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A Semantic Situation Awareness Framework for Indoor Cyber-Physical Systems

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Ph.D. in Engineering Dissertation Defense

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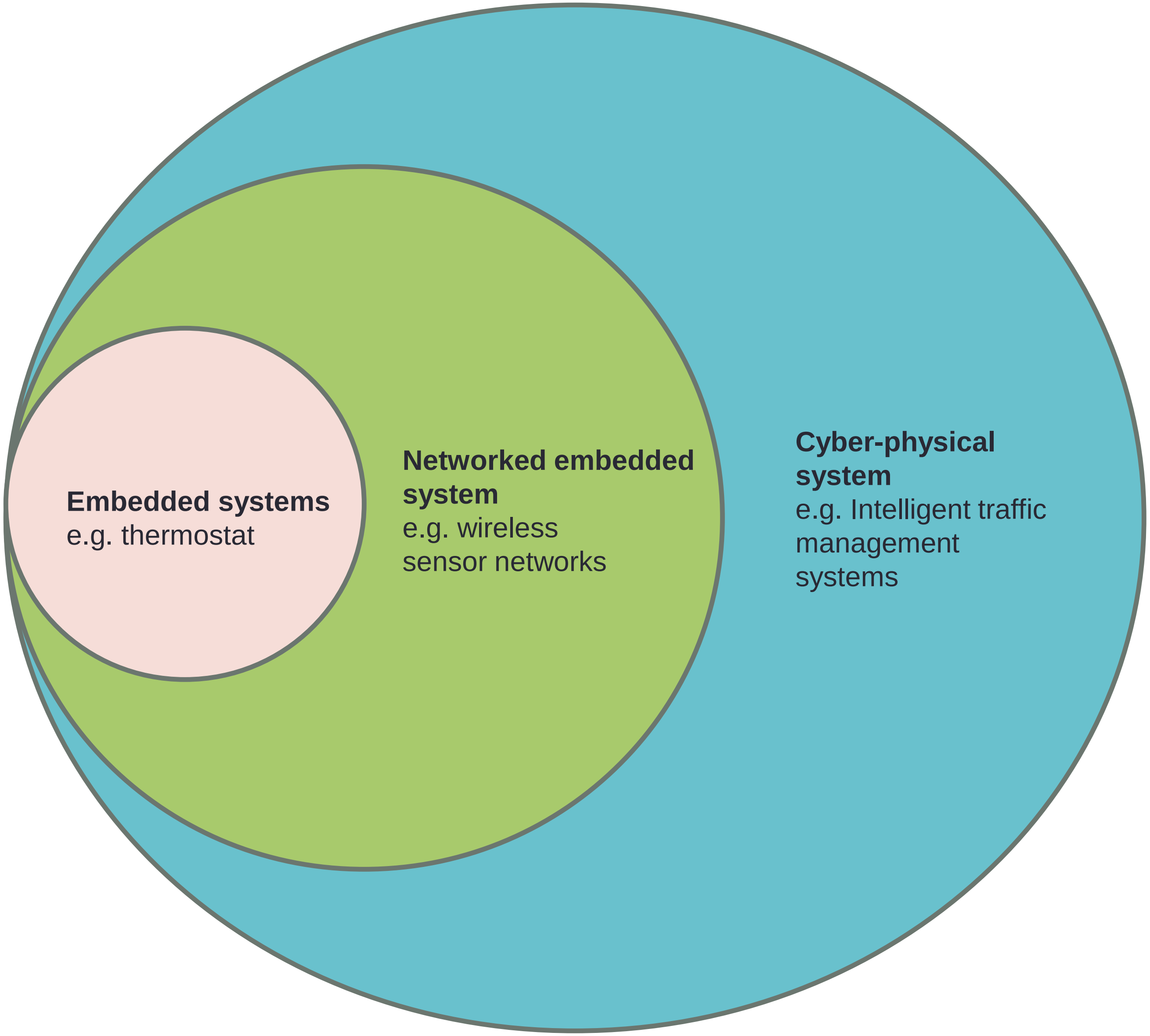
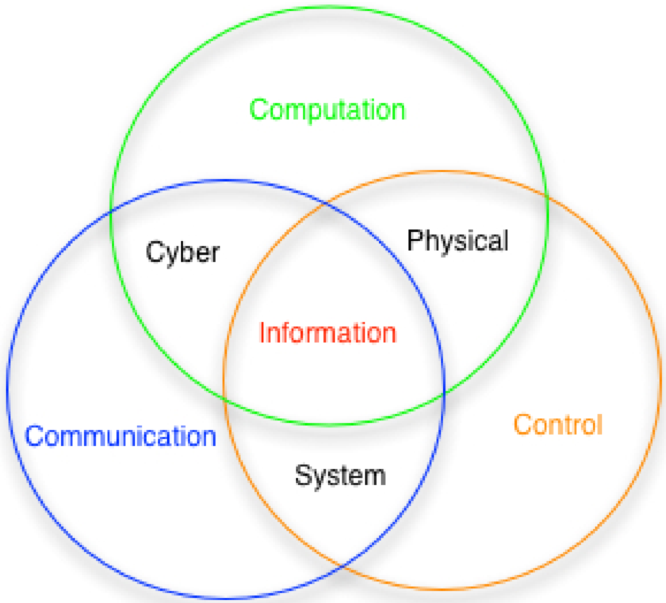

Embedded systems
e.g. thermostat
Networked embedded system
e.g. wireless sensor networks
Cyber-physical system
e.g. Intelligent traffic management systems

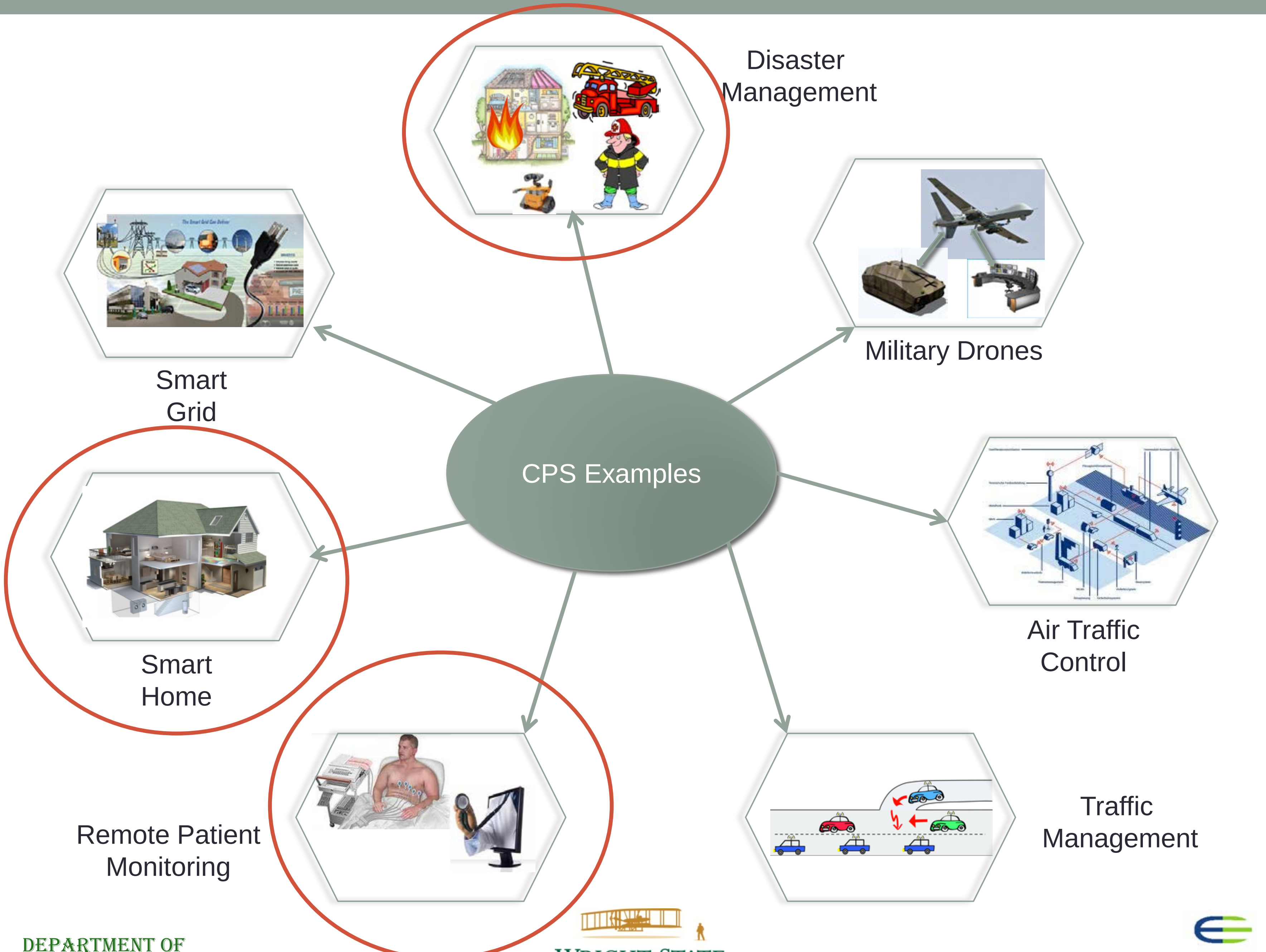
Cyber-Physical Systems



Cyber : Computation, communication, and control that are discrete, logical, and switched.

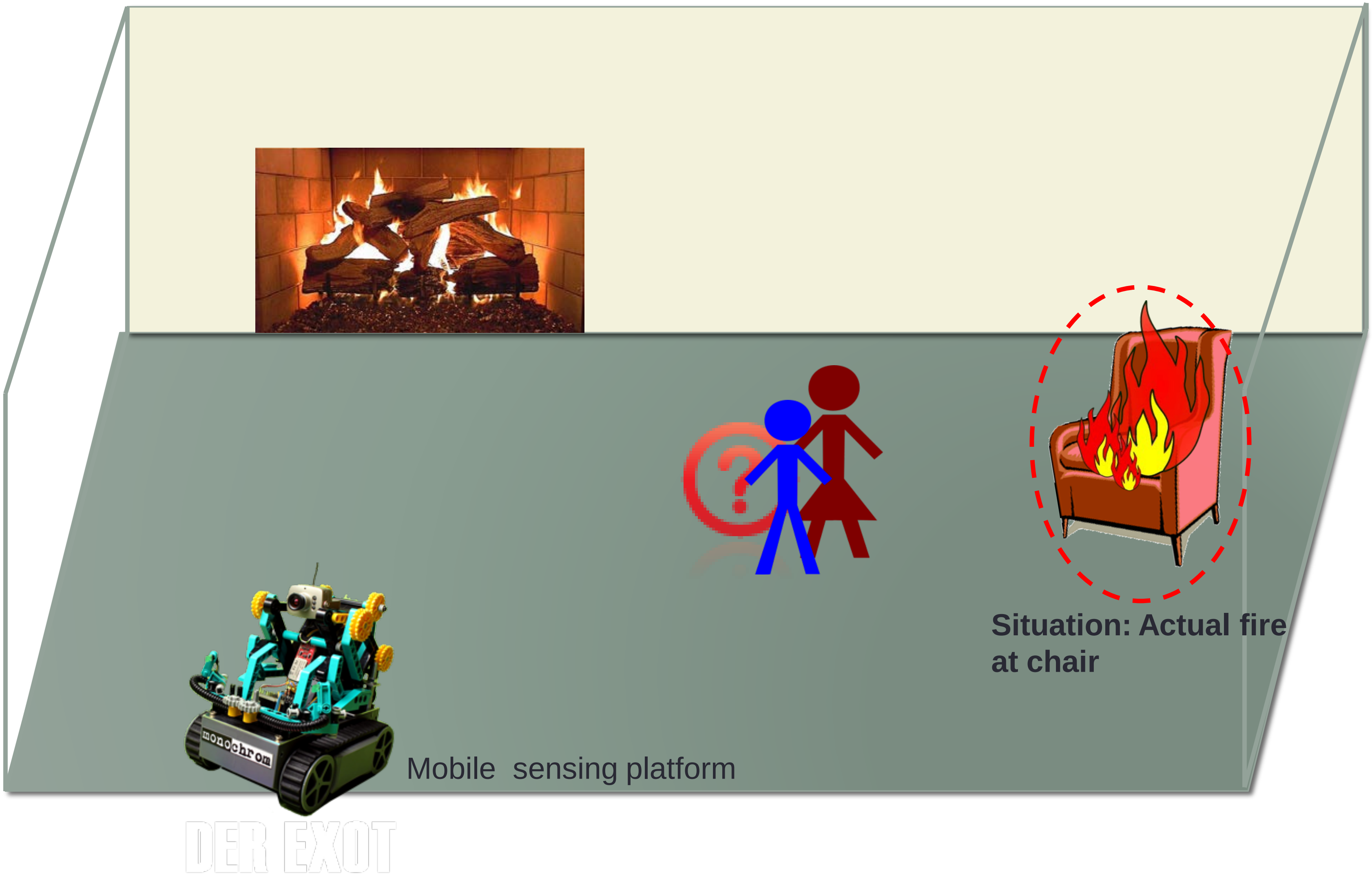
Physical : Natural and human-made systems governed by the laws of physics and operating in continuous time.

