Modeling Inhabited Smart Spaces to Support Interoperable IoT-Based Applications

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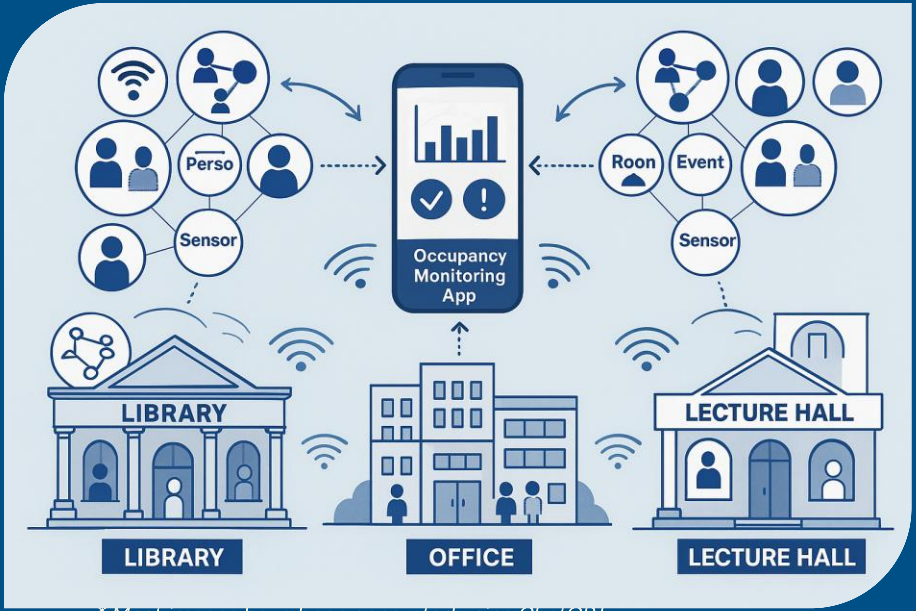
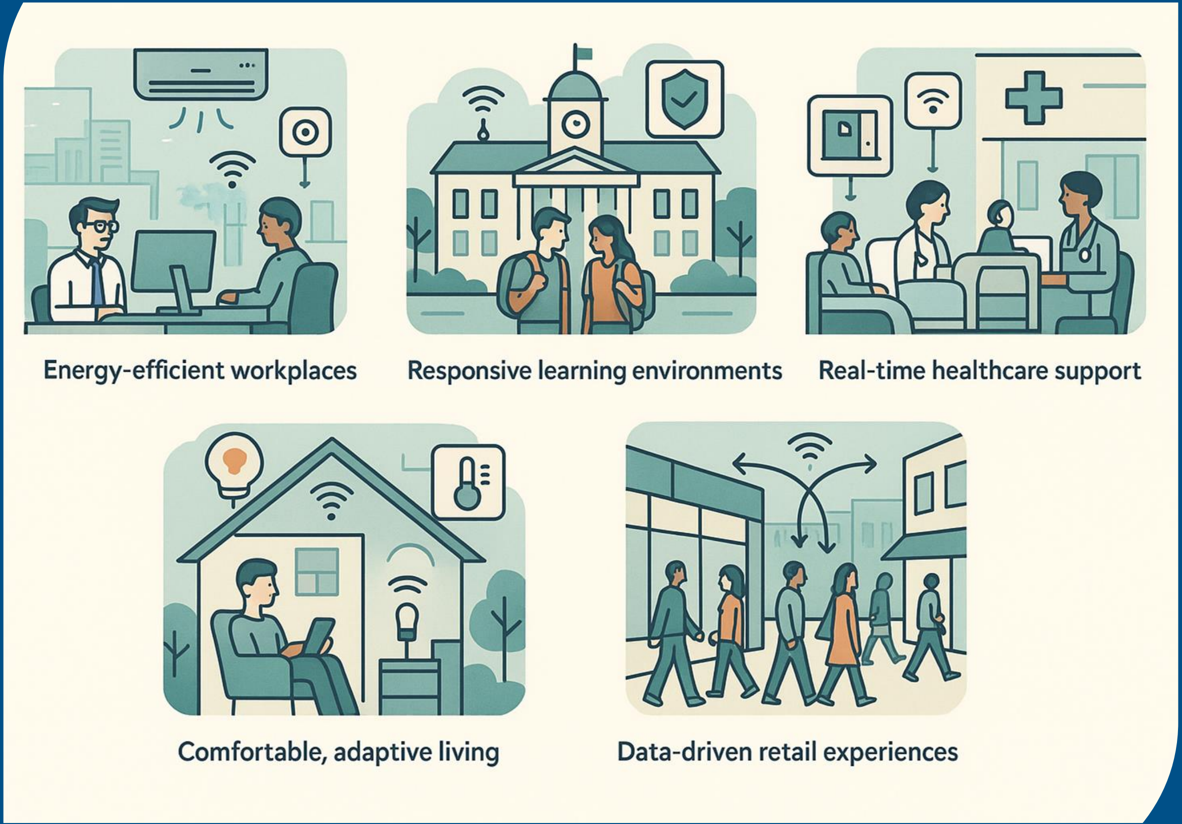


* Most images have been generated using ChatGPT

Why Smart Spaces Matter

Smart spaces improve comfort, efficiency, and safety — by making environments aware of and responsive to people.

