography* as the science, art, and technology of making and studying maps of indoor spaces, including and beyond the map’s mere use. This definition coincides with ICC’s general definition of cartography (Rystedt et al., 2003) since indoor spaces exist as artificial constructs within the continuum of the physical world, and many of the core concepts for outdoors (Kuhn, 2012) should also apply indoors. Nonetheless, the character of indoor spaces deviates substantially from outdoors in several ways, which requires taking different approaches to applying similar concepts indoors (Giudice, Walton, & Worboys, 2010; Gotlib & Marciniak, 2012; Worboys, 2011).

3.1. Defining indoors

The term “indoor” emerged in the early 18th century as a shortened form of the phrase “within-door,” originally meaning to be inside a house or building but later revised to being “situated, conducted, or used within a building or under cover” (“Indoor”, 2018). However, these definitions present an incomplete view of the indoors, since it can lead to a false dichotomy that to not be indoors implies being outdoors, when in reality ambiguous spaces exist in between. Within the GIScience community, the need to explicitly differentiate indoors from outdoors emerged in the mid- to late-2000s for supporting positioning and navigation (Anagnostopoulos, Tsetsos, Kikiras, & Hadjiefthymiades, 2005; Li, 2008). While Anagnostopoulos et al. (2005) provided an indoor ontology, Li (2008) proposed the first explicit characterization of indoors as space constrained by “architectural components, such as doors, corridors, floors, walls, and stairs,” which would later influence the development of the Indoor Geography Markup Language (IndoorGML). Table 1 summarizes various characterizations of indoor space from Li’s 2008 definition onward. Nearly all of these contain the notions of full enclosure created by physical constraints, a finite size as opposed to the unboundedness of the outdoors, and greater levels of complexity.

Characteristics that appear less universal include presence of built features, regular geometries, multi-layering, access to satellite positioning signals, digital representation techniques, and spatial referencing methodologies, some of which are illustrated in Fig. 2. While present in many indoor spaces, these non-essential characteristics may be missing in other types of indoor environments while present in some *outdoor* spaces. For instance, natural indoor spaces such as caves and tunnels lack built features and regular geometries (Fig. 2a), while outdoor environments can have a preponderance of these, such as the expansive gridded terrazzo at the U.S. Air Force Academy (Fig. 2b). Multi-layered structures also exist outdoors, such as with multi-deck highways, multi-level ramps, stadiums, and natural ledges (Figs. 2c–2e). While satellite positioning systems, e.g., GPS, will not reliably work indoors due to signal obstruction, there

Li (2008)

- Constrained by architectural components, e.g., doors, corridors, floors, walls, etc.

Jensen, Lu, and Yang (2009)

- Movements enabled and constrained by doors, rooms, and hallways

Walton and Worboys (2010)

- ~~Built space~~
- Enclosed
- Small area
- Connected via containment hierarchy
- ~~Modeled with solids or boundary rep~~
- ~~Uses different orientation methods~~

Giudice et al. (2010)

- ~~More "regular" geometries~~
- ~~Different dimensionality (3D or layered 2D)~~
- ~~Latitude & longitude not helpful~~
- Uses system of room numbers & levels
- Complicated by multi-level routing

Q. Zhu et al. (2016)

- Closed
- Narrow
- ~~Private~~
- ~~Contain obstacles and hidden objects~~
- ~~No access to GPS~~

Zlatanova and Isikdag (2017)

- Smaller
- Closed
- Constrained by walls, doors, stairs, furniture
- ~~Can be multi-layered~~
- Often contains intermediate, irregular spaces

Yan, Diakit, and Zlatanova (2018)

- Called "bounded" space, as opposed to "unbounded" (outdoors) and "semi-bounded"
- Boundaries consist of building or other components, e.g., vegetation, rocks, etc.
- Indoor space "surely has top(s) and sides [and is] enclosed completely by a top(s) and sides"

Note: Struck-through text indicates what the authors considered non-essential elements that either may not apply universally to all indoor spaces or can equally apply to outdoor spaces.

Table 1. Characteristics of indoor spaces as compared to outdoors

are also outdoor situations that prevent them from working, such as urban canyons and dense overhead foliage (Fig. 2f). Since we live in a 3D world, the limited dimensionalities of maps (2D and 2.5D for outdoors; 2D, 2.5D, and 3D for indoors) only reflect current technologies and paradigms rather than inherent physical properties. Consequently, 2D, 2.5D, and 3D approaches can work equally well both indoors and out. Finally, the use of referencing by identifiers is not exclusive to indoors nor is referencing by coordinates irrelevant when inside. Geographic identifiers such as addresses are widely used outdoors, and numerical coordinates are essential for indoor spatial referencing, since they form the basis of geocoding and machine-based positioning. While many of these non-essential qualities are important for indoors, treating them as defining features can limit the creative potential for making and using indoor maps.

3.2. Intermediate spaces

3.2.1. Prior proposals

Zhou, Zheng, Li, Li, and Shen (2012) characterized space as either indoor (inside a building), outdoor (outside of a building), or semi-outdoor based on the performance of sensors on a mobile phone. They defined semi-outdoors based not so much on


(a) (b) (c)

(d) (e) (f)

Figure 2. Examples of uncertain predictors of indoor space: (a) cave lacking built features and regular geometry; (b) highly built-up outdoor terrazzo with regular geometries; (c) outdoor multi-level highway; (d) ambiguous space inside the framework of the Eiffel Tower; (e) multi-level buildings inside a cave at Mesa Verde National Park; (f) dense foliage obstructing signals from navigation satellites. Image credits: (a), (d), and (e) Jorge Chen, CC BY-SA 3.0; (b) Liz Copan, public domain; (c) Joe Mabel, Wikimedia Commons, GFDL; and (f) Philip Halling, Wikimedia Commons, CC BY-SA 2.0.

architectural features but on a close proximity to the exterior of a building and the quality of signals from global navigation satellite systems (GNSS) or WiFi access points. For instance, they stated that an enclosed room with a large window could conceivably be considered semi-outdoors if a mobile phone could receive GNSS signals. While useful for engineering applications, classifications from this framework have no long-term stability since changes in technology will result in changes to a space's classification. Physical features offer greater stability and have far more relevance than electrical and optical signals for most indoor mapping uses.

Yan et al. (2018) defined space as "hollow (unoccupied)" areas, constrained by boundaries, where human activity takes place, classified as indoor (completely bounded), outdoor (unbounded), or semi-bounded in side- or top-bounded form, as illustrated in Fig. 3. Since their research looked only at the geometry of top-bounded spaces, they acknowledged that unanswered questions remained in terms of semantics, geometric proportionality, and side-bounded spaces. Notably, "indoor" and "outdoor" provide semantic labels to each respective space, but no such semantic descriptor exists for the intermediate space. In other words, if bounded is called *indoors*, unbounded is called *outdoors*, then what should semi-bounded space be called?