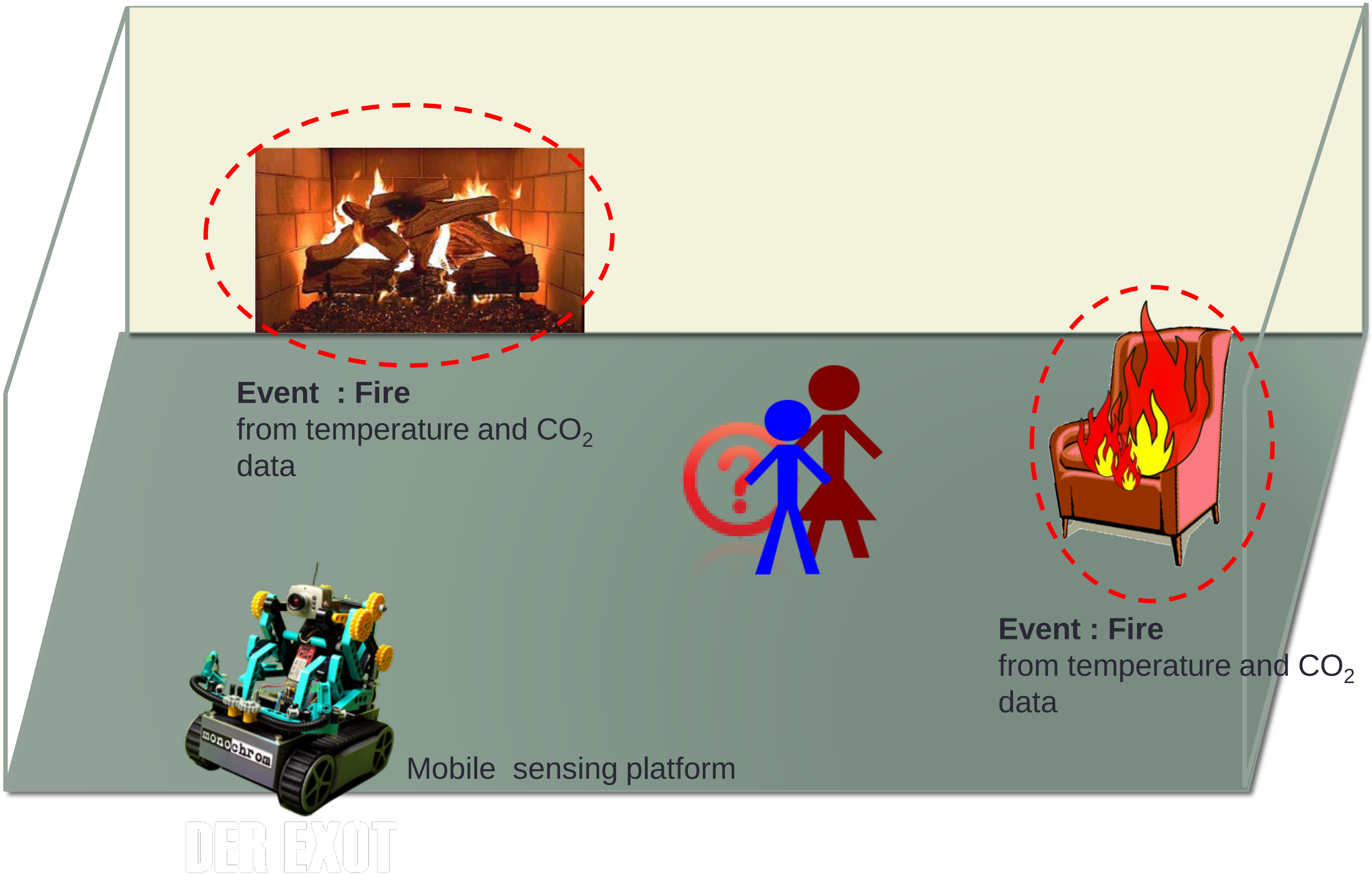
Cyber-Physical Systems (CPS) : Systems in which the cyber and physical systems are tightly integrated at all scales and levels


CPS Examples
Disaster
Management
Military Drones
Smart
Grid
Air Traffic
Control
Smart
Home
Remote Patient
Monitoring
Traffic
Management

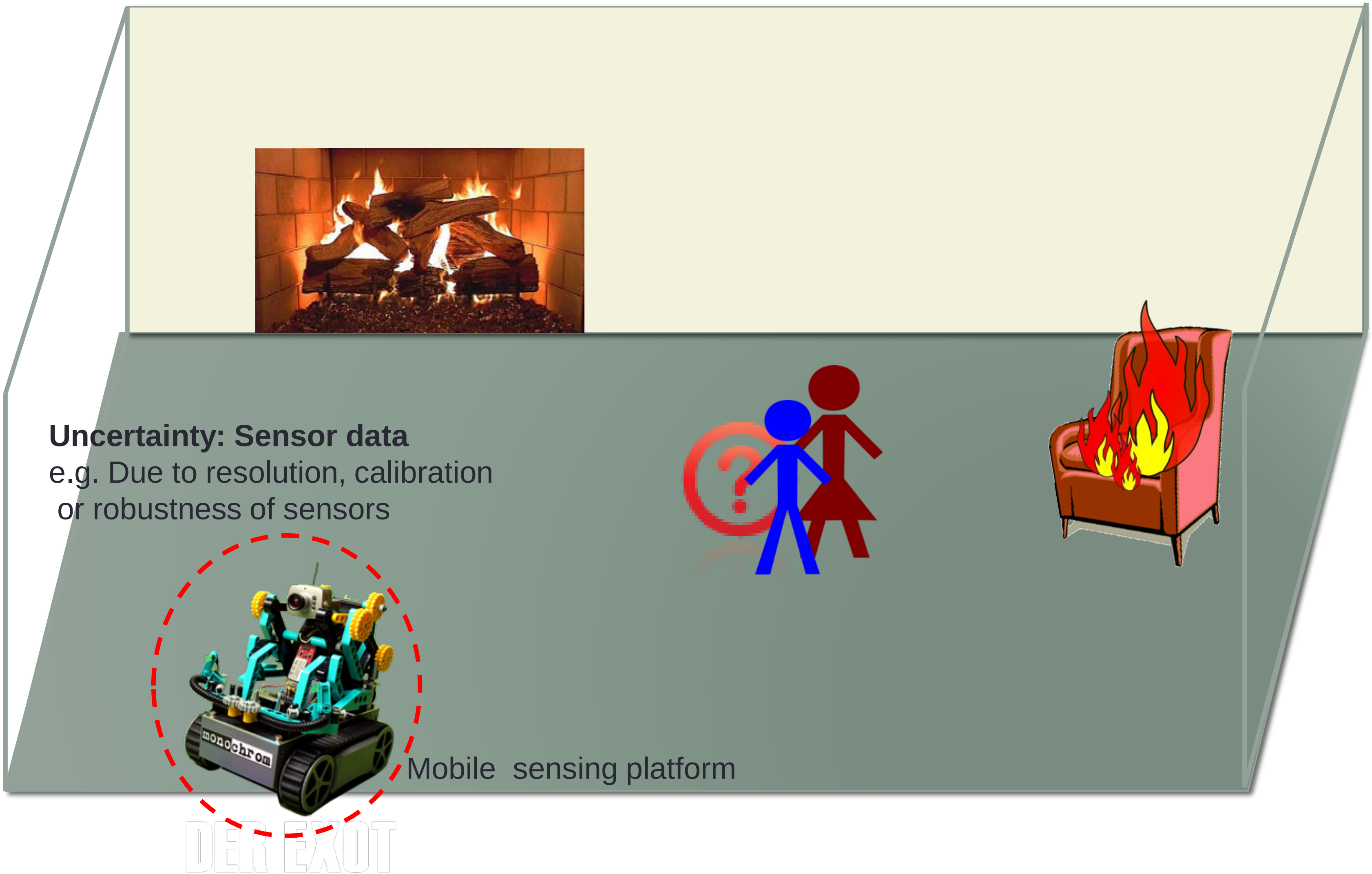
Motivation & Challenges

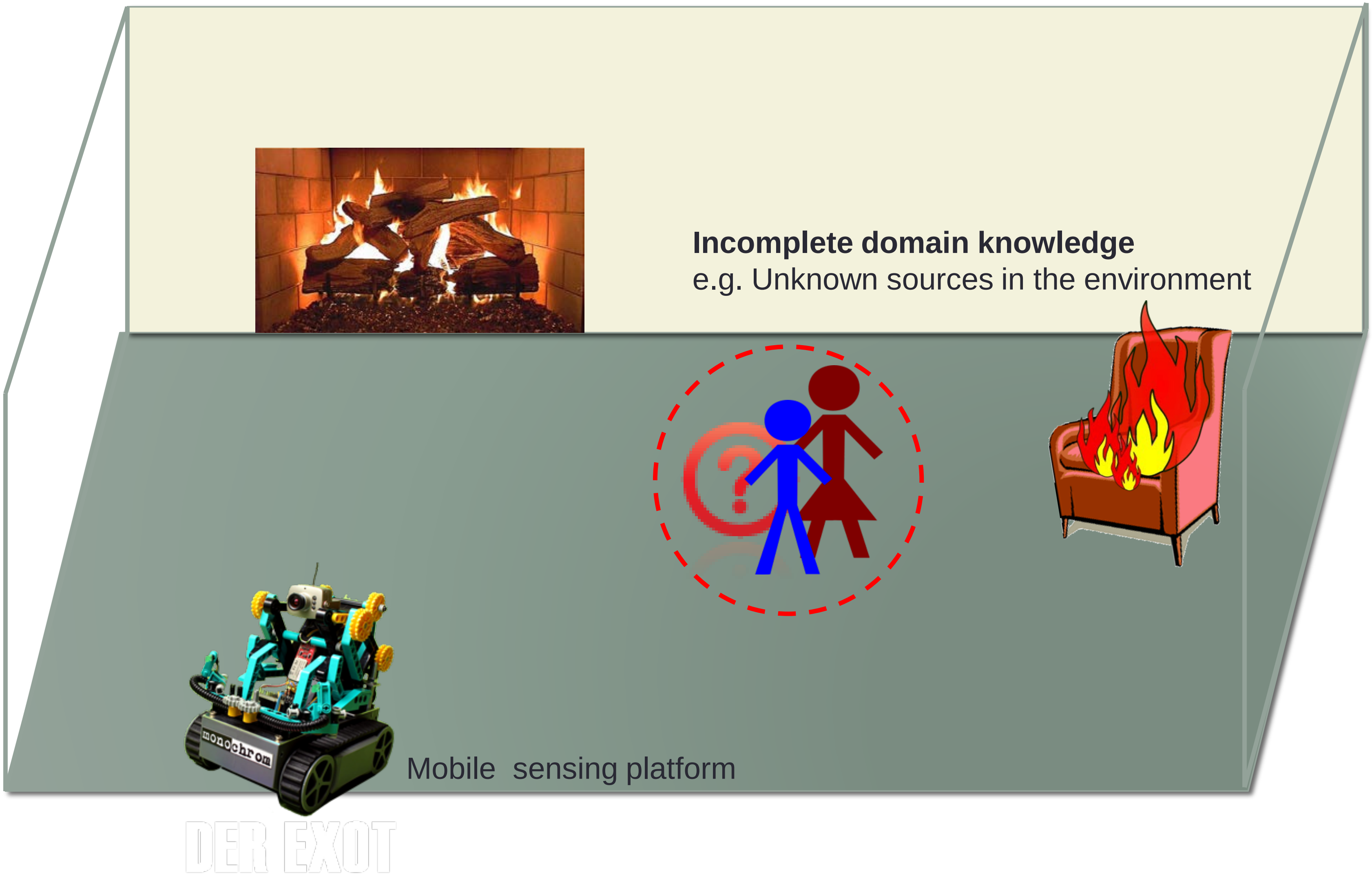
(Situation awareness)


Situation: Actual fire at chair
Mobile sensing platform
monochrom
DER EXOT

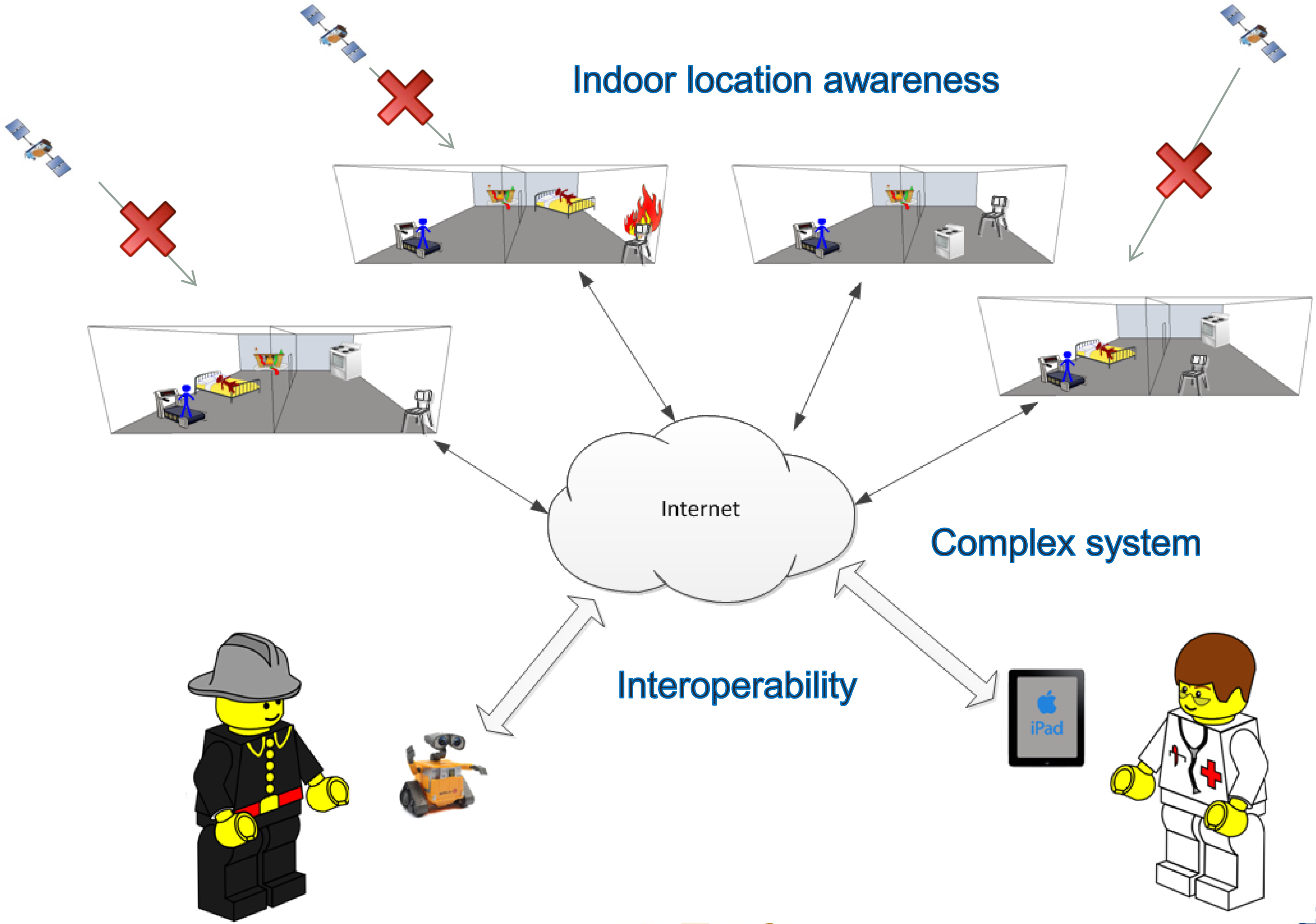


Event : Fire
from temperature and CO_2 data
Event : Fire
from temperature and CO_2 data
Mobile sensing platform
monochrom
DER EXOT


Uncertainty: Sensor data
e.g. Due to resolution, calibration
or robustness of sensors
monochrom
Mobile sensing platform
DER EXOT