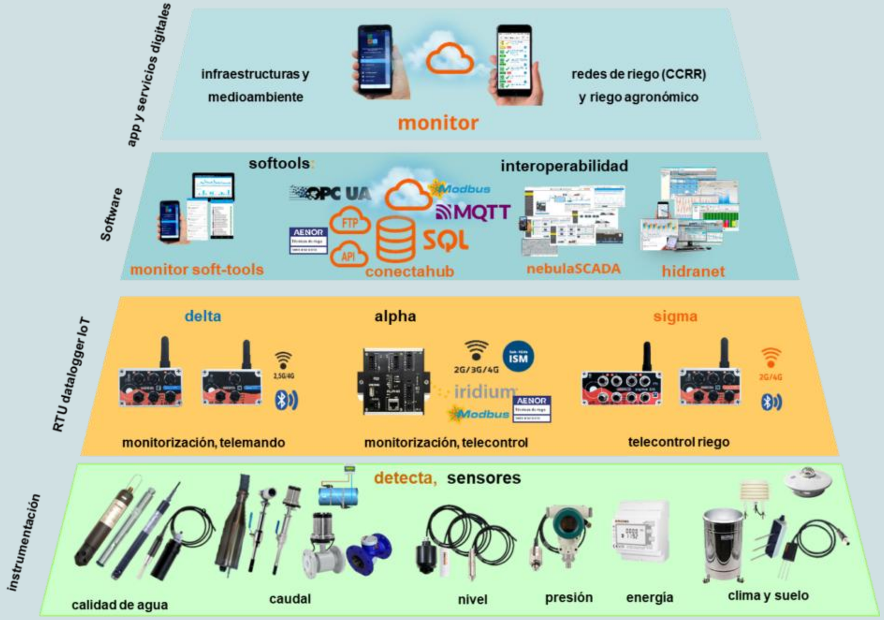


Typical IoT App Development

1. **Start from a Specific Deployment**
   - E.g., “Developing an occupancy app for Building A (e.g., an office)”
   - Uses particular sensors (e.g., WiFi APs, motion detectors)

1. **Hardcoded Logic and Data Access**
   - Floor plans and room names are manually embedded in code.
   - Sensor IDs / mappings are hardwired.
   - Activity definitions (e.g., meeting = conference room + schedule) are custom.

1. **App Works Only in That Space**
   - Cannot reuse in a different building (e.g., a classroom or shopping mall).
   - Logic /infrastructure assumptions tied to one space.



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   - Activity defini room + sched
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   - Cannot reuse classroom or
   - Logic /infrastr space.

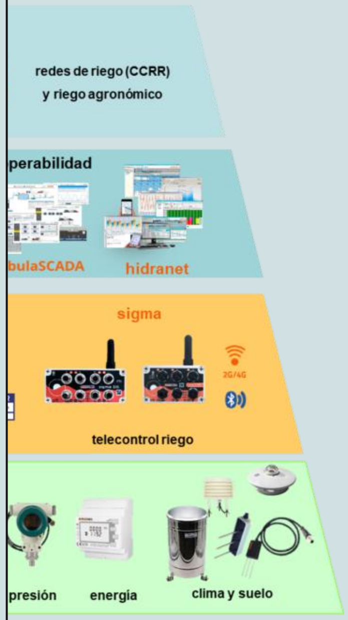
Limited Reusability

High Redundancy

Poor Maintainability

Lack of Interoperability

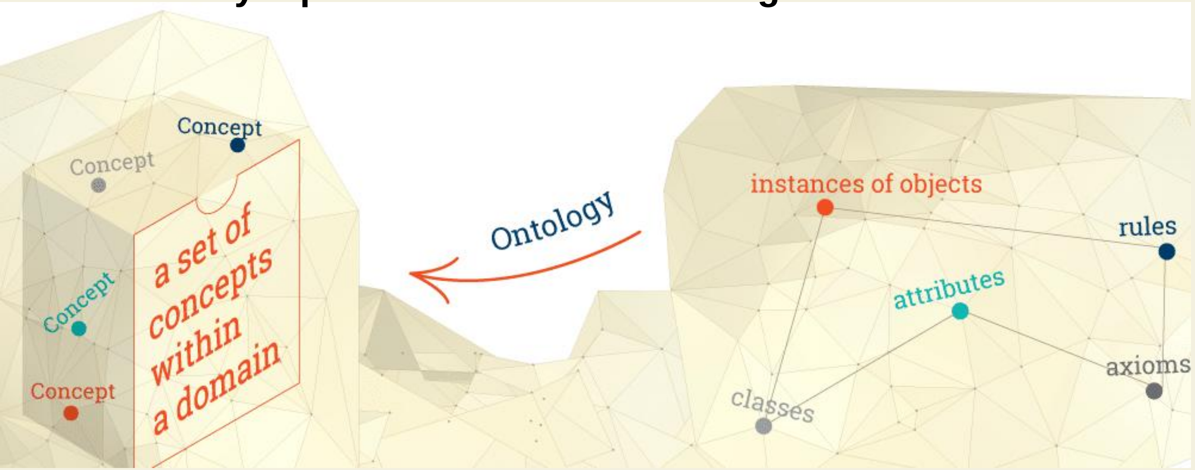
Difficult to Scale



Ontologies for Modeling Semantic Knowledge

- **Ontology: Knowledge structure that formally represents domain knowledge**
  - Classes/Concepts
  - Instances (Objects)
  - Properties/Attributes

    (Relationships)



Related Works and Challenges

- **Existing Ontologies in Smart Spaces**
  - **SSN & SOSA**
    - Focus on sensor, observation, and actuator descriptions
  - **SAREF & SAREF4Building**
    - Smart device roles and commercial building topologies.
  - **Brick Schema**
    - Sensor infrastructures in buildings (HVAC, lighting).
  - **BOT**
    - Spatial relationships (containment, adjacency) in lightweight fashion.

- **Gaps and Limitations**
  - **Existing vocabularies are:**
    - Primarily **system- and device-centric**, not **inhabitant-centric**.
    - **Lack integration of spatial-temporal uncertainty (e.g., probabilistic locations).**
    - **Provide limited support for recurring activities and spatial hierarchies across domains.**

- **Challenge: Semantic Interoperability Across Spaces**

Why Model Inhabited Smart Spaces?