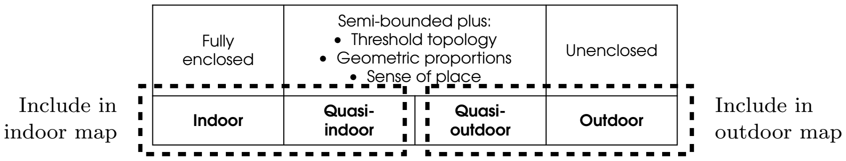
Criteria	Fully enclosed	Top- or side-bounded	Unenclosed
Classification	**Indoor**	**Semi-bounded**	**Outdoor**

Figure 3. Yan et al.'s framework for classifying space

3.2.2. Quasi spaces: a refined proposal

Clarifying the dividing line between indoors and out is vital to the development of indoor mapping. At its core, it answers the question of where the outdoor map ends and where the indoor one begins, a non-trivial task for creating automated mapping solutions that seek to seamlessly integrate outdoor and indoor maps that use vastly different coordinate reference systems. The progression from Li (2008) to Yan et al. (2018) in Table 1 shows increasingly sophisticated attempts to find this dividing line as well as greater clarity acknowledging that a simple indoor-outdoor dichotomy provides an insufficient framework.

We extend Yan et al.'s (2018) work by putting a name to their "semi-bounded" descriptor for intermediate space. Here, we use the term *quasi*, defined as something that partially resembles another, and divide intermediate space into *quasi-indoors* and *quasi-outdoors*, as shown in Fig. 4. This approach makes it possible to overcome the problem of intermediate spaces when using the indoor-outdoor dichotomy. For example, the side-enclosed quasi-indoor courtyard in Fig. 5 is an inseparable part of the surrounding building and should be included as part of the building's indoor map to provide map users with continuity in navigation. Conversely, combining side-enclosed spaces such as this one with their parent buildings can help simplify and reduce the complexity of symbols in outdoor maps.



Fully enclosed	Semi-bounded plus: • Threshold topology • Geometric proportions • Sense of place		Unenclosed
Indoor	**Quasi-indoor**	**Quasi-outdoor**	**Outdoor**

Figure 4. Proposed framework for classifying space

Three factors that can provide insights into these quasi-spaces are threshold topology, a subjective sense of place, and relative scale, as shown in Fig. 4. The idea of thresholds comes from architecture, which describes building space as a space with

Figure 5. Enclosed courtyard at the National Taiwan University Hospital. ©Jorge Chen, CC BY-SA 3.0

both physical and perceptual forms. In its physical form, thresholds consist of the "skin" of a building, that is, its walls, floors, rooftops, and other partitioning structures that isolate the environment of one space from another (Tombazis, 1996). In an indoor-outdoor context, these would be the outer walls, doors, windows, roof, etc. The outer surfaces of a threshold represent its boundaries as well as those of the neighboring spaces, so that two spaces joined by a plane-shaped threshold, such as a wall, results in three different spaces, e.g., outdoor space–to–threshold (wall)–to–indoor space. In its perceptual form, thresholds tap into human perceptions of space or what geographers commonly call *place* (Tuan, 1975, 1979). In this context, a threshold serves as a transition for changing spatial awareness or conscience between two different spaces, and it has a *liminal* quality of in-betweenness (Smith, 2001). An analogy from outdoor cartography is the ambiguous littoral zone that separates land (maps) from sea (charts).

In discussing buildings, Walton and Worboys (2010), Q. Zhu et al. (2016), and Diakit and Zlatanova (2018) used geometric size and topology to characterize different aspects of indoor space. Central to these frameworks is the size of a space relative to a human being for determining its quasi-indoor or quasi-outdoor qualities. Considering that indoor spaces can include natural environments, we can generalize this idea to that of the scale of the space relative to a human being. Further work in this area can include developing more structured approaches to defining the placedness of quasi-spaces and extending prior works on geometry to include natural scenes.

3.3. Levels of detail: Managing representational complexity

Maps reduce the complexity of the real world to something that humans or machines can more readily understand. In the digital age, interactive outdoor maps allow users to zoom in and out to get different perspectives of the outdoor environment, whether in the complex details of small areas or the simplified bird's eye view of large areas. Level of detail (LOD) describes this step-wise *process* to managing representational complexity, but no single universal approach exists for the limitless number of possible mapping applications. Rather than attempting to define an ideal LOD framework for indoors, which may unintentionally limit other approaches, our goal in this section is to provide an overview of common approaches to LOD and to review those most relevant to indoors.

3.3.1. Three prevailing LOD approaches

Domain-specific LOD approaches can be found in computer graphics; the architecture, engineering, and construction (AEC) industry; and cartography and geographic information science. In computer graphics, the goal of LOD involves optimizing the time it takes to render graphics on a computer display, accomplished by adjusting the geometric coarseness of objects, such as through polygon counts (Fig. 6a) (Luebke et al., 2003). AEC uses a similar-sounding concept called *level of development* that uses the same "LOD" acronym, which people often mistaken for level of detail. Here, we use LODt to distinguish level of development from LOD. LODt reflects the level of confidence associated with each phase of a construction project and has been formalized into five levels in architecture (100, 200, 300, 400, and 500) and six in building information modeling (BIM) (LODts 100 to 500 plus LODt 350), with 100 signifying the lowest confidence (e.g., a conceptual sketch) and 500 the state of as-built construction (Fig. 6b) (Reinhardt & Bedrick, 2016). While BIM software is more of a construction management tool than a mapping platform, LODt has significance to indoor mapping since BIM models can serve as rich data sources for map making. Therefore, having an understanding of LODt can lead to better decisions on using BIM data.

Finally, cartography and GIS use an LOD concept that relies more on abstract representation than just pure geometry, i.e., polygon counts; this approach augments the computer graphics concept of LOD with other factors such as semantics, topology, and the appearance of mapped features (Fig. 6c) (Open Geospatial Consortium, 2012; Robinson et al., 1978). We call this cartographic LOD. The wide range of uses for GIS in mapping and modeling the outdoor environment means that no universal LOD standard exists for GIS applications, although industry-backed best practices do exist, e.g., the 20 zoom levels used by Google Earth and the various industry-specific Esri data models.