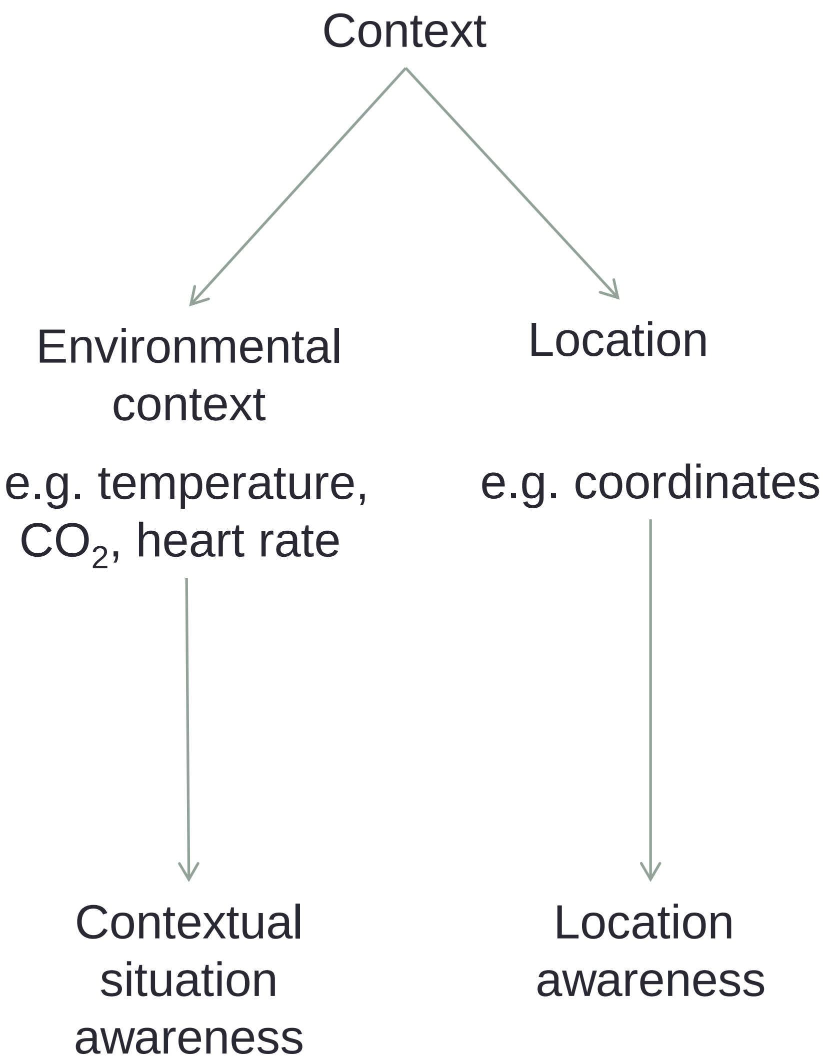

Incomplete domain knowledge
e.g. Unknown sources in the environment
Mobile sensing platform
monochrom
DER EXOT

Indoor location awareness



Complex system

Interoperability

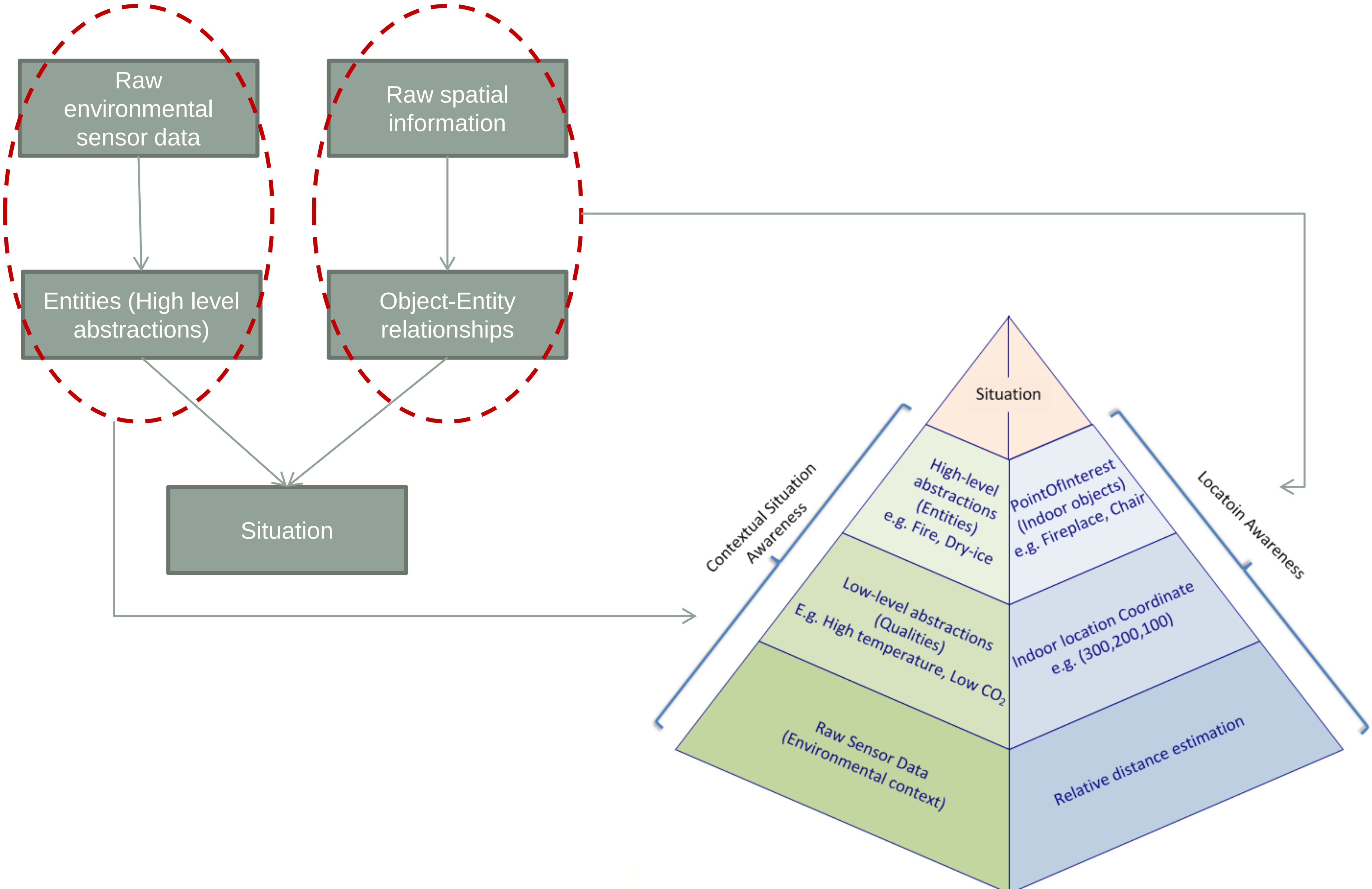


Context
“is a physical phenomenon, measured using sensors, and product of an event”

Contextual situation awareness:
“is a process of comprehending meaning of environmental context in terms of events or entities”

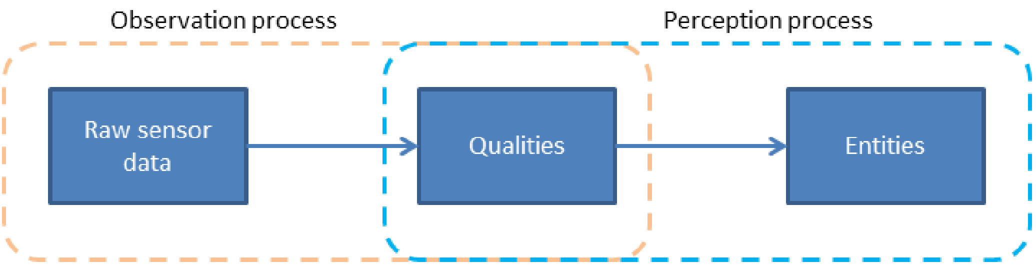
Location awareness:
“is a process of identifying objects from raw spatial information and their relationship with the ongoing events”

Contextual situation awareness + Location awareness



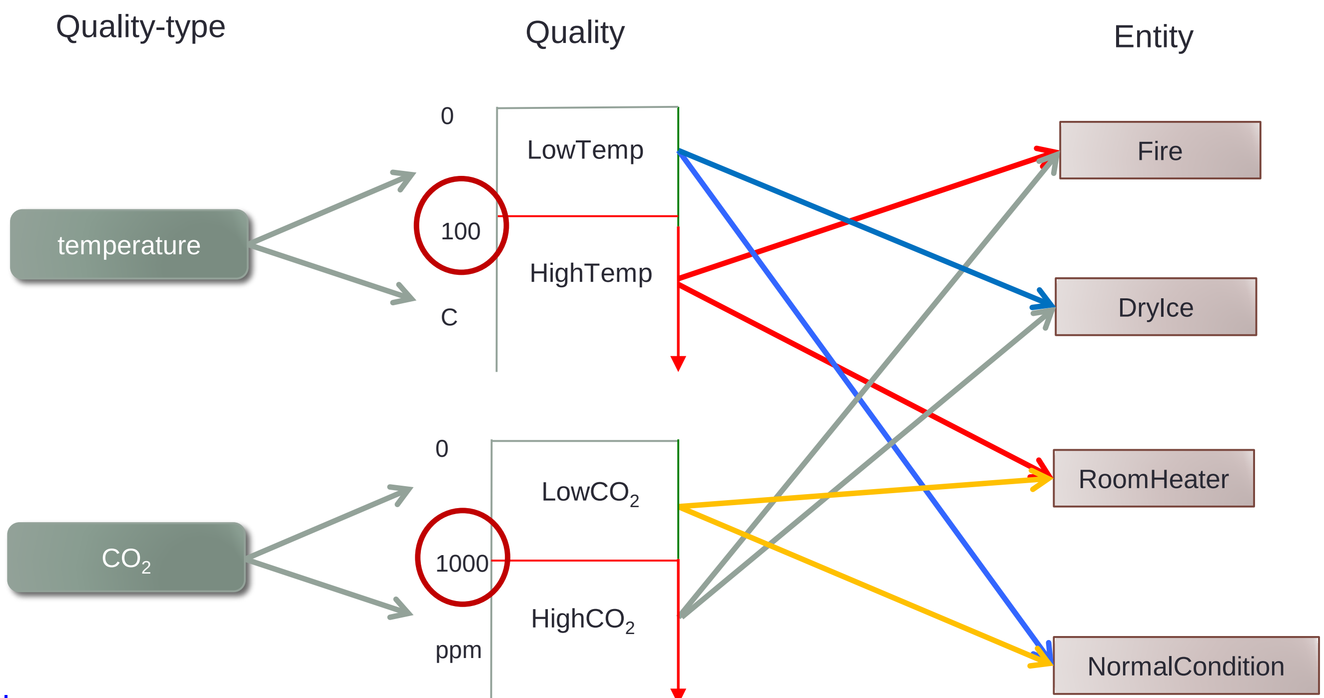
Contextual Situation Awareness

IntellegO

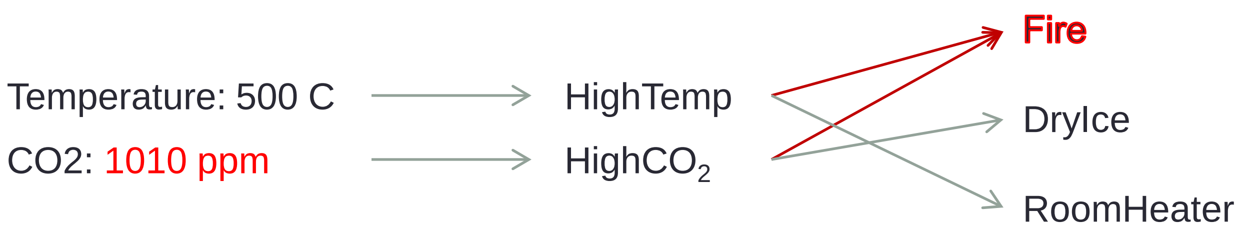


- Abductive reasoning
- Crisp abstractions

Domain Knowledge Base



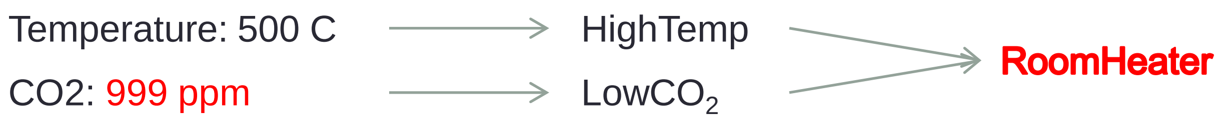
http://wiki.knoesis.org/index.php/Intellego

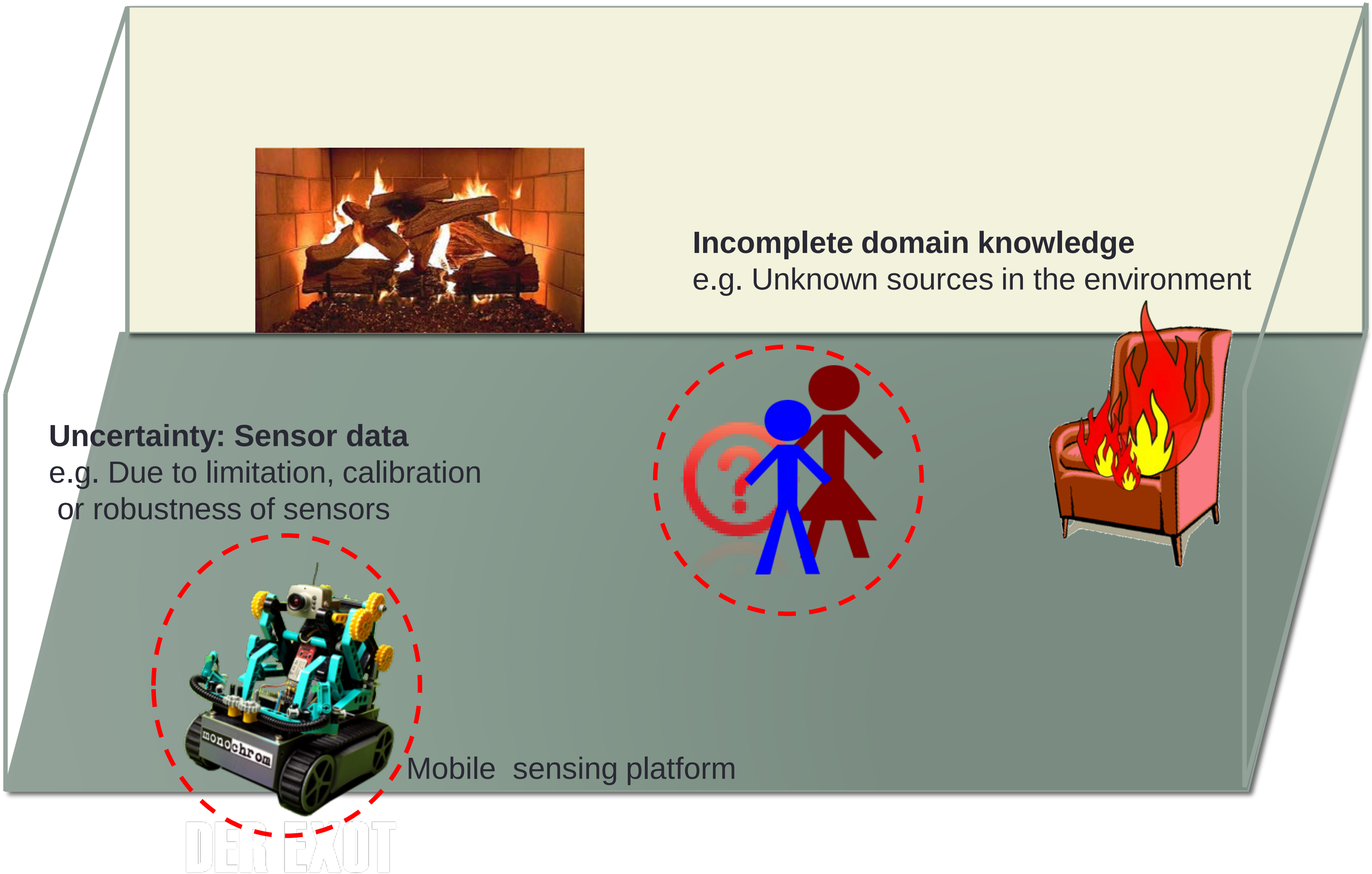


$$io\!:\!entity \equiv \exists\, io\!:\!inheresIn.\{HighTemp\} \sqcap \exists\, io\!:\!inheresIn.\{HighCO_2\}$$