- **Smart Spaces Are People-Centric**
  - IoT-enabled environments (e.g., campuses, offices, homes) aim to enhance human experience.
  - Applications include personalized HVAC control, occupancy-based regulation compliance, and activity tracking.
  - Human presence and behavior must be central to smart space modeling

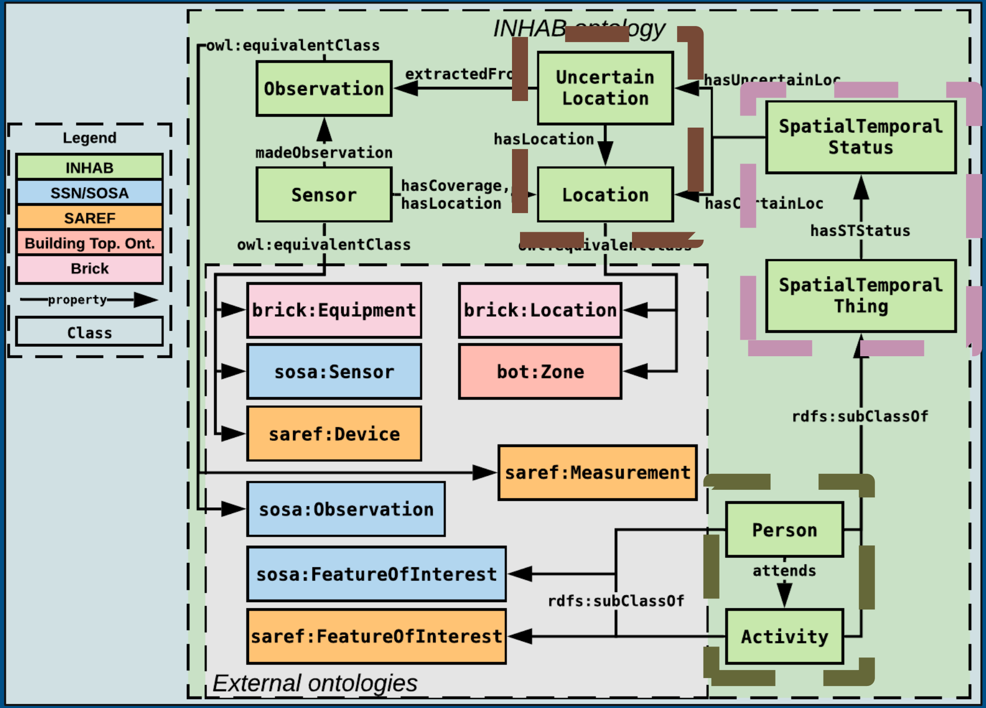
Our goal:

- Develop a schema that enables semantic modeling of **inhabited smart spaces** (i.e., **people, activities, spatial hierarchies, and uncertain sensor data).**

- Support the development of **interoperable, space-agnostic IoT-based applications.**

The INHAB Schema Overview

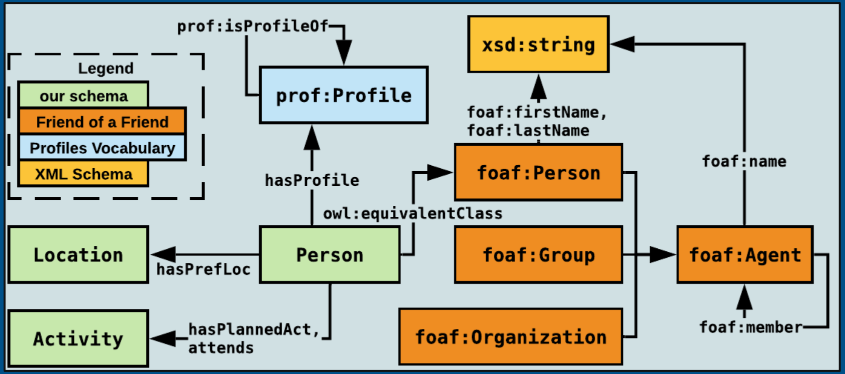
- **Key Features**
  - Integrates existing ontologies (e.g., SSN/SOSA, SAREF, Brick, BOT).
  - Models people, activities, spatial hierarchies, and uncertainty in sensor data.
- **Three Core Modules**
  - **People & Activities**
  - **Location & Topology**
  - **Spatial-Temporal Representation**

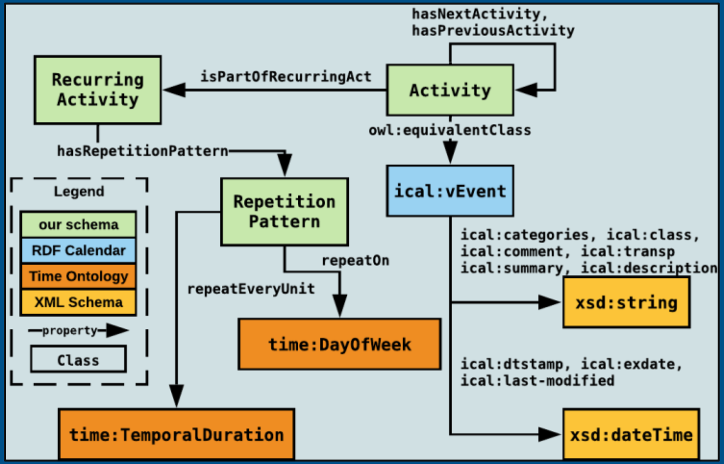


People & Activities Module

- **People Representation**
  - Uses FOAF, DX-Prof for profiles (e.g., faculty, staff).
  - Links to locations (e.g., office) and scheduled activities.