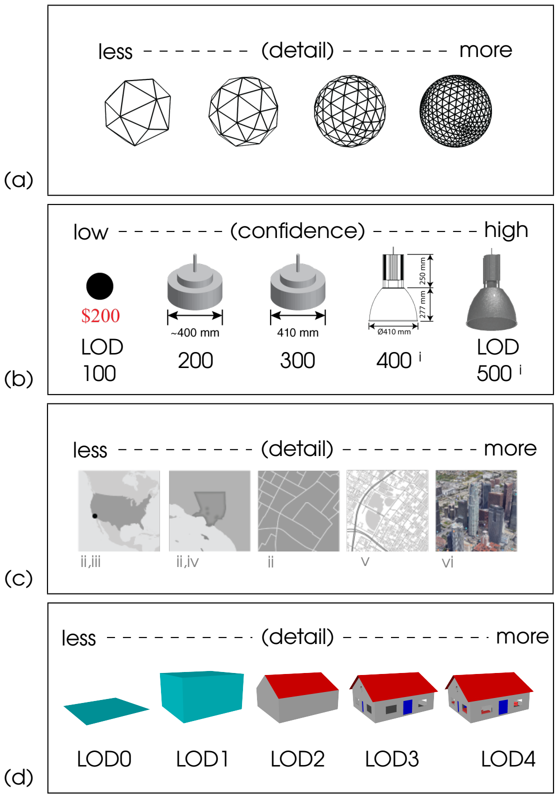


Figure 6. Different approaches to LOD: (a) computer graphics, (b) architecture, engineering, and construction, (c) cartography and GIS, and (d) CityGML[vii]. Data sources: i. Luminaires Group; ii. U.S. Census; iii. Natural Earth; iv. County of Los Angeles; v. OpenStreetMap; vi. Google; vii. Applied Computer Science at Karlsruhe Institute of Technology.

3.3.2. CityGML and the concept of indoor LODs

Within the GIS domain, city modeling comes closest to providing an LOD framework for indoor cartography, with the Open Geospatial Consortium's (2012) City Geography Markup Language (CityGML) serving as the prevailing international standard. CityGML has thirteen modules, each with five progressively detailed LODs, numbered from LOD0 to LOD4 for capturing different details of a city. One of these is the Building Module, which uses LOD to discretize both the semantics of building features (i.e., including or omitting elements such as the roof or openings) alongside geometric generalization (e.g., representing the shape of a building as a cuboid versus its exact form). Of these, only LOD4 supports the building interior, which remains empty from LOD0 to LOD3. This effectively means no LOD capability exists for indoors in the current CityGML version 2 framework (Fig. 6d).

Several proposals have been made to expand CityGML's indoor LODs (Billen, LaPlanche, Zlatanova, & Emgard, 2008; Hagedorn, Trapp, Glander, & Döllner, 2009; Jung, Kang, & Lee, 2016; Kang & Lee, 2014; Kemec, Zlatanova, & Duzgun, 2012; Löwner, Gröger, Benner, Biljecki, & Nagel, 2016). Notably, Benner, Geiger, Gröger, Häfele, and Löwner (2013) and Löwner, Benner, Gröger, and Häfele (2013) proposed completely decoupling semantics from geometry for indoor features, which provides an intriguing starting point for developing a general concept of indoor LODs. Their proposals eventually re-coupled semantics and geometry to work within the limits of CityGML, as reflected in version 3.0 of the standard due for release in 2019 (Kolbe & Kutzner, 2018).

Chen (2018b) further developed the theoretical concepts of indoor LOD where Benner et al. (2013) and Löwner et al. (2013) left off. Rather than proposing specific rules for indoor LODs, Chen incorporated the prior work mentioned above and proposed the development of a generic semantics-based *process* that could accommodate application specific implementations of LODs for generalizations in semantics, geometry, topology, etc. Under this framework, illustrated in Fig. 7, semantics anchors the indoor map and defines what elements to include or omit at a specific LOD. These semantic LODs can be discretized in any coherent manner, such as having LODs that control space subdivisions or the presence of building structures and furniture. These abstract semantic objects can then be expressed in different forms, each having its own independent set of LODs supporting application-specific designs.

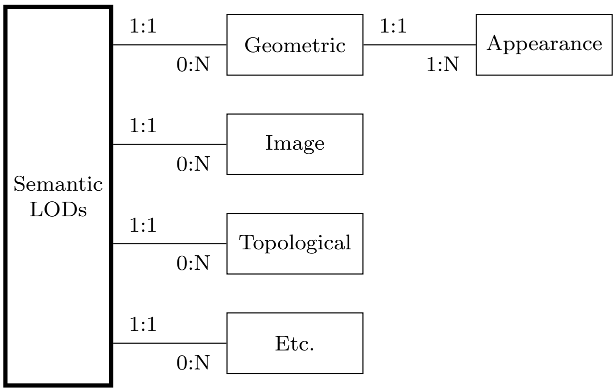


Figure 7. Proposed generic framework for indoor LODs

3.4. Location referencing: Describing the "where" of indoors

Everything in the physical world inherently has a location value, that is, everywhere exists somewhere. These values often take the form of either geographic identifiers or coordinates, which respectively use place names or numerical measurements. Place names represent the most natural form of describing location and can include such things as city names, landmark names, and street addresses; for indoors, this often means building number, floor number, and room number. Gazetteers store and catalog place names to mitigate redundancy, one of the shortcomings of geographic identifiers. While not as intuitive, coordinates use measurements from a datum—i.e., an arbitrary starting point and orientation—to provide an exact and unambiguous description of location in space, and when formalized, the measurement system and datum together form a coordinate reference system (CRS).

For horizontal referencing, geographic and grid coordinates make up the two primary measurement systems, with the former *typically* using angular latitude and longitude values based on a 3D representation of Earth and the latter using linear eastings and northings based on a flat plane. Notably, geographic coordinates can be based on astronomic, geodetic, or geocentric angles, depending on whether they are measured relative to the stars, near an ellipsoid's center from a vector normal to its surface, or exactly at the ellipsoid's center (Van Sickle, 2010). In modern usage, most geographic coordinates take the geodetic form due to the proliferation of satellite navigation; however, astronomic coordinates dominated before the age of satellites, and GPS natively uses geocentric cartesian coordinates, i.e., earth-centered earth-fixed (ECEF), that are later transformed into geodetic coordinates. At a regional level, the planet's curved surface can be projected onto a flat plane within certain error tolerances; regular grids overlayed on the projection make it possible to replace longitude and latitude values with more intuitive linear measurements (e.g., meters and feet), which form the basis of grid coordinates. Vertical referencing uses linear *height* measurements relative to a vertical datum, typically the ellipsoid, mean sea level (MSL), or a gravity-based proxy for MSL called the geoid. Geoid-based heights are often called orthometric heights or elevations as opposed to ellipsoid heights, natively used in GNSS and often mistaken for elevations.

International standards for specifying coordinate reference systems include ISO 19111 *Geographic information—Spatial referencing by coordinates* and the OGC Abstract Specification *Topic 2: Spatial referencing by coordinates* (International Organization for Standardization, 2002; Open Geospatial Consortium, 2010), while a number of databases exist for collecting and disseminating CRSs, with the most widely known being the EPSG Geodetic Parameter Dataset containing over 5,000 CRSs worldwide. An international standard also exists for specifying geographic identifiers, ISO 19112 (International Organization for Standardization, 2003) as well as an OGC best practices document. However, no universal gazetteer repository exists but instead there are several local repositories that reflect local knowledge (Hill, 2006).