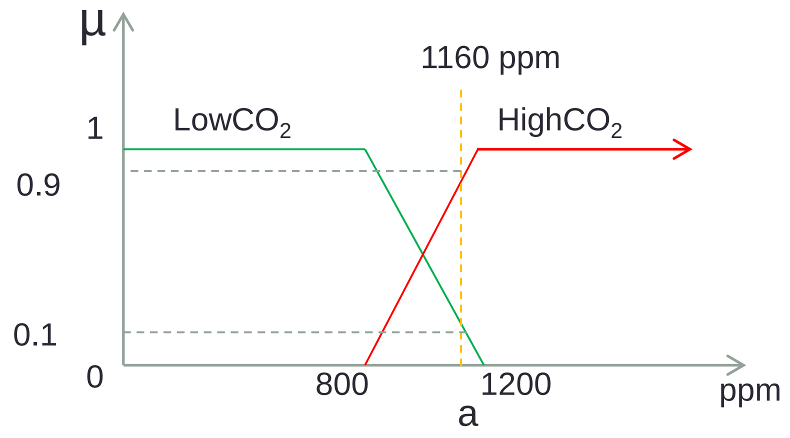
$$\equiv \{Fire, RoomHeater\} \sqcap \{Fire, DryIce\}$$

$$\equiv \{Fire\}$$




Incomplete domain knowledge
e.g. Unknown sources in the environment
Uncertainty: Sensor data
e.g. Due to limitation, calibration
or robustness of sensors
monochrom
Mobile sensing platform
DER EXOT

Fuzzy abstractions

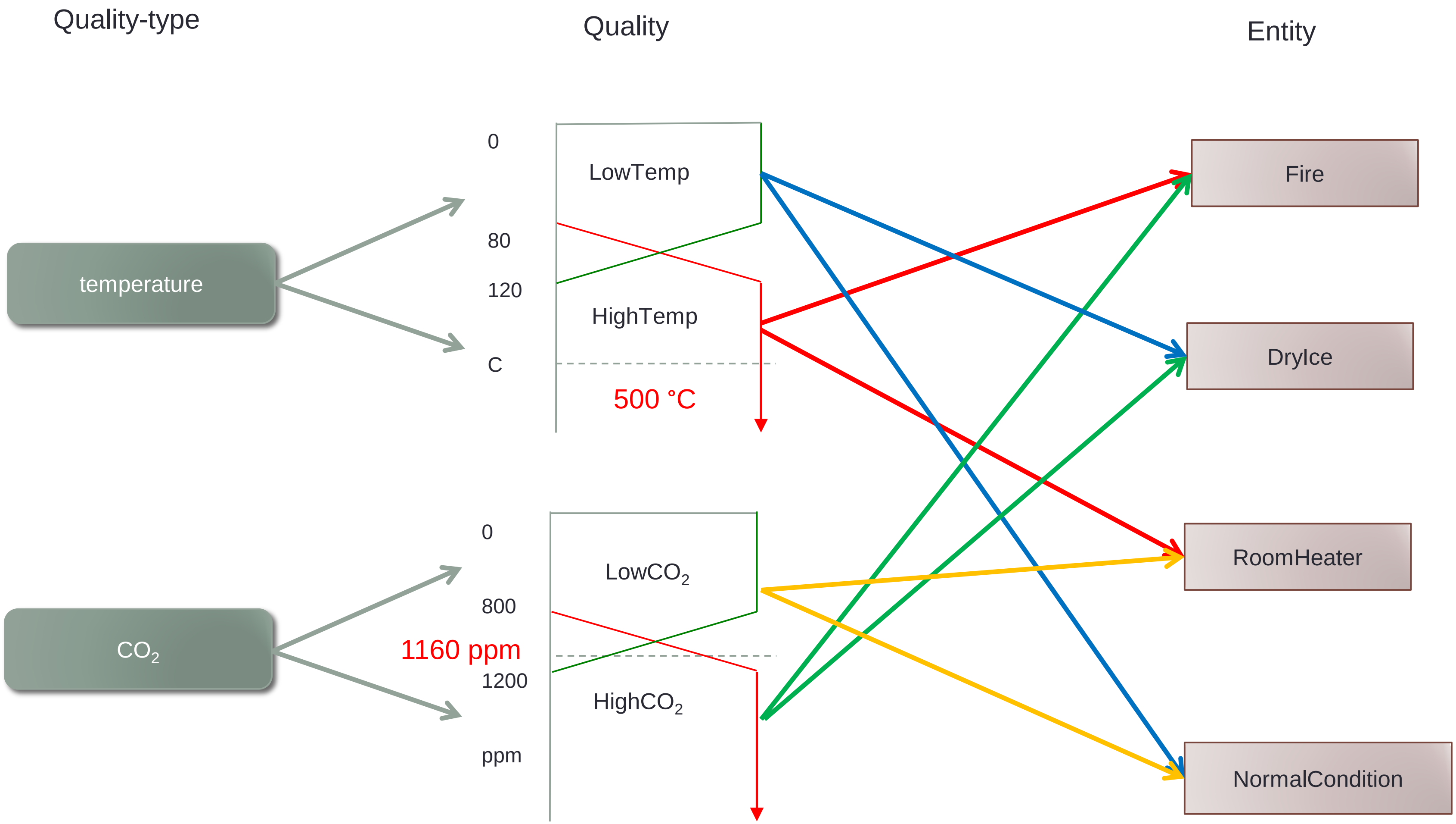


$$\mu_{LowCO_2}(a) = \frac{1200 - 1160}{400} = 0.1$$

Membership function μ

$$\mu_{HighCO_2}(a) = \frac{1160 - 800}{400} = 0.9$$

Fuzzy abductive reasoning



$$\mu_{Fire}(a) = \mu_{HighTemp}(a) \wedge \mu_{HighCO_2}(a)$$

$$io:entity \equiv \{\exists\, io:inheresIn.\{HighCO_2\} \sqcup \exists\, io:inheresIn.\{LowCO_2\}\} \sqcap \{\exists\, io:inheresIn.\{HighTemp\}\}$$

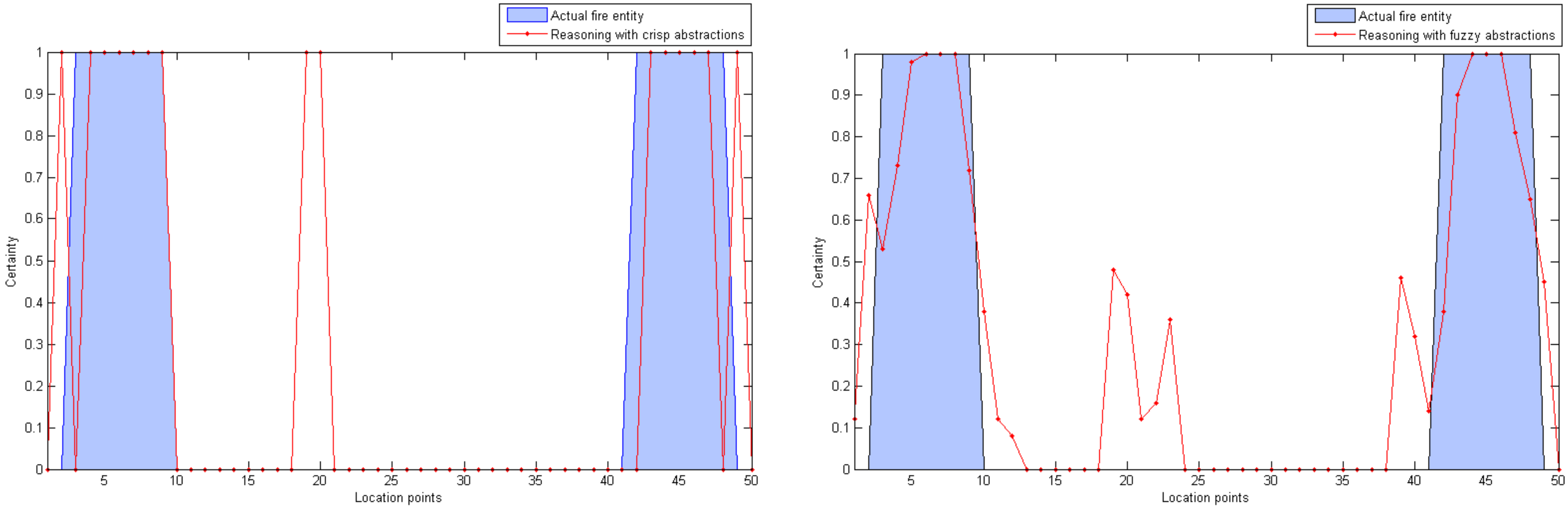
$$\equiv \{\{Fire, DryIce\} \sqcup \{NormalCondition, RoomHeater\}\} \sqcap \{Fire, RoomHeater\}$$

$$\equiv \{Fire, RoomHeater\}$$

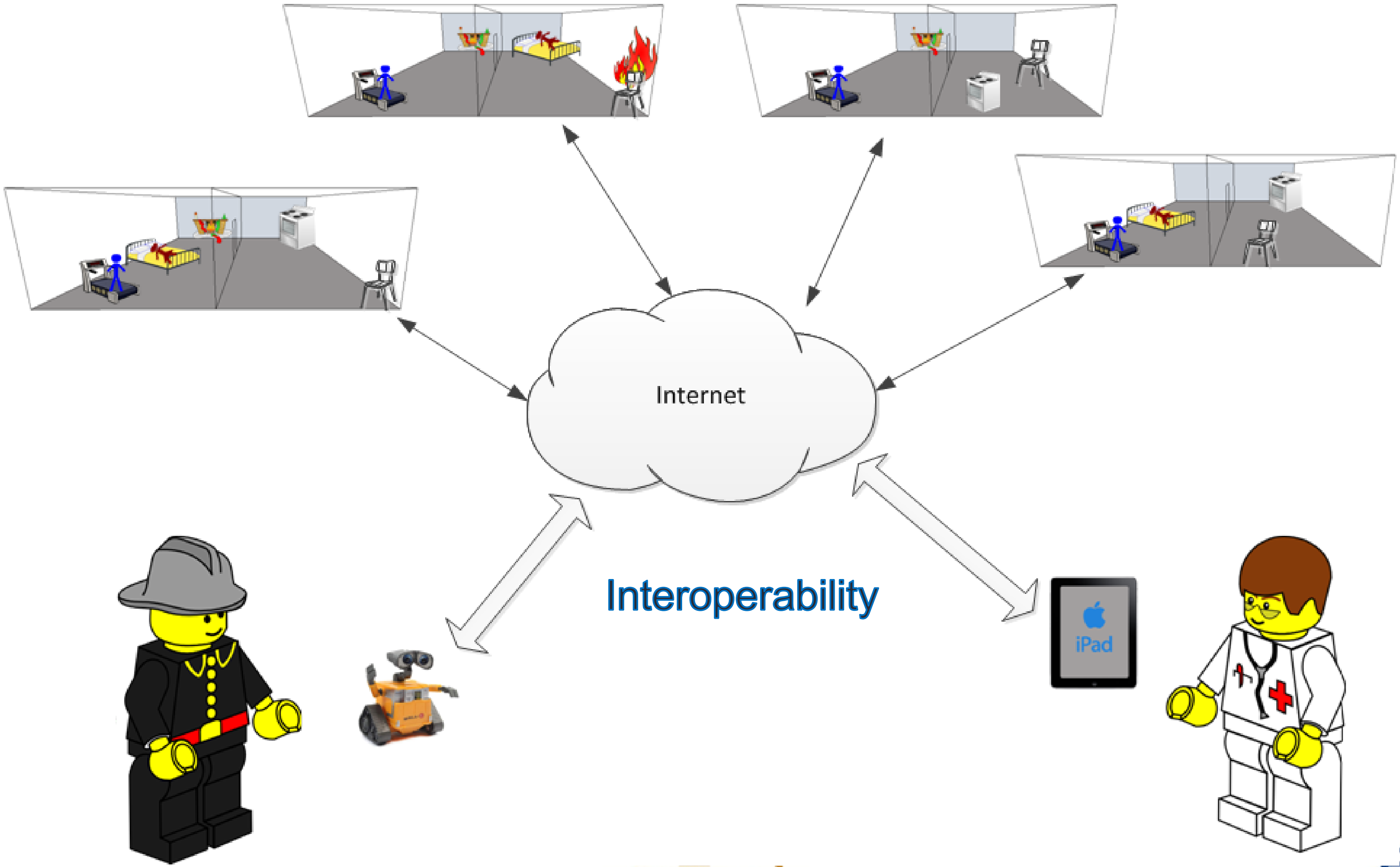
$$\mu_{Fire}(a) = \mu_{HighTemp}(a) \wedge \mu_{HighCO_2}(a) = \min(1{,}0.9) = 0.9$$

$$\mu_{RoomHeater}(a) = \mu_{HighTemp}(a) \wedge \mu_{LowCO_2}(a) = \min(1{,}0.1) = 0.1$$