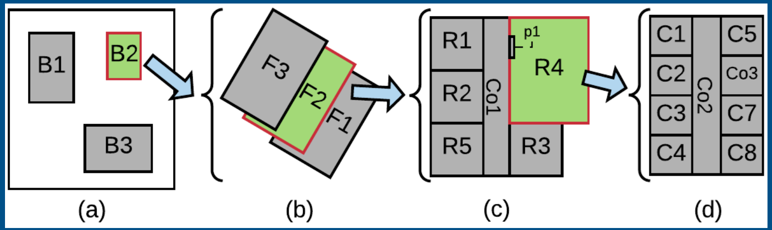
- **Activity Representation**
  - Uses RDFcal and OWL-time for metadata (name, time, recurrence).
  - Supports recurring activities for optimizing building operations.

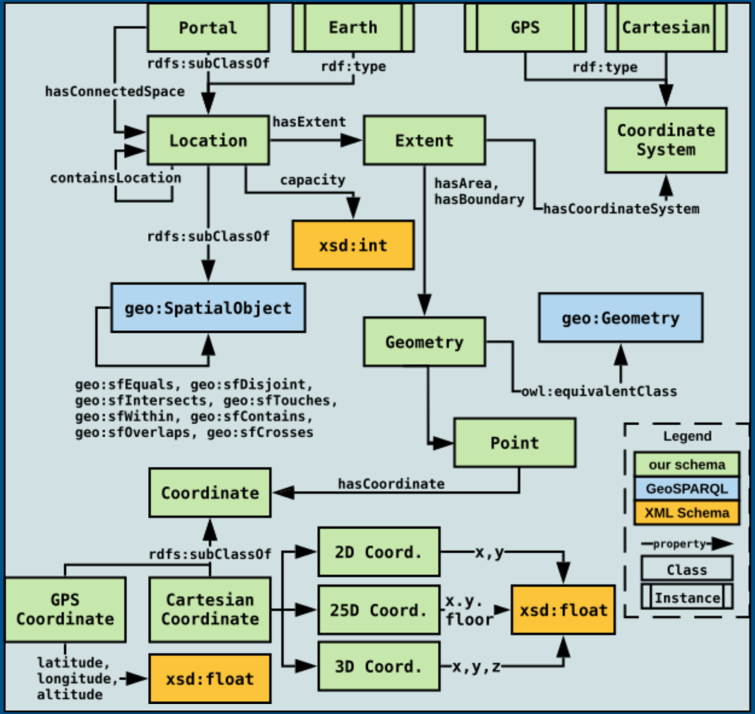




Location Modeling

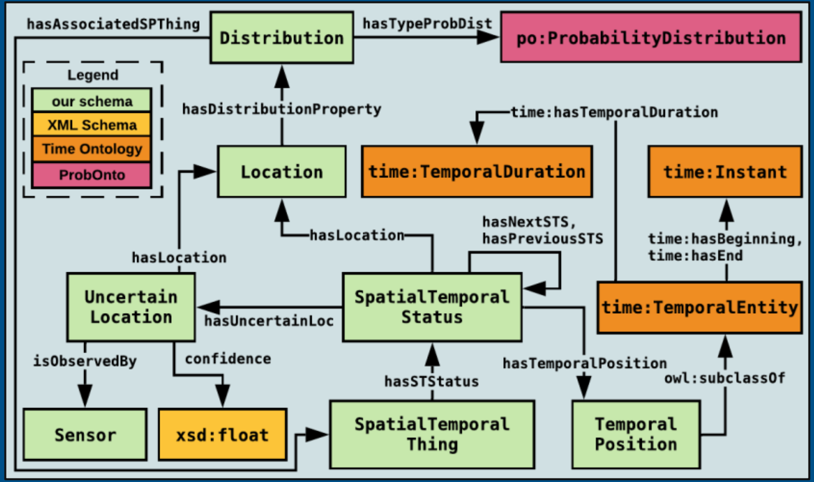
- **Spatial Hierarchy**
  - Buildings → Floors → Rooms → Subspaces (e.g., cubicles).
- **Topological Relationships**
  - Explicit definitions: containment, adjacency, intersection.
- **Coordinate Systems**
  - Supports both GPS and Cartesian systems.
  - Allows definition of areas and boundaries using extensible geometry.





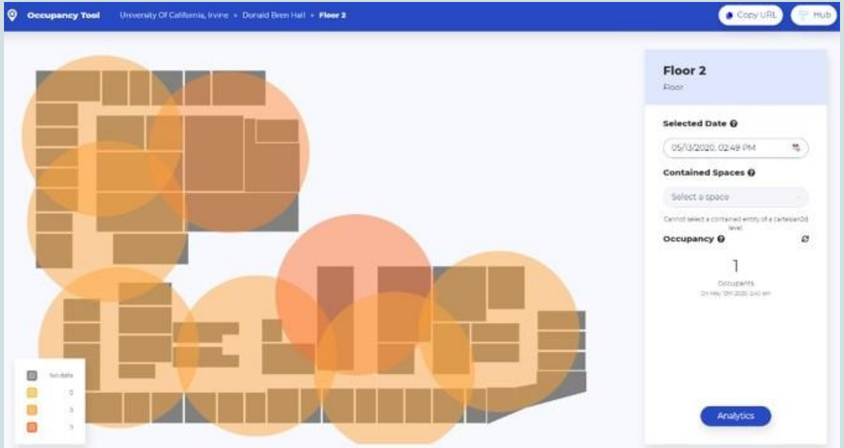
Spatial-Temporal Representation

- **Temporal Localization**
  - People and activities linked to time-bound locations.
- **Handling Uncertainty**
  - inhab:UncertainLocation class includes confidence levels.
  - Allows probabilistic modeling via distributions (e.g., uniform).
- **Coordinate Systems**
  - Supports both GPS and Cartesian systems.
  - Allows definition of areas and boundaries using extensible geometry.