Since spatial measurements transcend physical boundaries, spatial referencing methods used for the outdoors can also be used indoors. However, the multitude of approaches poses many challenges for indoor cartography due to a need for lower tolerance of errors, an expectation to seamlessly integrate indoor CRSs with outdoor CRSs, and more common use of identifiers. The dynamic nature of Earth's geology means that all coordinate references exist relative to an arbitrary moving datum, whether that is Earth's rotational axis, the magnetic poles, the principal point for a prime meridian, or a shifting gravity field influenced by changing geology and long-term changes in groundwater. As a result, CRSs vary not only by system (e.g., WGS 84, NAD 83, etc.) but also by epoch or time. The slow movement of Earth may not make much difference for large area mapping but for indoor spaces, errors of 1 m due to poor transformations can mean the difference of being indoors or out. Indoor-outdoor CRS integration appears simple at first but is actually a complex process due to these considerations. Many approaches have been proposed to address this problem but oftentimes they involve one-to-one transformations between specific CRSs; an alternative and more robust approach would be to focus on the process instead of a single implementation. Chen (2018c) proposed such a process that uses local grids for buildings but leverages existing transformations built into widely available software, as illustrated in Fig. 8.

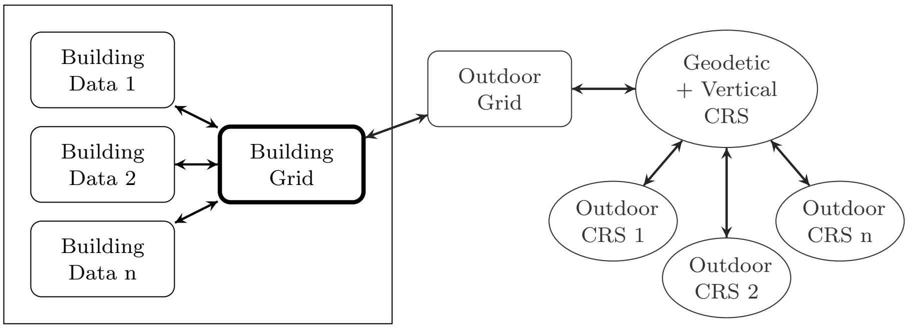


Figure 8. Building grid in the context of other coordinate reference systems

3.5. What is a map?: Distinguishing maps from models

In physics, the classical model of gravitational forces takes the form of theories and equations, while in geographic information systems, models of the physical environment take the form of structured data. These two examples show that the specific meaning of the term *model* varies by context. In the broadest sense, however, a model simply describes a representation of something in the real world created for human or machine understanding (Koperski, 2018; Stanford Encyclopedia of Philosophy, 2012). Maps thus represent a form of models under this broad definition. Nonetheless, the terms *mapping* and *modeling* are sometimes used interchangeably, implying identical meaning, while at other times they are juxtaposed to imply different meanings. This inconsistency makes it difficult to identify key characteristics of maps and models and appreciate their relative strengths and weaknesses.

Here we attempt to address this ambiguity by examining the meaning of cartographic maps in the context of both general scientific modeling and common usage in the cartography and AEC domains. Figure 9 presents two frameworks for scientific modeling along with an analogy from linguistics. On the left end of the spectrum reside literal representations of reality, which Koperski (2018) called *replicas* and the Stanford Encyclopedia of Philosophy (2012) called *raw data*, while on the right end reside figurative representations such as metaphors in literature, which Koperski and Stanford called *analogue* or *analogical* models. The Stanford Encyclopedia of Philosophy categorized raw and minimally processed data as *data models* while calling more abstract (i.e., figurative) representations *phenomena models*.

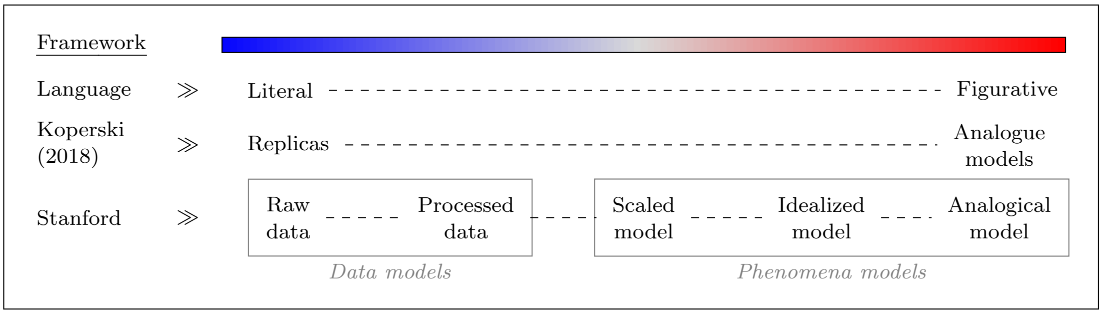
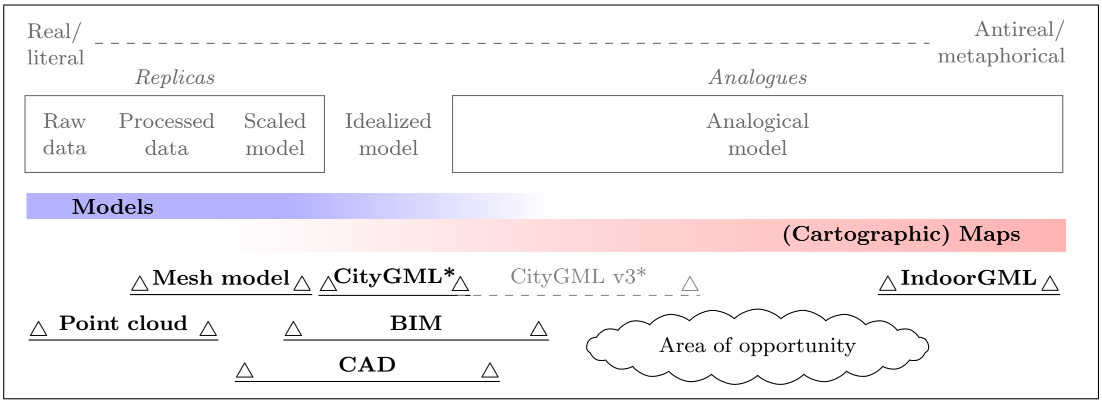


Figure 9. Levels of abstractions for various indoor representations

Cartography and GIScience typically focus on the representation, analysis, and exploitation of geographic phenomena, with Goodchild (2010) noting that representation had historically presented the greatest research challenge in GIScience. Under the Stanford framework, representation falls under the modeling of phenomena, with cartographic maps resting further to the right near analogical models. Rearranging Fig. 9 to account for the representation of *indoor space* results in Fig. 10, which shows an expanded section for analogical models, prevailing indoor data and modeling approaches, and two graduated scale bars differentiating maps from “models.” In the context of indoor cartography, we interpret *indoor models* as literal representations of the environment with little to no semantic information and *indoor maps* as abstracted representations rich in semantics, noting that this perspective focuses more on abstraction than data structure. Under this framework, raw measurements such as point clouds would fall well within the models classification while highly abstract topological representations such as IndoorGML would fall under maps. In between rest all other representations that have elements of both. Notably, this framework puts BIM and CityGML into perspective showing that a conventional BIM-GIS framework provides a false dichotomy for indoor mapping, when other possibilities exist for representing and using indoor spatial information. We hope this paper will raise awareness of the need to develop best practices and principles for creating and using indoor cartographic products that leverage BIM, GIS, and other data sources.