Evaluation – Contextual Situation Awareness

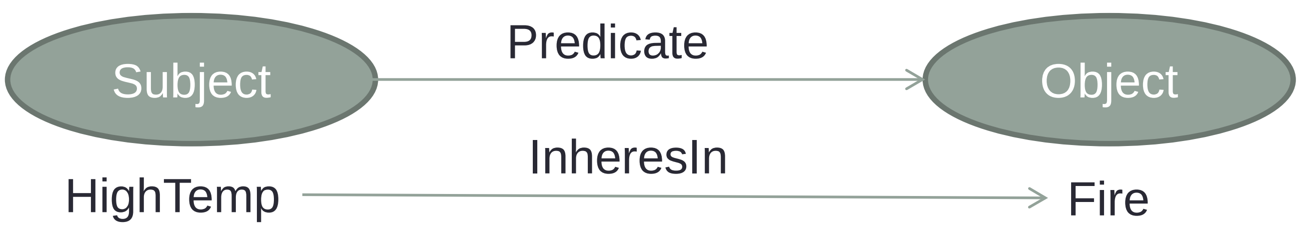


Reasoning approach	Accuracy	Precision	Recall
Crisp abductive reasoning	86 %	78.57 %	73.33 %
Fuzzy abductive reasoning	94 %	92.85 %	86.66 %


Internet
Interoperability
iPad

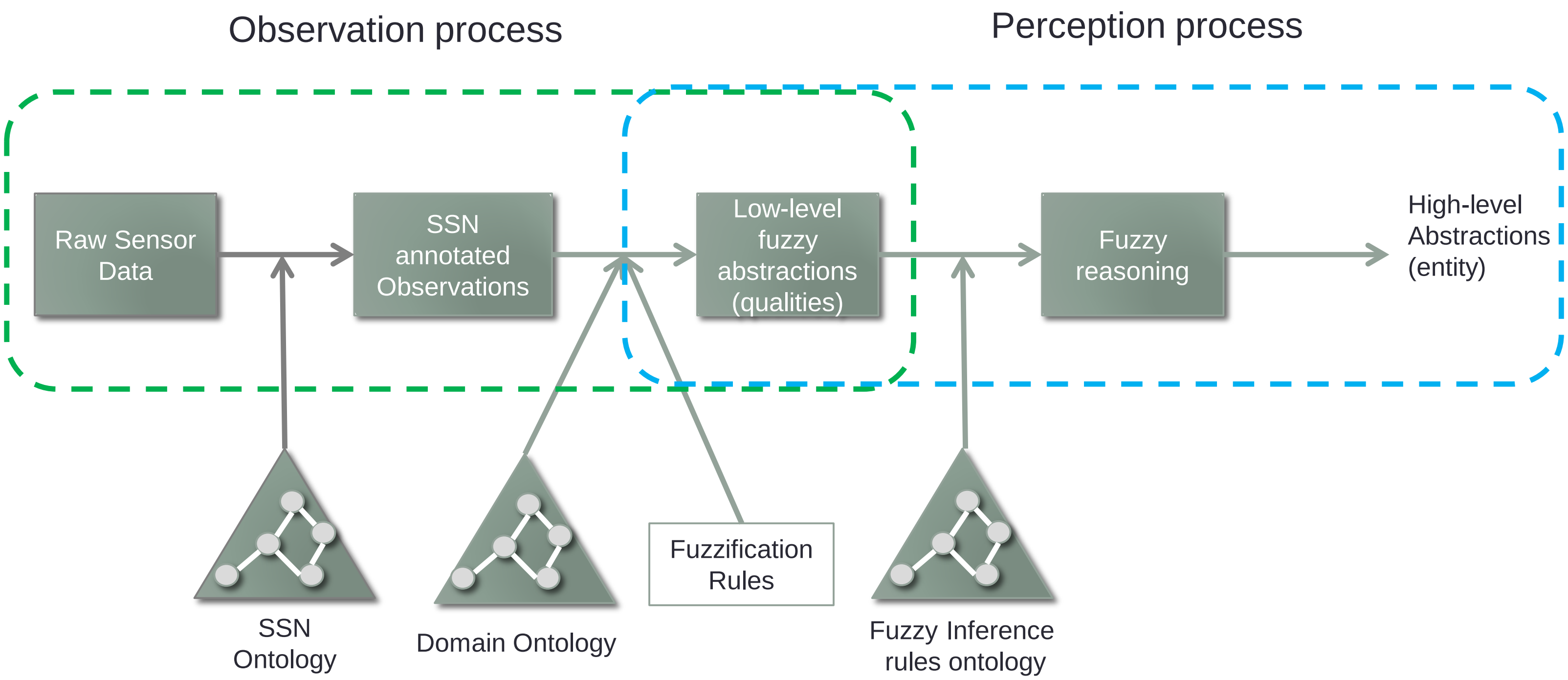
Semantic Web

- Semantic web:
  - Formally define the meaning of information on web.
  - Provide expressive representation, formal analysis of resources.
- Ontology
  - Formally represents knowledge as a set of concepts within a domain and the relationships between pairs of concepts.
- RDF (Resource Description Framework)
  - Graph-based language for modeling of information.
  - Allows linking of data through named properties.



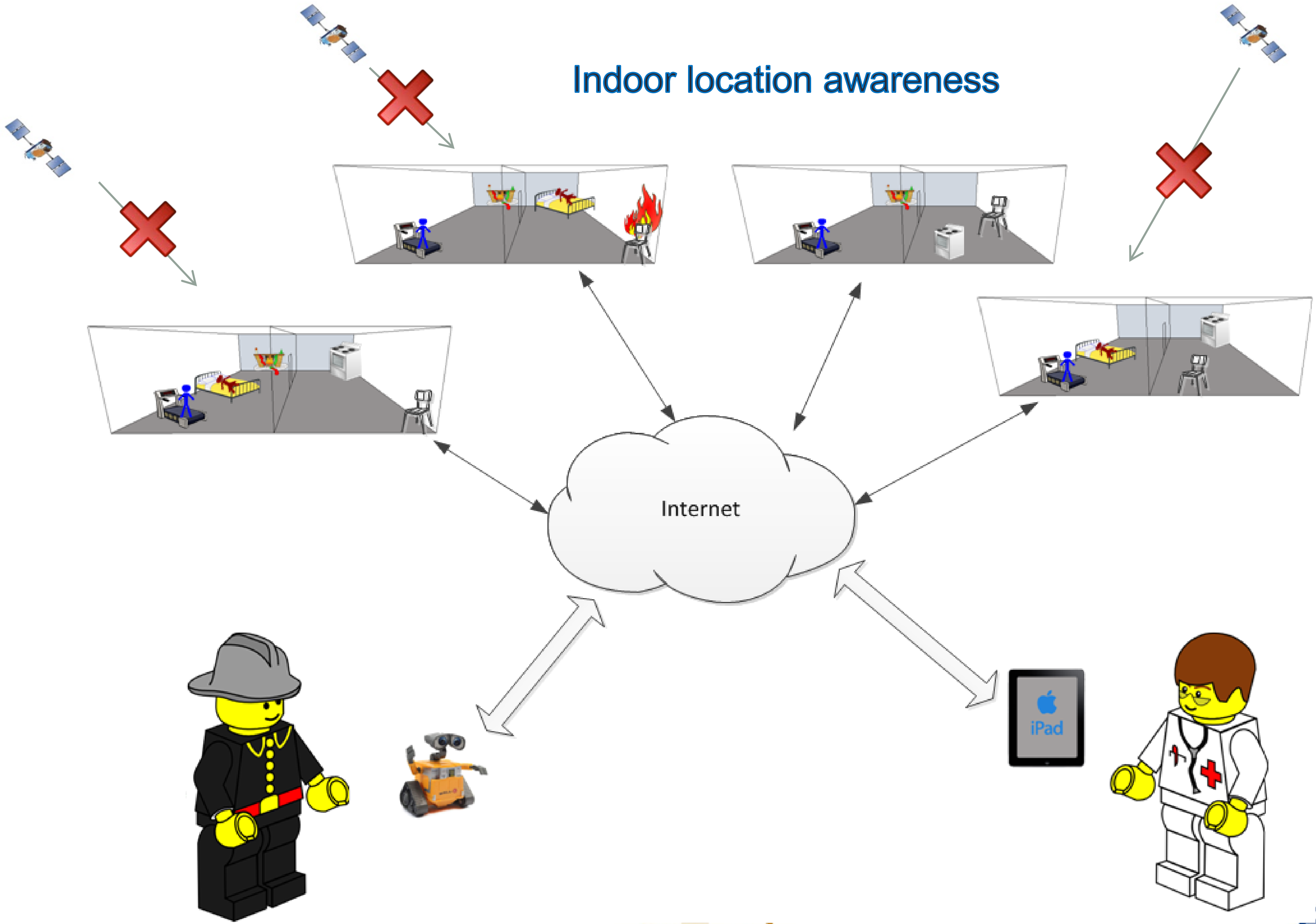
http://www-ksl.stanford.edu/kst/what-is-an-ontology.html

Contextual situation awareness (Semantic modeling)



Indoor Localization

Indoor location awareness



Traditional Indoor Localization Techniques

- Active Badge and Active Bat system.
- RADAR: An In-building RF-based user location and tracking system.
- RFID radar

RF

- Object tracking with multiple cameras
- Computer vision based localization

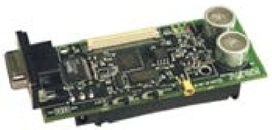
Camera

- Wireless Sensor Network

TDoA

TDoA (Time Difference of Arrival)

Stage 1: Beacon transmits RF and Us signals together



Beacon

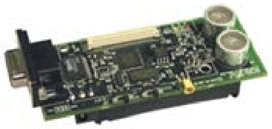
RF Signal

Ultrasonic Signal

Stage 2: Listener receives RF signal first at T_{rf} and starts the clock

Stage 3: At T_{us} time US signals is received by Listener

Stage 3: Distance is calculated using ΔT and speed of signals

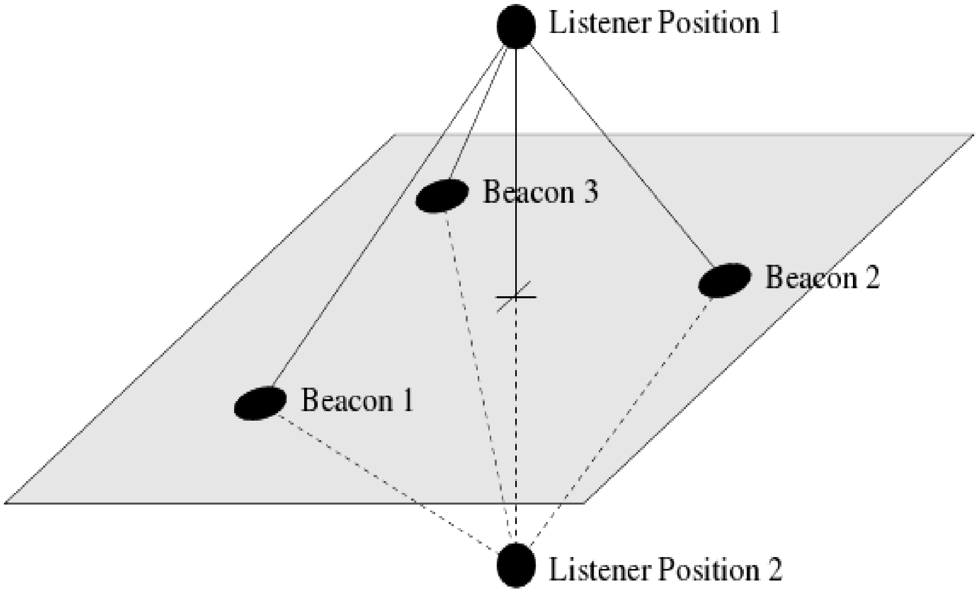


Listener

Trilateration

Number of nodes = 3.

$$d_i^{\,2} = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \text{ for } i = 1, 2, 3$$



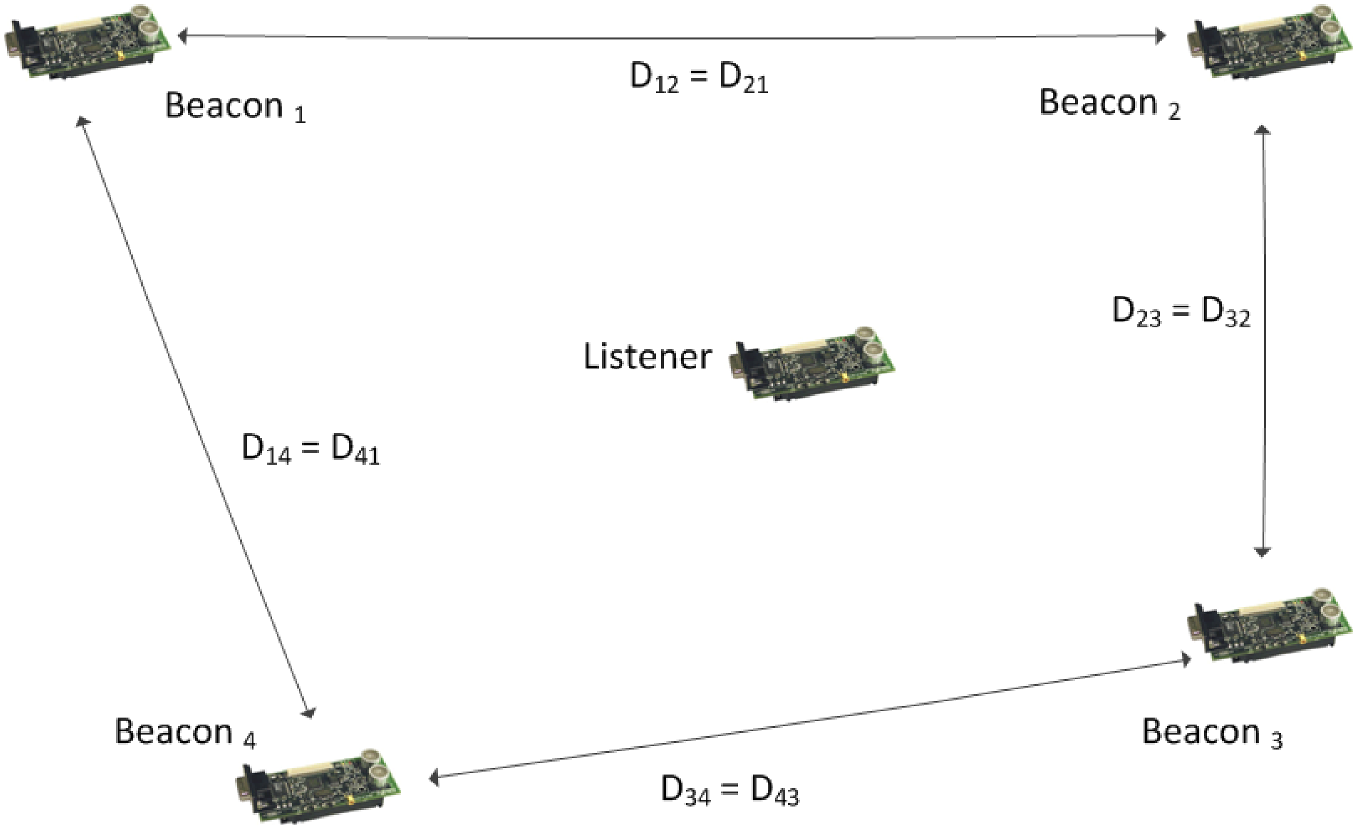
Outlier rejection and Multilateration

The Proposed Algorithm

- Utilizes fusion of RSS (received signal strength) of RF signal and TDoA data for accurate distance estimation.
- The algorithm stages:-
  - RSSI data training
  - Distance estimation
  - Localization