Usage via SPARQL Queries

- Occupancy monitoring



Count number of people per building, floor, region, etc.

Retrieve people and their spatial-temporal location

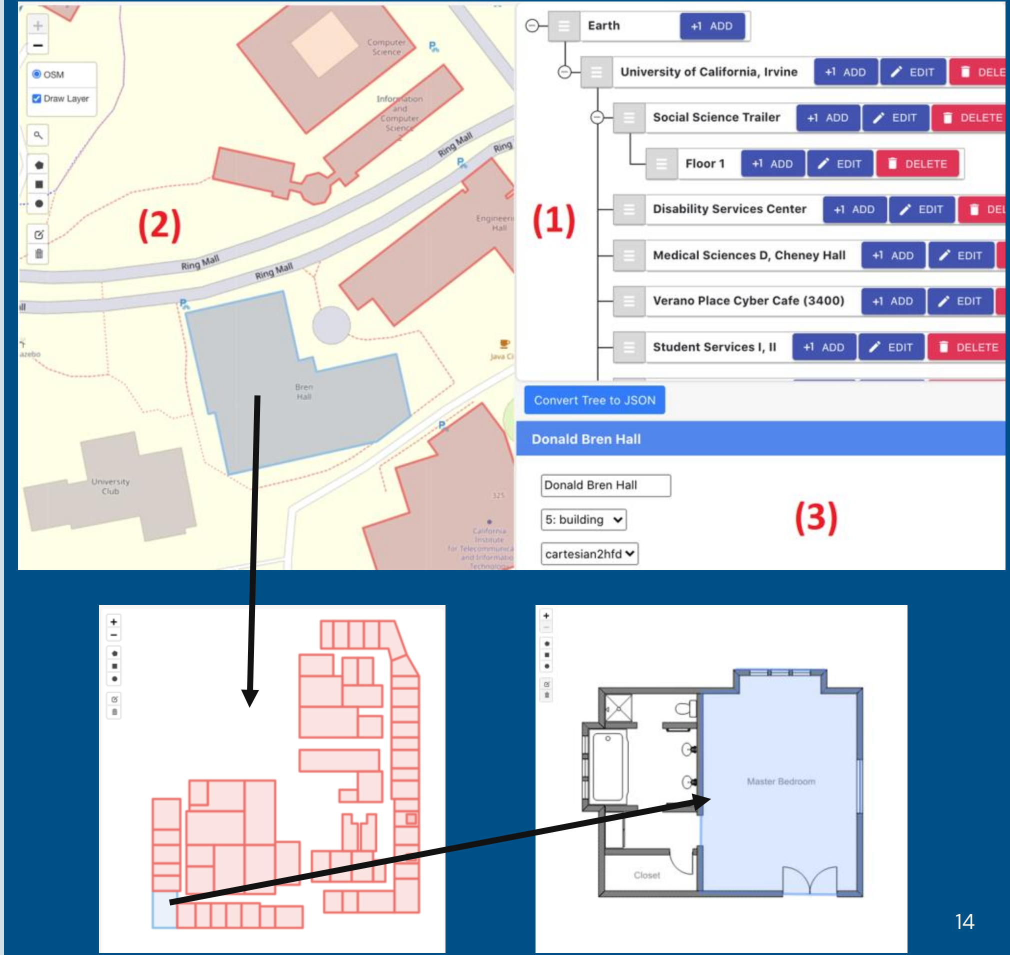
For those on the smart space (last 10 minutes)

Count them, taking into account an "uncertain location" (i.e., they are on campus, they are in the building, they *might* be in a floor or another)

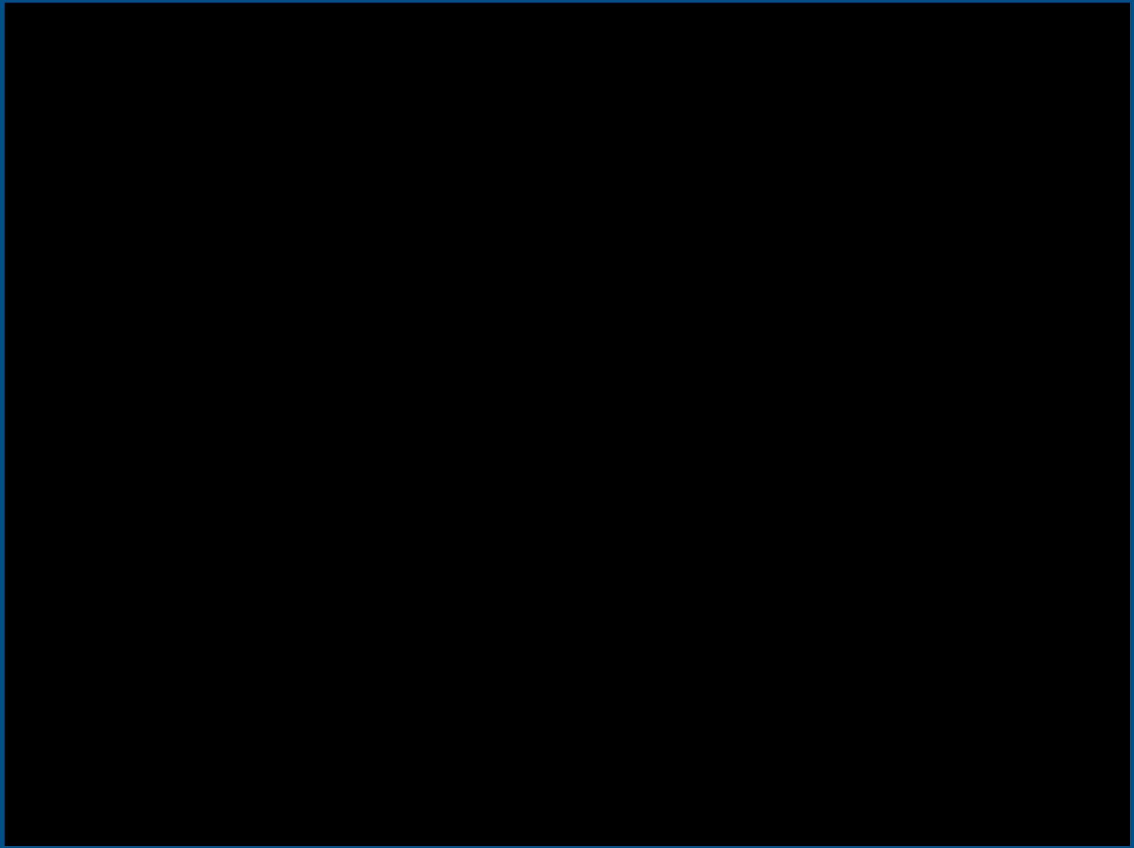
Count them, taking into account a "certain location" (i.e., they are on campus, they are in the building, they *are in this floor X*)