* Indoor LOD(s) only

Figure 10. Current approaches to representing indoor spaces in the context of mapping and modeling

4. Present forms of indoor maps

Indoor cartography both overlaps with and is separate from other disciplines that model interior spaces. Aside from the very basic cartographic indoor map exemplified by Fig. 1f, three other existing forms of indoor representation include computer aided design (CAD) drawings, 3D BIM models, and environmental scans produced by robots and remote sensing systems, as also illustrated in Fig. 11. Architects, engineers, and construction professionals use CAD and BIM to document and coordinate the design and construction of buildings, while remote sensing systems are widely used for producing indoor measurements. The latter notably takes the form of point clouds and derived mesh models produced using a variety of indoor remote sensing techniques, such as terrestrial laser scanners, structured light, and simultaneous localization and mapping (SLAM) (Dissanayake, Newman, Clark, Durrant-Whyte, & Csorba, 2001; Thrun, Burgard, & Fox, 2005). However, none taps into the full potential of cartographic mapping.

Remote sensing can produce visually stunning point clouds and mesh models, but they provide literal “readings” of the environment that can be too complex to analyze and offer little support for abstract symbolization. While CAD and BIM provide

Figure 11. Examples of present forms of indoor representation: (a) CAD, (b) BIM, (c) point cloud, and (d) textured mesh. Image credits: (a) public domain, (b) Autodesk, and (c) and (d) Jorge Chen, CC BY-SA 3.0.

greater support for symbolization (Chen & Clarke, 2017; Petrie, 2016), their niche focus on building construction ends up working against sound cartographic principles due to excessive detail, limited geometric and semantic flexibility, no support for levels of detail (LODs), and with BIM, unwieldy data sizes. If the main focus of cartographic mapping is to promote spatial understanding, then point clouds and meshed models hardly qualify as maps while CAD and BIM can be seen as primitive or proto-maps. Lacking other options, though, most indoor map users accept and use these sub-optimal approaches, especially BIM, to perform activities such as 3D heat transfer modeling, inventory management, and navigation planning.

4.1. Emerging forms of indoor maps

Recent interest in mapping the built environment has led to a growing number of GIS-based solutions for indoor spaces, with each solution tailored to meet specific application needs. On the one hand are open standards developed to encourage indoor data generation and sharing while on the other hand are proprietary formats used by commercial firms for generating revenue. While none of these solutions provide a comprehensive framework for indoor mapping, they do demonstrate the difficulty of mapping in full 3D and touch on important issues of cartography.

4.1.1. Open formats

Four major open standards relevant to indoor mapping include City Geography Markup Language (CityGML), Indoor Geography Markup Language (IndoorGML), OpenStreetMap (OSM), and the Facilities Information Spatial Data Model (FISDM). CityGML is an international Open Geospatial Consortium (OGC) standard that provides a modeling framework for urban environments and represents buildings through five progressively finer levels of detail from LOD0 to LOD4, with LODs 0 to 3 providing abstractions of building exteriors and LOD4 adding interior features to LOD3 (Open Geospatial Consortium, 2012). IndoorGML is another OGC standard that complements CityGML and BIM by providing a compatible framework for indoor navigation using topologically connected cells, i.e., occupied and unoccupied "spaces" (Open Geospatial Consortium, 2018). Both CityGML and IndoorGML are limited by CityGML's single indoor LOD4; however, the upcoming CityGML version 3 will have four indoor LODs(Kolbe & Kutzner, 2018), which may eventually lead to multi-LOD representations in IndoorGML.

OSM was originally designed as a 2D web-based map for crowdsourcing outdoor features but later included provisions for basic indoor mapping in layered 2D form (Goetz & Zipf, 2011), with on-going development of 3D exteriors and interiors (Knoth, Mittlboeck, & Vockner, 2017; Wang & Zipf, 2017). While less feature-rich than CityGML and IndoorGML, OSM provides a valuable proving ground for testing the feasibility of indoor volunteered geographic information (VGI) (Goodchild, 2007). If Google's abandoned experiment with using SketchUp to crowdsource Google Earth provides any indication (McClendon, 2012), the future of indoor VGI may involve a greater amount of crowdsourcing data rather than mapped features, especially as automated indoor feature extraction algorithms improve. Finally, FISDM is an indoor data aggregation framework developed by GIS software maker Esri and its partners to consolidate CAD, BIM, CityGML, and other indoor formats into a single indoor mapping platform built around Esri's ArcGIS software. While the software itself is proprietary, the framework is open source and is significant in the wide adoption and use of ArcGIS. However, Esri has also recently released its own ArcGIS Indoors platform that appears to compete with FISDM (Esri, 2018).

4.1.2. Proprietary formats

Commercial enterprises stand to benefit immensely from the monetization of indoor location based services (LBS), which has a forecast compound annual growth rate of roughly 37% from 2014 to 2025, translating to a market size of nearly US$18 billion by 2025 (Grand View Research, 2018; Malabocchia & Napolitano, 2014). This lucrative market potential has triggered a race to develop the next generation of indoor maps, which will serve as the backbone of this future indoor spatial infrastructure. While most indoor mapping companies continue to rely on the time-tested 2D floor plan as shown in Table 2, several have also taken other innovative approaches by using panoramic images—often supplemented with range data; mixed reality (MR); and true cartographic 3D maps with semantics and abstract symbolism, e.g., WRLD3D (www.wrld3d.com).

4.2. Future prospects

These yet-to-be-seen future maps will greatly expand the reach of mapping applications and drive a demand for new theories and definitions; exploit new measurement technologies that provide extraordinary levels of detail, coverage, and accuracy; and confront challenges and prospects that will drive a new generation of cartographic research (Clarke, Johnson, & Trainor, 2019). Just as the USGS took 114 years to map and inventory the United States outdoors, might it be possible to map the entire inte-

	Mapping approach						
	Model based				Image based		Mixed reality
Company[a]	2D	2.5D[b]	3D mesh	3D map	Pano[c]	Range	AR, VR, etc.
Aisle411	●	—	—	—	—	—	●
Apple	●	—	—	—	—	—	—
Esri	●	●	—	—	—	—	—
Google	●	—	—	—	●	—	—
Here	●	—	—	—	—	—	—
indoo.rs	●	—	—	—	—	—	—
IndoorAtlas	●	—	—	—	—	—	—
Indoor Reality	●	—	—	—	●	●	—
Matterport	●	—	●	—	●	●	●
MazeMap	●	—	—	—	—	—	—
TIMMS	●	—	●	●	●	●	—
WRLD	—	●	—	●	—	—	●

[a] Companies listed in alphabetical order; [b] 2.5D–vertical extrusion from 2D; [c] Panoramic images
Note: This list reflects only interactive online maps and excludes experimental prototypes and export formats. For instance, Indoor Reality can export data as 3D Autodesk Revit BIM models but does not offer a 3D mapping service.