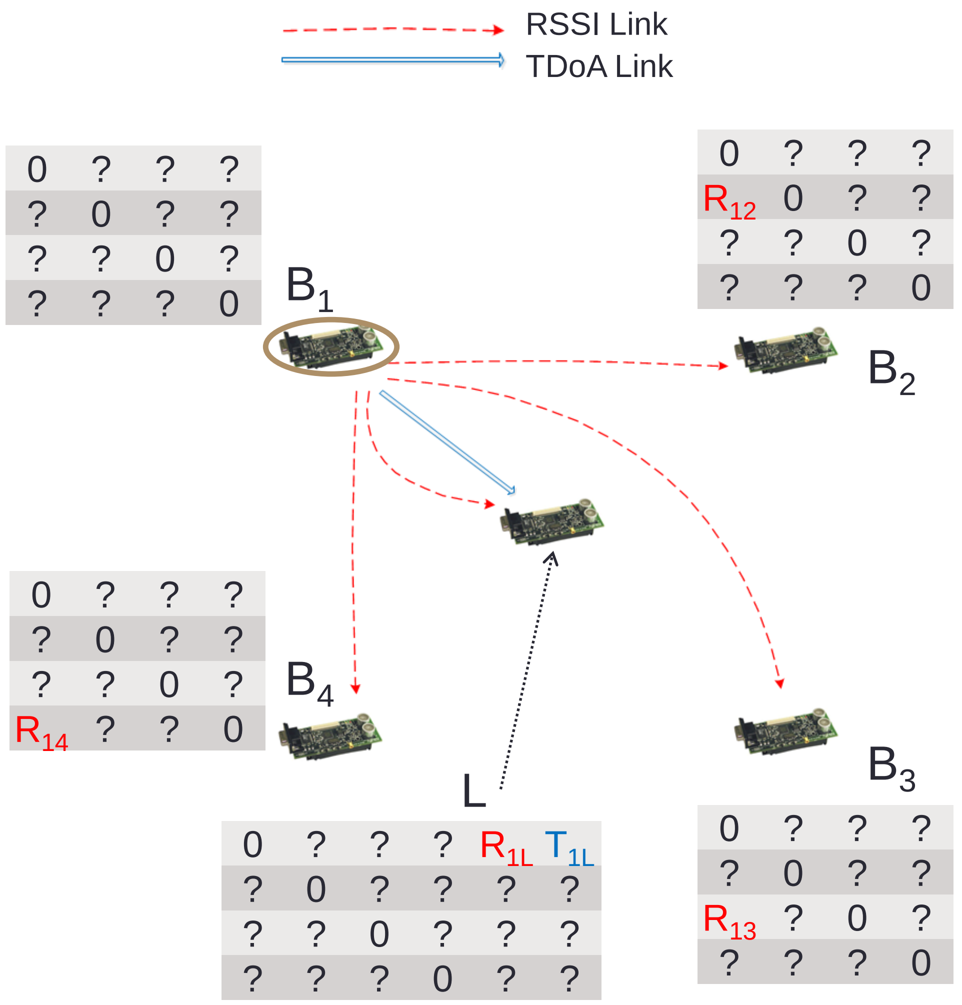
- Uses TDoA as a primary distance estimation technique.
- RSSI data is trained and converted into appropriate distance measurements.
- The proposed algorithm can be used in absence of one or many TDoA links.

Initial Conditions

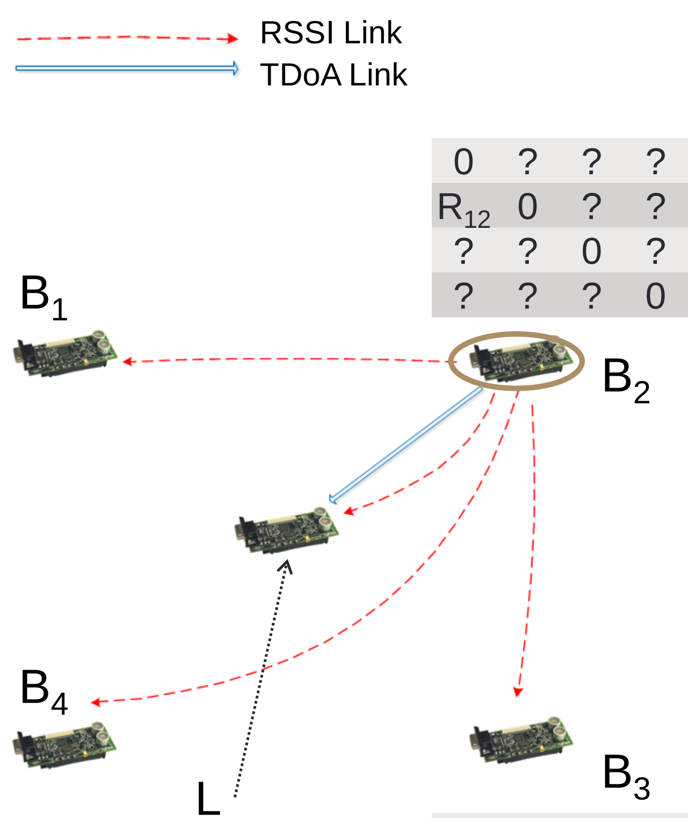


- Distances between all beacons are known and fixed

Beacon B_1 Transmit Data



Beacon B_2 Transmit Data



B1:

0	R_{21}	?	?
R_{12}	0	?	?
?	?	0	?
?	?	?	0

B2:

0	?	?	?
R_{12}	0	?	?
?	?	0	?
?	?	?	0

B4:

0	?	?	?
R_{12}	0	?	?
?	?	0	?
R_{14}	R_{24}	?	0

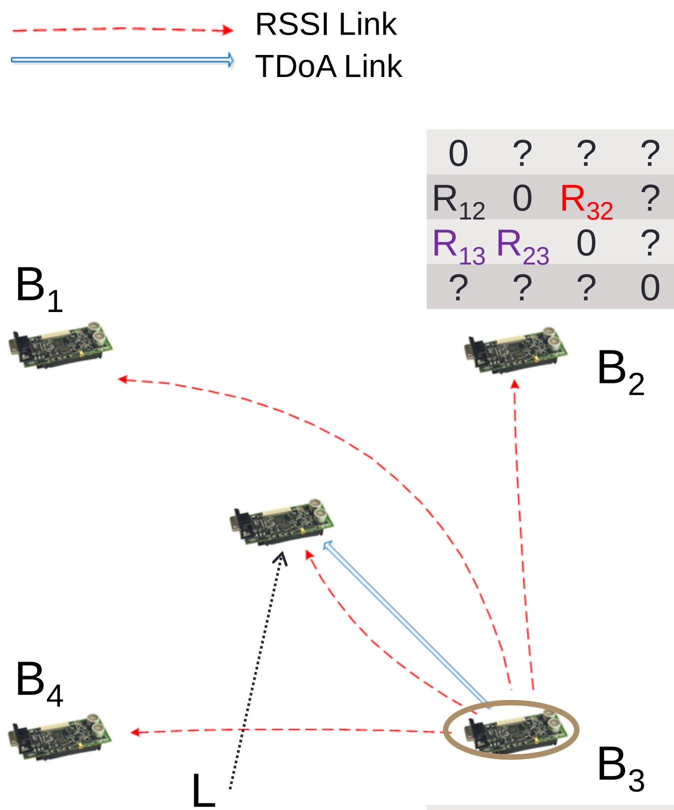
L:

0	?	?	?	R_{1L}	T_{1L}
R_{12}	0	?	?	R_{2L}	T_{2L}
?	?	0	?	?	?
?	?	?	0	?	?

B3:

0	?	?	?
R_{12}	0	?	?
R_{13}	R_{23}	0	?
?	?	?	0

Beacon B_3 Transmit Data



B_1:

0	R_{21}	R_{31}	?
R_{12}	0	?	?
R_{13}	R_{23}	0	?
?	?	?	0

B_2:

0	?	?	?
R_{12}	0	R_{32}	?
R_{13}	R_{23}	0	?
?	?	?	0

B_4:

0	?	?	?
R_{12}	0	?	?
R_{13}	R_{23}	0	?
R_{14}	R_{24}	R_{34}	0

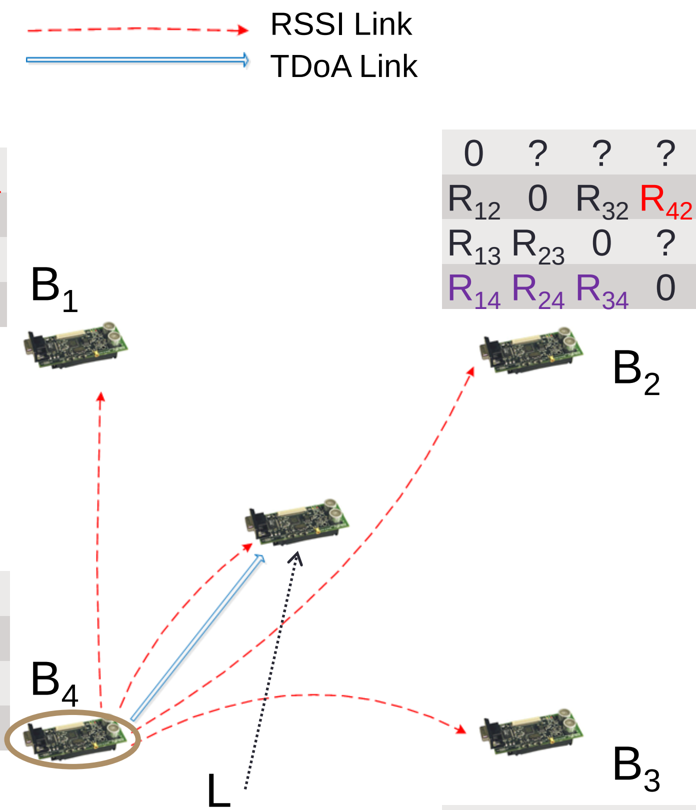
L:

0	?	?	?	R_{1L}	T_{1L}
R_{12}	0	?	?	R_{2L}	T_{2L}
R_{13}	R_{23}	0	?	R_{3L}	T_{3L}
?	?	?	0	?	?

B_3:

0	?	?	?
R_{12}	0	?	?
R_{13}	R_{23}	0	?
?	?	?	0

Beacon B_4 Transmit Data



0	R_{21}	R_{31}	R_{41}
R_{12}	0	?	?
R_{13}	R_{23}	0	?
R_{14}	R_{24}	R_{34}	0

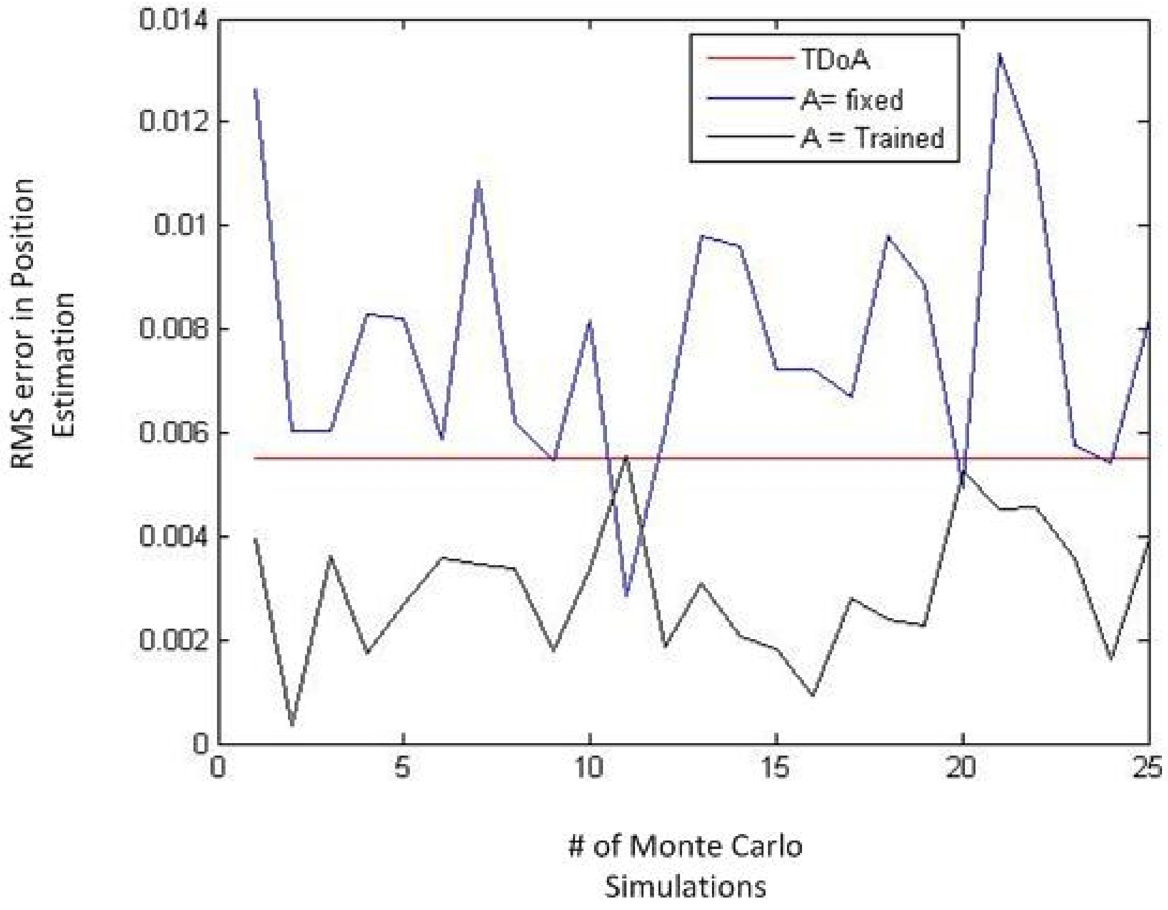
0	?	?	?
R_{12}	0	R_{32}	R_{42}
R_{13}	R_{23}	0	?
R_{14}	R_{24}	R_{34}	0