Annotation Tool

- **Purpose**
  - GUI for modeling spaces using INHAB schema.
- **Components**
  - Hierarchy Definition
  - Extent Drawing (map or floor plan)
  - Metadata Entry
- **Advantages**
  - Reduces annotation errors and complexity
  - Helps visualize spatial extent



Annotation Tool: Demo



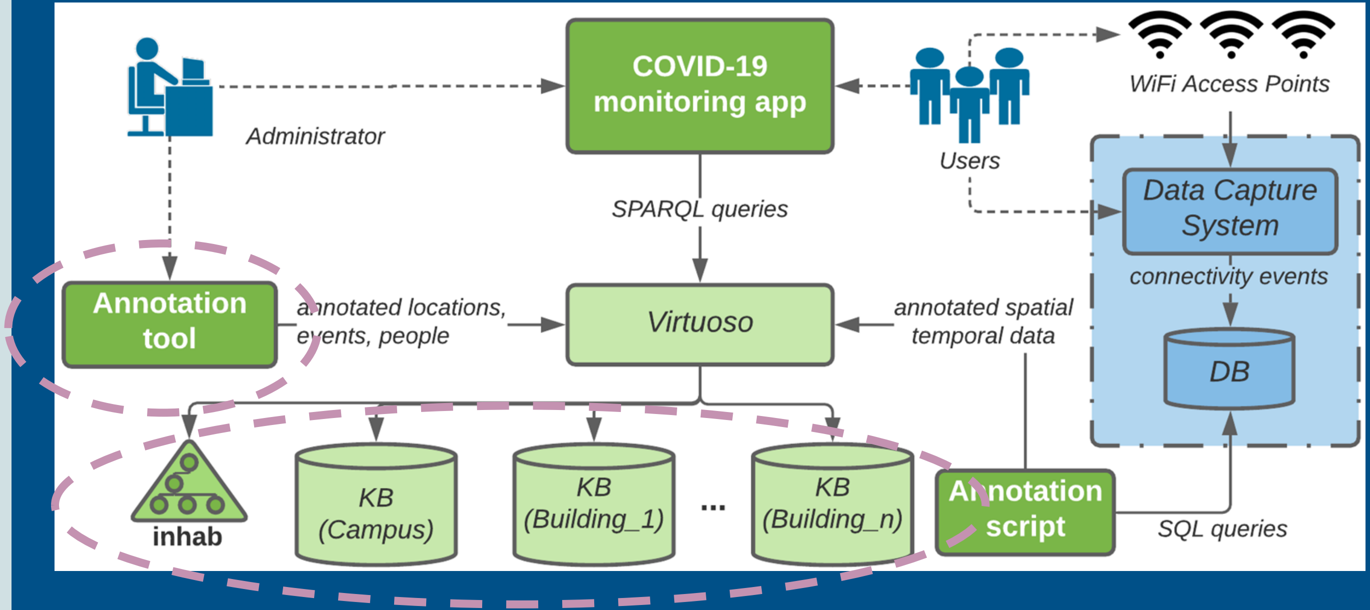
Developing Inhab-Enabled Systems

UC Irvine campus

154 annotated buildings

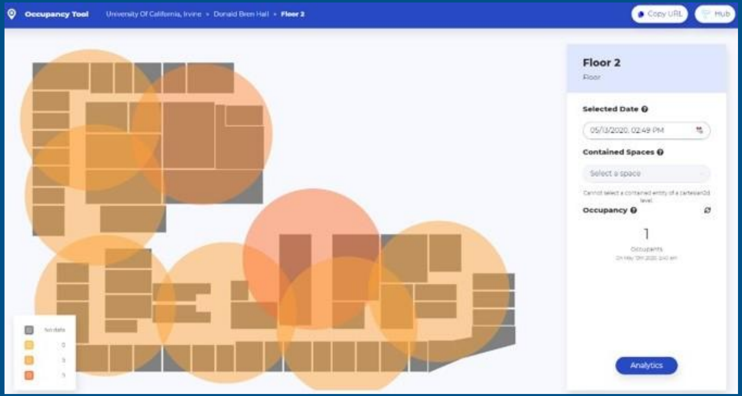
Detailed spatial hierarchy for selected buildings (e.g., DBH → 360 rooms / 6 floors)