Table 2. Indoor mapping approaches used by a selection of online services as of 2018

rior space of the U.S. building stock (Goodchild, 2011)? And if it were possible, would it be desirable given the nation's privacy and ownership laws and security constraints? What are the intellectual and scientific challenges of an indoor cartography, and how might they best be addressed? And lastly, what new capabilities, perhaps even entire industries and markets, might indoor cartography introduce?

5. Applications of indoor maps

The number of potential applications for indoor maps, both 2D and 3D, is abundant and limited only by the imagination, as illustrated in Table 3. There is little doubt that navigation and guidance will lead the initial advance of indoor cartography, but this is merely a starting point for the plethora of possible practical and scientific applications. Just as outdoor location based services (LBS) introduced a new application "layer" for marketing and commerce, spatial information about the indoor world—where people spend the majority of their lives (Klepeis et al., 2001; Roberts, 2016)—will present many other new value-added layers involving both the push (e.g., notifying indoor pedestrians of optimal routes) and pull of spatially-enabled information (e.g., providing information about available meeting rooms). A growing list of potential applications can make it difficult to see developments at the strategic level. To help provide a more manageable overview of these applications, we have grouped indoor applications into three broad categories of indoor spatial understanding, automation, and mediated reality, recognizing that some overlap may exist for certain applications. Spatial understanding applications will lead initial development of indoor cartography since they can draw from an existing base of cartographic and GIScience knowledge. A growing body of indoor maps will then open the way for other applications in the areas of automation and mediated reality.

Indoor spatial understanding	**Automation**	**Mediated reality**
indoor navigation & guidance	elder care & monitoring	augmented disaster response
space planning	autonomous wheelchairs	law enforcement
administration & taxation	robot navigation	anti-terrorism
resource management	facility sensing & monitoring	disaster simulation & training
noise studies	smart buildings & IoT	construction visualization
energy & HVAC studies		gamification
foot traffic analysis		
emergency response		
mining of urban metals		

Table 3. Potential uses of indoor maps

6. Challenges and future prospects

Cartography has only recently begun to move beyond the 2D floor plan for interior space mapping, a design dating back thousands of years. In this review we have shown that a convergence of technologies, standards, needs, and theory is taking place that will make advanced 3D indoor maps a reality, wherein cartography has an opportunity to influence its development. LiDAR and other interior space mapping technologies can now provide the means to expand the amount of digitally mapped space, moving from limited experimental data sets (Khoshelham, Díaz-Vilariño, Peter, Kang, & Acharya, 2017) and ad hoc research projects toward a more uniform, interdisciplinary, and reusable interior space data infrastructure for operational use. Such map "collections" in the traditional sense could have metadata, standard file formats, and a web-based distribution system that would be of great use to society. Whether the maps come from data capture from existing plans and blueprints, from systematic conversion from CADD files or LiDAR scans, or from volunteered citizen science data, there is a distinct opportunity to have a national indoor map, of at least public places, for use by indoor positioning systems as they reach operational levels of accuracy and precision.

Future applications of indoor cartographic maps are limited only by the imagination. These can include an automatically guided wheelchair that takes its user to indoor locations based on spoken room numbers; a visor-projected guidance system could give routing information to firefighters in smoke-filled rooms to guide them to sensors detecting live victims; and a cell phone app that guides a job candidate not just to the right building, but to the room being used for interviews. Analytically there are even more possibilities: shortest path routes across a campus that exploit walking through buildings on cold or wet days; automatically closing off sections of buildings that have hazardous zones, for example chemical storage; and determining what structural changes can be made at least expense to improve energy efficiency, reduce pedestrian confusion, or minimize walk-time.

Realizing this future vision of indoor maps will require much needed research. We have briefly touched on broad ideas in positioning systems, theory, standards, and applications for exploiting indoor spatial information, but an urgent need exists to find ways to process the vast amounts of indoor data that will eventually be generated. How can we convert this flood of data into compact and meaningful maps, useable across spatial scales and integrated with outdoor maps and their different coordinate reference systems? Should we devise a national system for the creation, contribution, maintenance, discovery, and dissemination of indoor maps? If so, how should we go about doing it while protecting the constitutional protections of house and home as embodied in the U.S. Bill of Rights? Just as the internet, the world wide web, and GNSS have revolutionized outdoor cartography, advancements in indoor cartography promise to also revolutionize the way we understand and relate to the space we spend 80% of our lives occupying.

Funding

This research was funded by the National Geospatial-Intelligence Agency's Academic Research Program (Award No. HM0476-17-1-2002, Project Title: Automated Level of Detail and Feature Extraction for 3D Indoor Mapping and Modeling). Approved for

public release, XX-XXX. All unattributed graphics and images were produced by the first author.

References

Abrahami, P. (2016, March 11). *Les dessins de bâtiment dans la documentation cunéiforme de Mésopotamie* [Blog post]. Retrieved from https://archeorient.hypotheses.org/5680/.

Ali, M. U., Hur, S., & Park, Y. (2019, January). Wi-Fi-based effortless indoor positioning system using IoT sensors. *Sensors*, *19*(7), 1496. doi:

Anagnostopoulos, C., Tsetsos, V., Kikiras, P., & Hadjiefthymiades, S. P. (2005). OntoNav: a semantic indoor navigation system. In W. Mansoor, M. Khedr, D. Benslimane, Z. Maamar, M. Hauswirth, & K. Aberer (Eds.), *Proceedings of the first international workshop on managing context information in mobile and pervasive environments.*

Benner, J., Geiger, A., Gröger, G., Häfele, K.-H., & Löwner, M.-O. (2013). Enhanced LOD concepts for virtual 3D city models. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II-2/W1*, 51–61. doi:

Billen, R., LaPlanche, F., Zlatanova, S., & Emgard, L. (2008). Vers la création d'un métamodèle générique de l'information spatiale 3D urbaine. *Revue XYZ*(114), 37–42.

Chen, J. (2018a). *Automated indoor mapping with point clouds* (Ph.D.). University of California, Santa Barbara, Santa Barbara, California.

Chen, J. (2018b). Defining semantic levels of detail for indoor maps. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-4/W7*, 27–34. doi:

Chen, J. (2018c, January). Grid referencing of buildings. In P. Kiefer, H. Huang, N. Van de Weghe, & M. Raubal (Eds.), *Adjunct proceedings of the 14th Conference on Location Based Services.* Zurich: ETH Zurich.