0	?	?	?
R_{12}	0	?	?
R_{13}	R_{23}	0	?
R_{14}	R_{24}	R_{34}	0

0	?	?	?	R_{1L}	T_{1L}
R_{12}	0	?	?	R_{2L}	T_{2L}
R_{13}	R_{23}	0	?	R_{3L}	T_{3L}
R_{14}	R_{24}	R_{34}	0	R_{4L}	T_{4L}

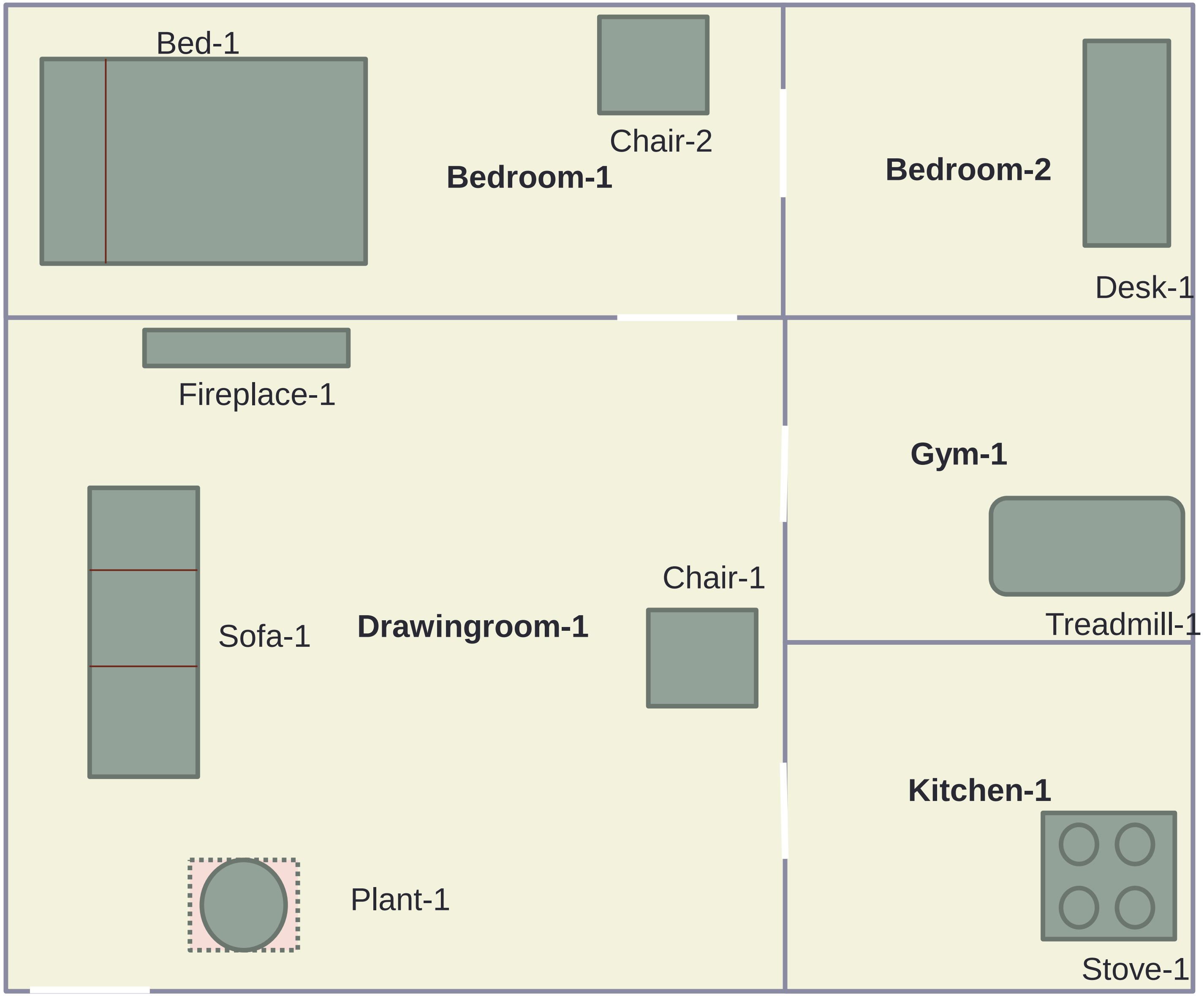
0	?	?	?
R_{12}	0	?	?
R_{13}	R_{23}	0	R_{43}
R_{14}	R_{24}	R_{34}	0

Evaluation– Proposed Algorithm

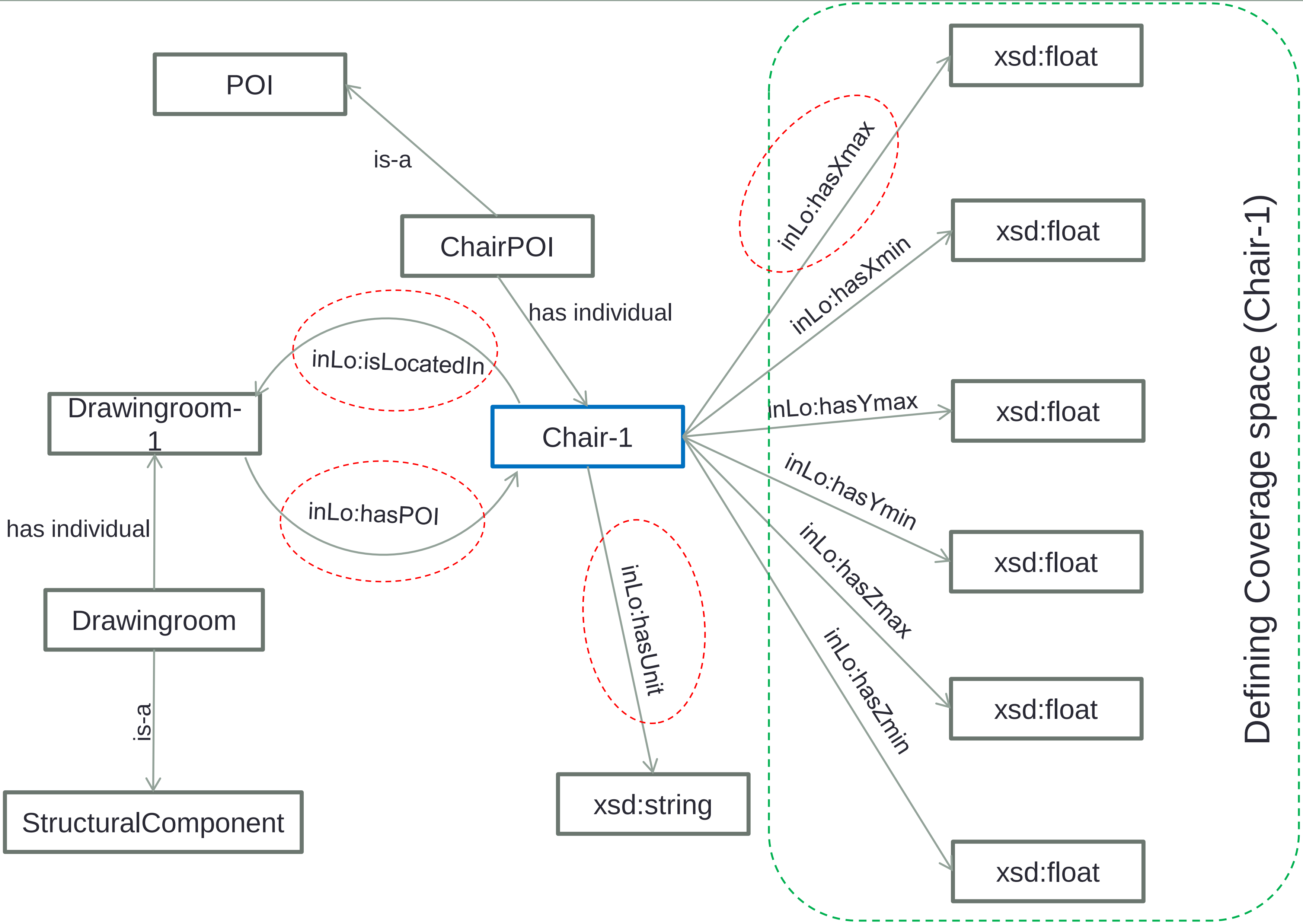


Location Awareness

Indoor Environment



Hierarchical mapping of the indoor environment


POI
is-a
ChairPOI
has individual
inLo:isLocatedIn
Drawingroom-1
Chair-1
inLo:hasPOI
has individual
Drawingroom
is-a
StructuralComponent
inLo:hasUnit
xsd:string
inLo:hasXmax
inLo:hasXmin
inLo:hasYmax
inLo:hasYmin
inLo:hasZmax
inLo:hasZmin
xsd:float
xsd:float
xsd:float
xsd:float
xsd:float
xsd:float
Defining Coverage space (Chair-1)

Raw location : *(x, y) = (190 cm, 570 cm)*

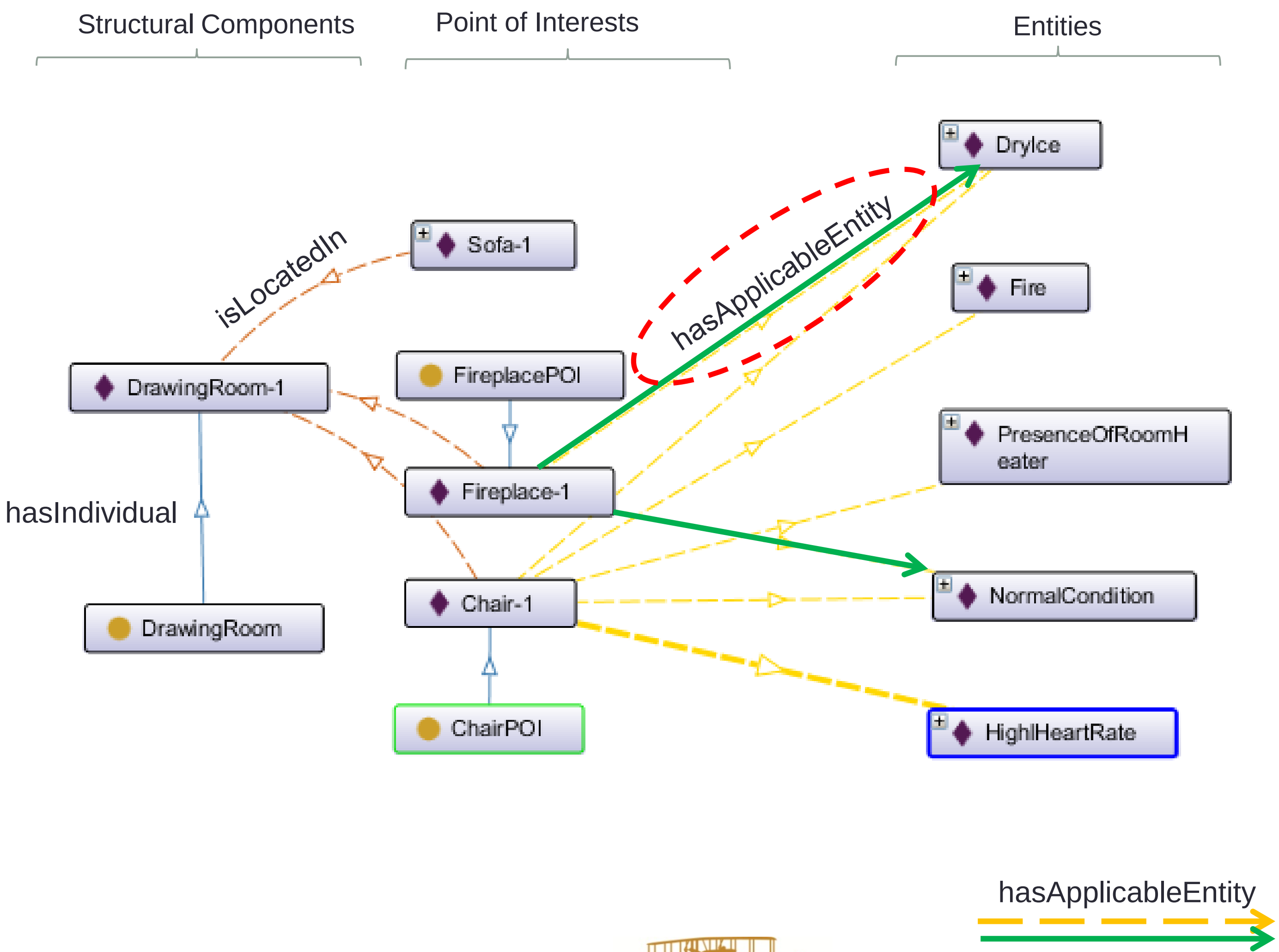
$$IdentifiedPOI$$

$$\equiv \{\exists inLO: PointOfInterest.\{inLo: hasXmax \geq 190\}\}$$
$$\sqcap \{\exists inLO: PointOfInterest.\{inLo: hasXmin \leq 190\}\}$$
$$\sqcap \{\exists inLO: PointOfInterest.\{inLo: hasYmax \geq 570\}\}$$
$$\sqcap \{\exists inLO: PointOfInterest.\{inLo: hasYmin \leq 570\}\}$$