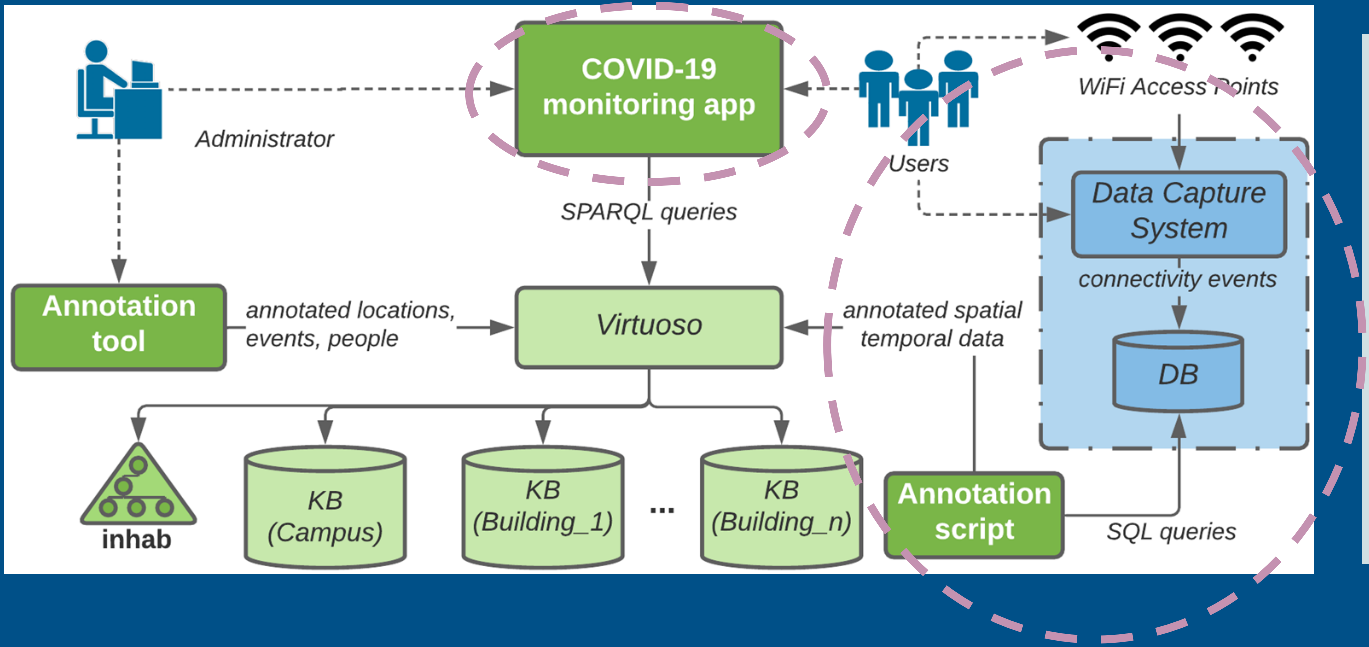
Containment relationships for over 350 WiFi AP coverage areas.



UCI-KB –> includes people and high-level spatial structure.

DBH-KB, FRH-KB, etc. –> detailed space layouts and temporal event data per building





Converts WiFi connectivity logs into RDF triples describing spatial-temporal events

Syslog records (device MAC address, timestamp, and WiFi AP ID).

Models uncertain location using `inhab:UncertainLocation` with confidence values based on AP coverage.

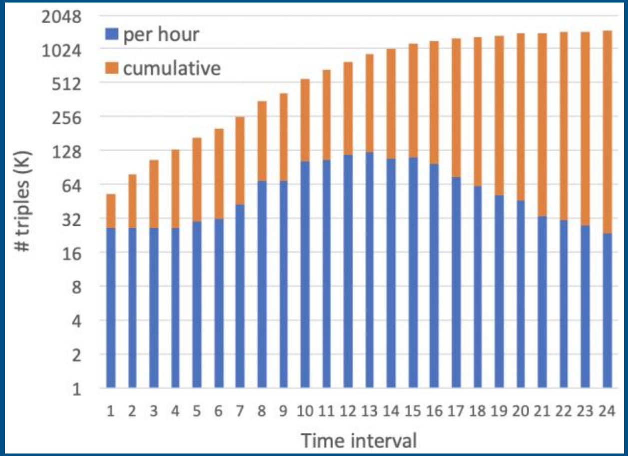
Size of KB

- Two one-week data snapshots—pre and post campus partial closure due to COVID-19 (early and late March 2020, respectively).
- ≈ 800 triples to annotate a building
- ≈ 2M pre-closure and ≈ 600K during closure triples required to represent "people"
- spatial-temporal triples per building proportional to its size and inhabitants (e.g., ≈ 5M for DBH)

#triples	UCI-KB	DBH-KB	ICS-KB	ICS2-KB	FRH-KB
space	379	8,731	124	193	289
activity	-	21	0	0	105
people†	2,255,778	-	-	-	-
people§	584,052	-	-	-	-
spat-temp†	-	5,192,778	1,013,339	713,543	2,796,318
spat-temp§	-	2,487,957	283,925	69,809	949,746
total	135,609	7,689,466	1,297,388	783,545	3,746,353

TABLE I: Triples per KB. pre-campus closure†, during closure§.