Chen, J., & Clarke, K. C. (2017, June). Modeling standards and file formats for indoor mapping. In L. Ragia, J. G. Rocha, & R. Laurini (Eds.), *Proceedings of the 3rd International Conference on Geographical Information Systems Theory, Applications and Management* (Vol. 1, pp. 268–275). Setúbal: SciTePress. doi:

Clarke, K. C. (1995). *Analytical and Computer Cartography* (2nd ed.). Englewood Cliffs, NJ: Prentice Hall.

Clarke, K. C. (2003). *Getting Started with Geographic Information Systems.* Upper Saddle River, NJ: Pearson Education.

Clarke, K. C., Johnson, J. M., & Trainor, T. (2019). Contemporary American cartographic research: a review and prospective. *Cartography and Geographic Information Science*, *46*(3), 196–209.

Dardari, D., Closas, P., & Djuri, P. M. (2015, April). Indoor tracking: theory, methods, and technologies. *IEEE Transactions on Vehicular Technology*, *64*(4), 1263–1278. doi:

Diakit, A. A., & Zlatanova, S. (2018, February). Spatial subdivision of complex indoor environments for 3D indoor navigation. *International Journal of Geographical Information Science*, *32*(2), 213–235. doi:

Dissanayake, M. W. M. G., Newman, P., Clark, S., Durrant-Whyte, H. F., & Csorba, M. (2001, June). A solution to the simultaneous localization and map building (SLAM) problem. *IEEE Transactions on Robotics and Automation*, *17*(3), 229–241. doi:

Esri. (2018, July 9). *Esri announces new indoor mapping product.* Retrieved from https://www.esri.com/esri-news/releases/18-3qtr/esri-announces-new-indoor-mapping-product.

Giudice, N. A., Walton, L. A., & Worboys, M. (2010). The informatics of indoor and outdoor space: a research agenda. In S. Winter, C. S. Jensen, & K.-J. Li (Eds.), *Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 47–53). New York, NY: ACM. doi:

Goetz, M., & Zipf, A. (2011, September). Extending OpenStreetMap to indoor environments: bringing volunteered geographic information to the next level. In S. Zlatanova, H. Ledoux, E. M. Fendel, & M. Rumor (Eds.), *Urban and Regional Data Management: Proceedings of the Urban Data Management Society Symposium, 2011* (pp. 51–61). Leiden: CRC Press. doi:

González-Baños, H. H., & Latombe, J.-C. (2002). Navigation strategies for exploring indoor environments. *The International Journal of Robotics Research*, *21*(10-11), 829–848. doi:

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, *69*(4), 211–221. doi:

Goodchild, M. F. (2010, July). Twenty years of progress: GIScience in 2010. *Journal of Spatial Information Science*(1), 3–20. doi:

Goodchild, M. F. (2011, February). *Esri ArcWatch February 2011 - Looking forward: five thoughts on the future of GIS.* Retrieved from http://www.esri.com/news/arcwatch/0211/future-of-gis.html.

Gotlib, D., & Marciniak, J. (2012). Cartographical aspects in the design of indoor navigation systems. *Annual of Navigation*, *19*(1), 35–48. doi:

Grand View Research. (2018, September). *Report summary: Indoor Location-based Services (LBS) Market Analysis Report By Product, By Technology (RFID and NFC, Wi-Fi/WLAN and BT/BLE), By Application (Tracking, Proximity, Navigation), By End Use, And Segment Forecasts, 2018 - 2025* (Tech. Rep. No. GVR-2-68038-448-2). Grand View Research. Retrieved from https://www.grandviewresearch.com/industry-analysis/indoor-lbs-market.

Hagedorn, B., Trapp, M., Glander, T., & Döllner, J. (2009, May). Towards an indoor level-of-detail model for route visualization. In *Proceedings of the 2009 Tenth International Conference on Mobile Data Management: Systems, Services and Middleware* (pp. 692–697). Los Alamitos, CA: IEEE. doi:

Hill, L. L. (2006). *Georeferencing: the geographic associations of information.* Cambridge, Mass: MIT Press.

Hossain, A. K. M. M., & Soh, W.-S. (2015, July). A survey of calibration-free indoor positioning systems. *Computer Communications*, *66*, 1–13. doi:

Indoor. (2018). In *Oxford Living Dictionaries.* Oxford University Press. Retrieved from https://en.oxforddictionaries.com/definition/us/indoor.

International Organization for Standardization. (2002). *Geographic information – Spatial referencing by coordinates (ISO 19111)* (Tech. Rep. No. ISO/FDIS 19111:2002(E)).

International Organization for Standardization. (2003). *Geographic information – Spatial referencing by geographic identifiers (ISO 19112)* (Tech. Rep. No. ISO/FDIS 19112:2003(E)).

Jensen, C. S., Lu, H., & Yang, B. (2009). Indexing the trajectories of moving objects in symbolic indoor space. In N. Mamoulis, T. Seidl, T. B. Pedersen, K. Torp, & I. Assent (Eds.), *Advances in Spatial and Temporal Databases* (pp. 208–227). Berlin: Springer.

Jung, H.-J., Kang, H., & Lee, J. (2016, May). The concepts of level of detail in 3D indoor models. In *FIG Working Week 2016.*

Kang, H.-Y., & Lee, J. (2014). A study on the LOD (level of detail) model for applications based on indoor space data. *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, *32*(2), 143–151. doi:

Kemec, S., Zlatanova, S., & Duzgun, S. (2012, June). A new LoD definition hierarchy for 3D city models used for natural disaster risk communication tool. In T. Bandrova, M. Konecny, & G. Zhelezov (Eds.), (Vol. 2, pp. 95–103). Sofia: Bulgarian Cartographic Association.

Khoshelham, K., Díaz-Vilariño, L., Peter, M., Kang, Z., & Acharya, D. (2017, September). The ISPRS benchmark on indoor modelling. *International Archives of the Photogrammetry,* *Remote Sensing and Spatial Information Sciences*, *XLII-2/W7*, 367–372. doi:

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., ... Engelmann, W. H. (2001, July). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science and Environmental Epidemiology*, *11*(3), 231–252. doi:

Knoth, L., Mittlboeck, M., & Vockner, B. (2017). 3D building maps for everyone–mapping buildings using VGI. In *Societal Geo-innovation* (pp. 77–91). Berlin: Springer.

Kolbe, T. H., & Kutzner, T. (2018, January). *Notes on the CityGML 3.0 conceptual model.* Retrieved from https://github.com/opengeospatial/CityGML-3.0. Open Geospatial Consortium.

Koperski, J. (2018). *Models.* Retrieved from https://www.iep.utm.edu/models/.

Koyuncu, H., & Yang, S. H. (2010). A survey of indoor positioning and object locating systems. *International Journal of Computer Science and Network Security*, *10*(5), 121–128.

Kuhn, W. (2012). Core concepts of spatial information for transdisciplinary research. *International Journal of Geographical Information Science*, *26*(12), 2267–2276. doi:

Lashkari, B., Rezazadeh, J., Farahbakhsh, R., & Sandrasegaran, K. (2019, April). Crowdsourcing and sensing for indoor localization in IoT: A review. *IEEE Sensors Journal*, *19*(7), 2408–2434. doi:

Li, K.-J. (2008). Indoor space: a new notion of space. In M. Bertolotto, C. Ray, & X. Li (Eds.), *Web and Wireless Geographical Information Systems* (pp. 1–3). Berlin: Springer.

Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007, November). Survey of wireless indoor positioning techniques and systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *37*(6), 1067–1080. doi:

Löwner, M.-O., Benner, J., Gröger, G., & Häfele, K.-H. (2013). New concepts for structuring 3D city models – an extended level of detail concept for CityGML buildings. In B. Murgante et al. (Eds.), *Computational Science and Its Applications – ICCSA 2013* (Vol. 7973, pp. 466–480). Berlin: Springer.

Löwner, M.-O., Gröger, G., Benner, J., Biljecki, F., & Nagel, C. (2016). Proposal for a new LOD and multi-representation concept for CityGML. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-2/W1*, 3–12. doi:

Luebke, D., Reddy, M., Cohen, J. D., Varshney, A., Watson, B., & Huebner, R. (Eds.). (2003). *Level of Detail for 3D Graphics.* San Francisco, CA: Morgan Kaufmann. doi:

Mainetti, L., Patrono, L., & Sergi, I. (2014, September). A survey on indoor positioning systems. In M. Sarie & P. Solie (Eds.), *2014 22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM)* (pp. 111–120). Split: University of Split. doi:

Malabocchia, F., & Napolitano, S. (2014, June). Emerging business models in innovation ecosystems: the case of indoor location based services. In *WTC 2014; World Telecommunications Congress 2014* (pp. 1–6). Berlin: VDE Verlag GmbH.

Mautz, R. (2012). *Indoor positioning technologies* (Habilitation Thesis). ETH Zurich, Zurich, Switzerland.

McClendon, B. (2012). *The never-ending quest for the perfect map.* Retrieved from https://googleblog.blogspot.com/2012/06/never-ending-quest-for-perfect-map.html.

Montello, D. R. (2010). You are where? The function and frustration of you-are-here (YAH) maps. *Spatial Cognition & Computation*, *10*(2-3), 94–104. doi:

Open Geospatial Consortium. (2010). *Topic 2: Spatial referencing by coordinates* (Tech. Rep. No. OGC 08-015r2).

Open Geospatial Consortium. (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard* (Tech. Rep. Nos. OGC 12-019, version 2.0.0).

Open Geospatial Consortium. (2018, 9). *OGC IndoorGML–with Corrigendum* (Tech. Rep. Nos. OGC 14-005r4, version 1.0.3).

Petrie, R. (2016, March). *buildingSMART Data Dictionary Strategic Overview.* Retrieved from https://buildingsmart.org/wp-content/uploads/2017/09/16-03-21-bSDD-Strategic-Overview-Webinar.pdf.

Reinhardt, J., & Bedrick, J. (2016, October). *2016 Level of Development Specification.* BIM Forum.

Roberts, T. (2016, December). *We spend 90% of our time indoors. Says who?* Retrieved from https://www.buildinggreen.com/blog/we-spend-90-our-time-indoors-says-who.

Robinson, A. H., Sale, R. D., & Morrison, J. L. (1978). *Elements of Cartography* (Fourth ed.). New York: Wiley.

Rystedt, B., Ormeling, F., Konecny, M., Li, L., Liebenberg, E., McMaster, R., … Wood, M. (2003, August). *A strategic plan for the International Cartographic Association 2003-2011.* International Cartographic Association.

Smith, C. (2001). Looking for liminality in architectural space. *Limen Journal*, *1*.

Stanford Encyclopedia of Philosophy. (2012, June). *Models in science.* Retrieved from https://plato.stanford.edu/entries/models-science/.

Thrun, S., Burgard, W., & Fox, D. (2005). *Probabilistic Robotics* (Intelligent Robotics and Autonomous Agents series ed.; R. C. Arkin, Ed.). Cambridge, MA: The MIT Press.

Tombazis, A. N. (1996). On skins and other preoccupations of architectural design. *Renewable Energy*, *8*(1), 51–55. doi:

Tuan, Y.-F. (1975). Place: an experiential perspective. *Geographical Review*, *65*(2), 151–165. doi:

Tuan, Y.-F. (1979). Space and place: humanistic perspective. In S. Gale & G. Olsson (Eds.), *Philosophy in Geography* (pp. 387–427). Dordrecht: D. Reidel Publishing Co.

Van Sickle, J. (2010). *Basic GIS Coordinates* (2nd ed.). Boca Raton, FL: CRC Press.

Walton, L., & Worboys, M. (2010). Indoor spatial theory. Technical report presented at the ISA project meeting held at the 2010 International Workshop on Indoor Spatial Awareness, Taipei, Taiwan.

Wang, Z., & Zipf, A. (2017). Using OpenStreetMap data to generate building models with their inner structures for 3D maps. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-2/W4*, 411–416. doi:

Worboys, M. (2011). Modeling indoor space. In L. Kulik, R. H. Guting, & H. Lu (Eds.), *Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 1–6). New York, NY: ACM. doi:

Yan, J., Diakit, A. A., & Zlatanova, S. (2018). An extraction approach of the top-bounded space formed by buildings for pedestrian navigation. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-4*, 247–254. doi:

Zhou, P., Zheng, Y., Li, Z., Li, M., & Shen, G. (2012). IODetector: a generic service for indoor outdoor detection. In R. Eskicioglu, A. Campbell, & K. Langendoen (Eds.), *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems - SenSys '12* (p. 113). New York: ACM. doi:

Zhu, L., Yang, A., Wu, D., & Liu, L. (2014). Survey of indoor positioning technologies and systems. In S. Ma, L. Jia, X. Li, L. Wang, H. Zhou, & X. Sun (Eds.), *Life System Modeling and Simulation* (pp. 400–409). Berlin: Springer.

Zhu, Q., Li, Y., Xiong, Q., Zlatanova, S., Ding, Y., Zhang, Y., & Zhou, Y. (2016). Indoor multi-dimensional location GML and its application for ubiquitous indoor location services. *ISPRS International Journal of Geo-Information*, *5*(12), 220. doi:

Zlatanova, S., & Isikdag, U. (2017). 3D indoor models and their applications. In *Encyclopedia of GIS* (pp. 9–20). Berlin: Springer. doi:

Zlatanova, S., Sithole, G., Nakagawa, M., & Zhu, Q. (2013). Problems in indoor mapping and modelling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-4/W4*, 63–68.