Size vs. Time


2048
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512
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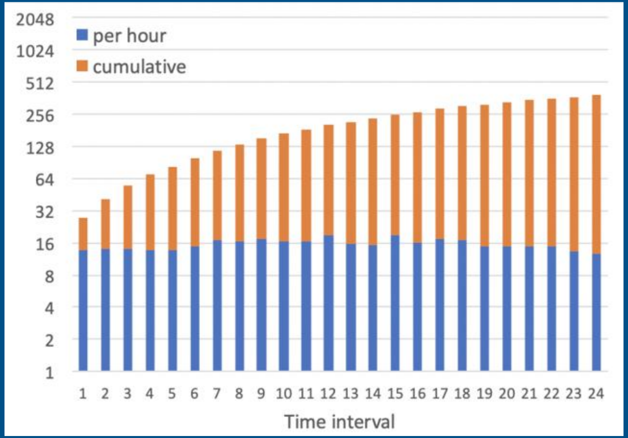
64
32
16
8
4
2
1
triples (K)
per hour
cumulative
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time interval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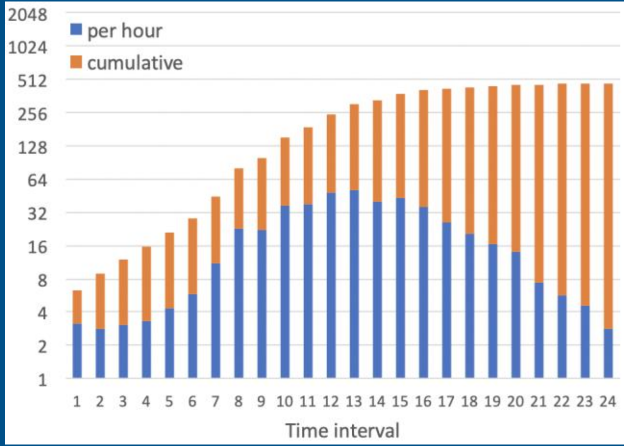
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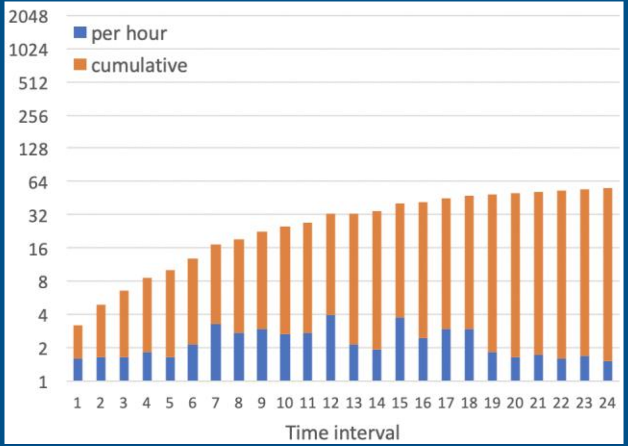
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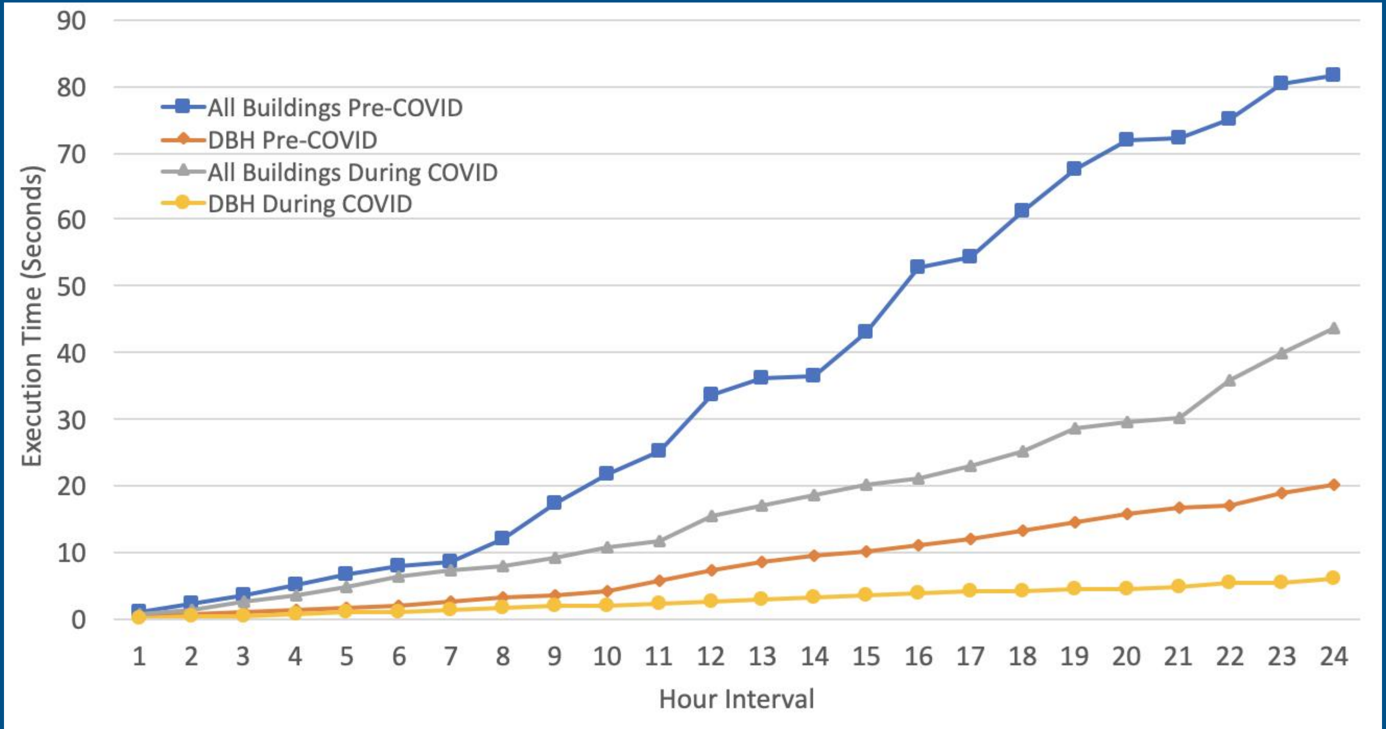
Query Performance



Discussion and Future Direction

- **INHAB** schema enables **interoperable, inhabitant-aware** applications.
- Aligns with existing ontologies, supports **uncertainty** and **spatial-temporal reasoning**.
- **Limitation:** More fine-grained representation, more size, slower queries
  - Common tradeoff in KGs/ontologies to achieve interoperability
  - Mitigations: Storing only current triples (e.g., last day) in the operational KG, use efficient RDF/KG DBs
- **Future Work:** Enhancing annotation tool and optimizing knowledge graph storage.

Thank you!
Questions?