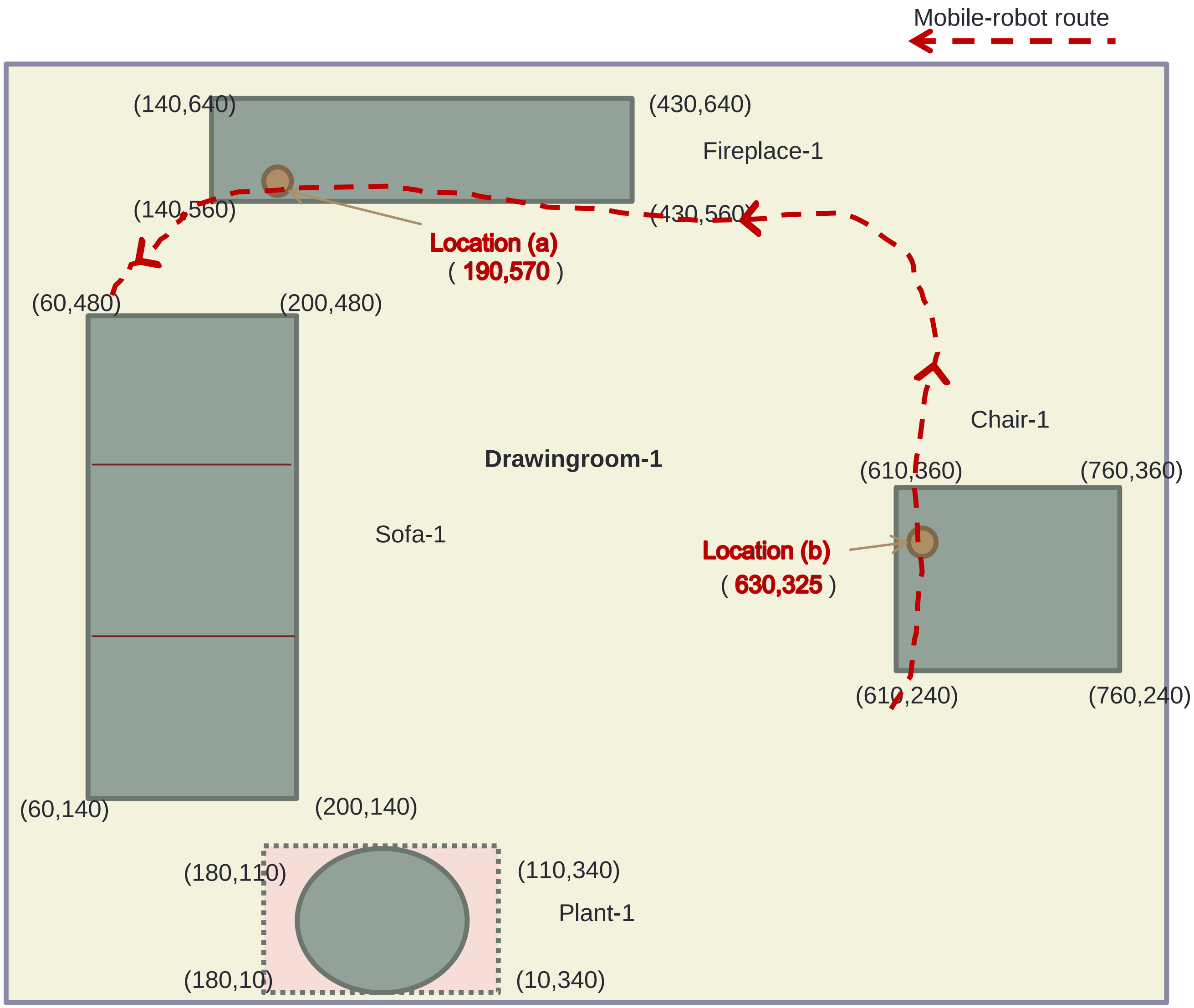
$$\equiv \{Sofa - 1, Chair - 1, Fireplace - 1\}$$
$$\sqcap \{Sofa - 1, Chair - 1, Fireplace - 1\}$$
$$\sqcap \{Chair - 1\}$$
$$\sqcap \{Sofa - 1, Plant - 1, Fireplace - 1, Chair - 1\}$$

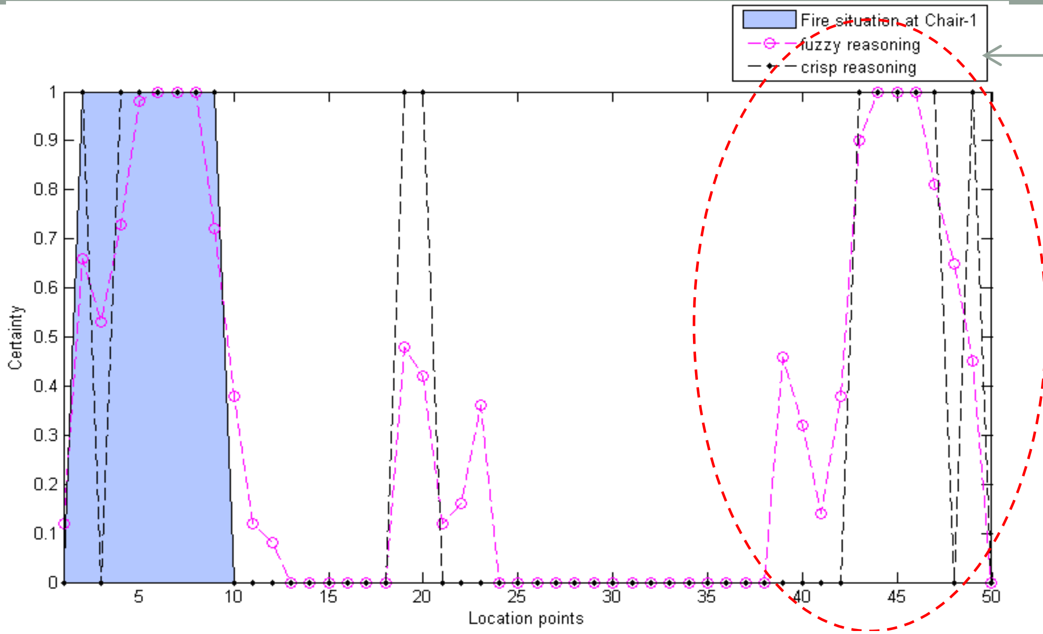
$$\equiv \{Chair - 1\}$$

Object-entity relationship



Evaluation – Location Awareness

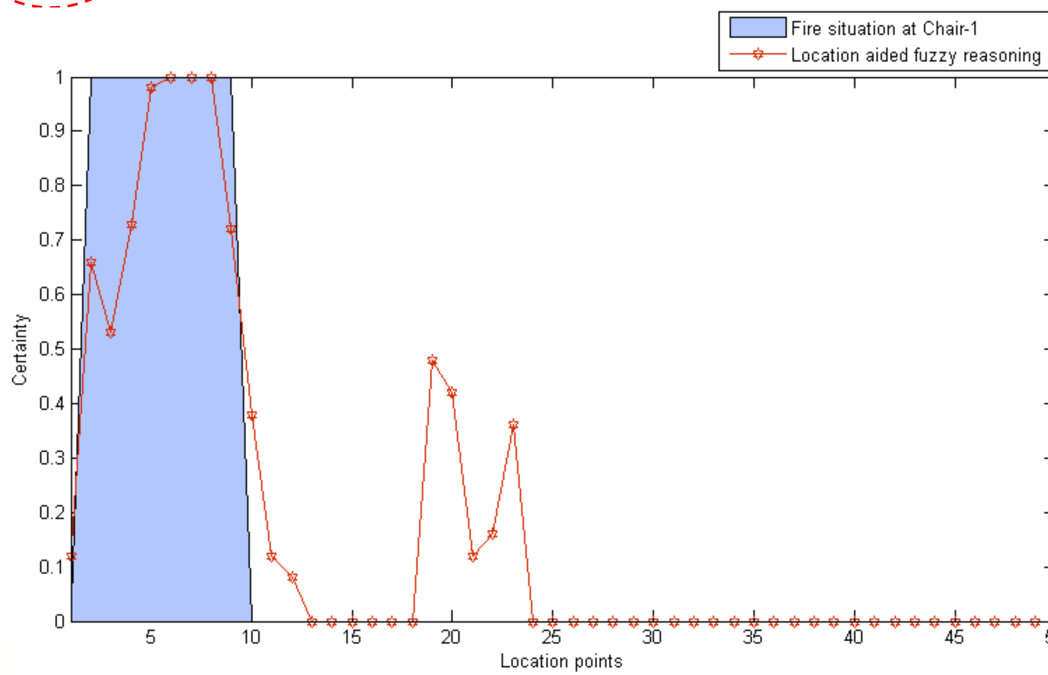




Location independent reasoning

Fireplace

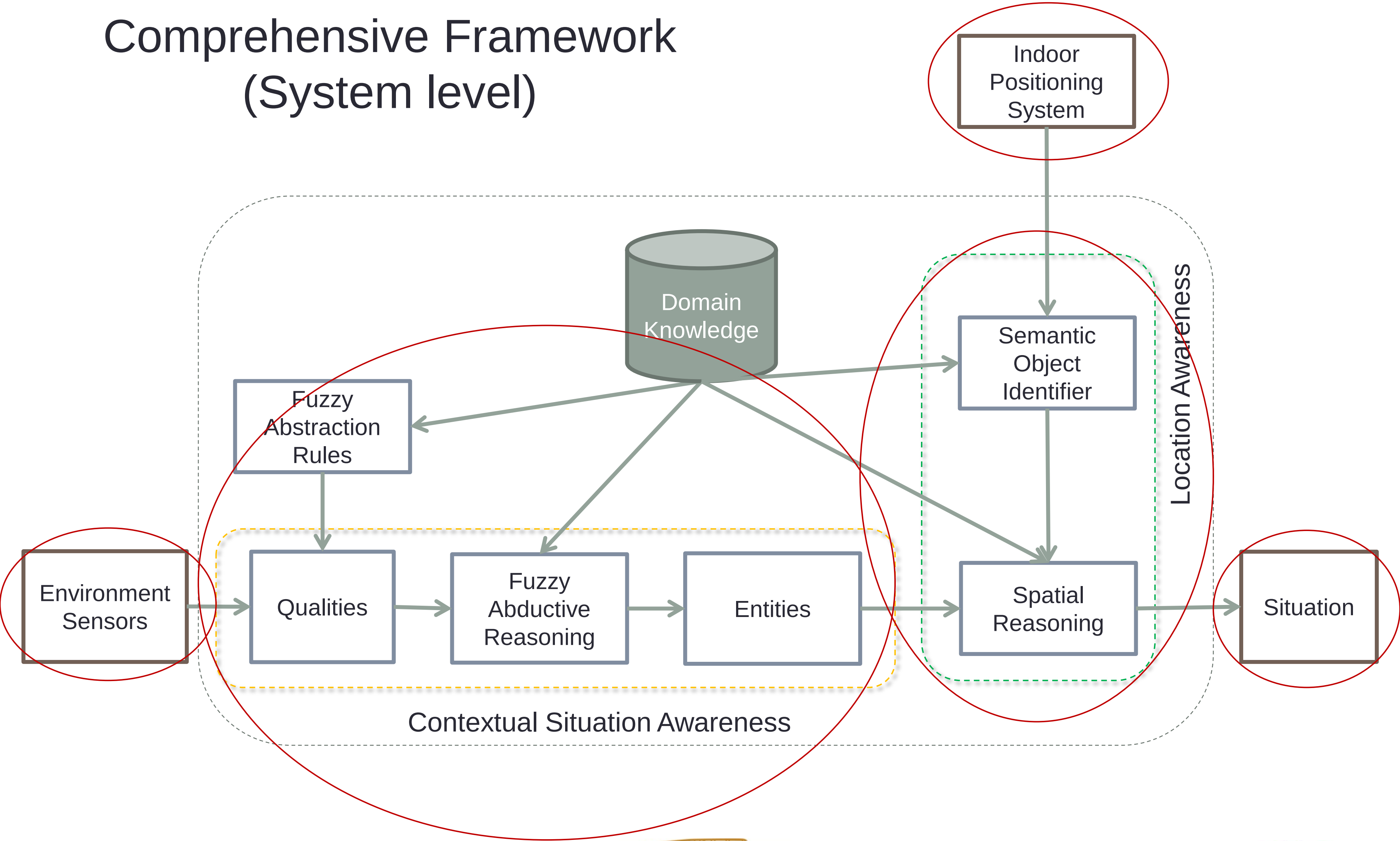
Location aided reasoning



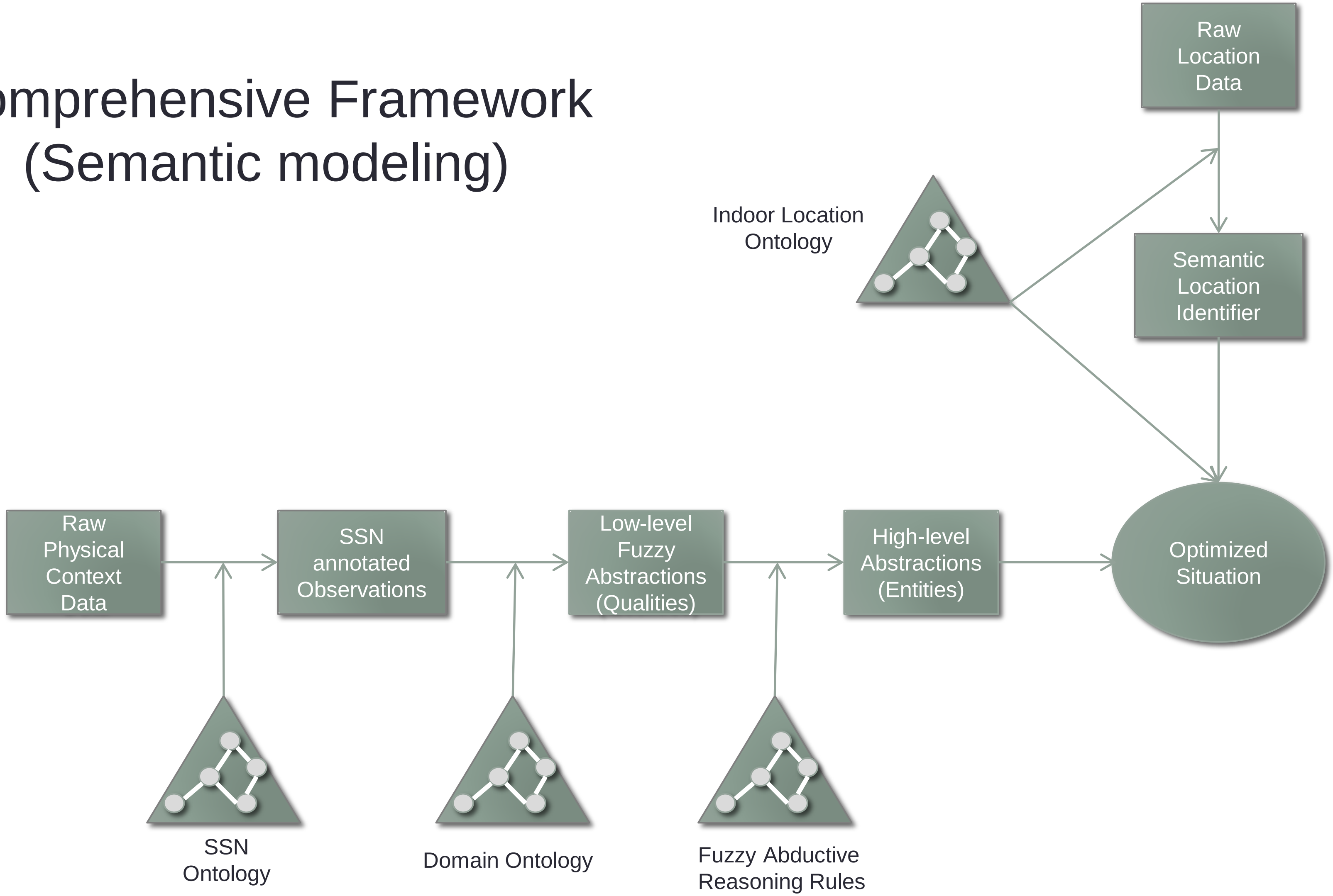
Reasoning approach	Precision	Recall
Crisp abductive reasoning	87.5 %	43.75 %
Fuzzy abductive reasoning	100 %	50 %
Location aided fuzzy abductive reasoning	100 %	88.89 %

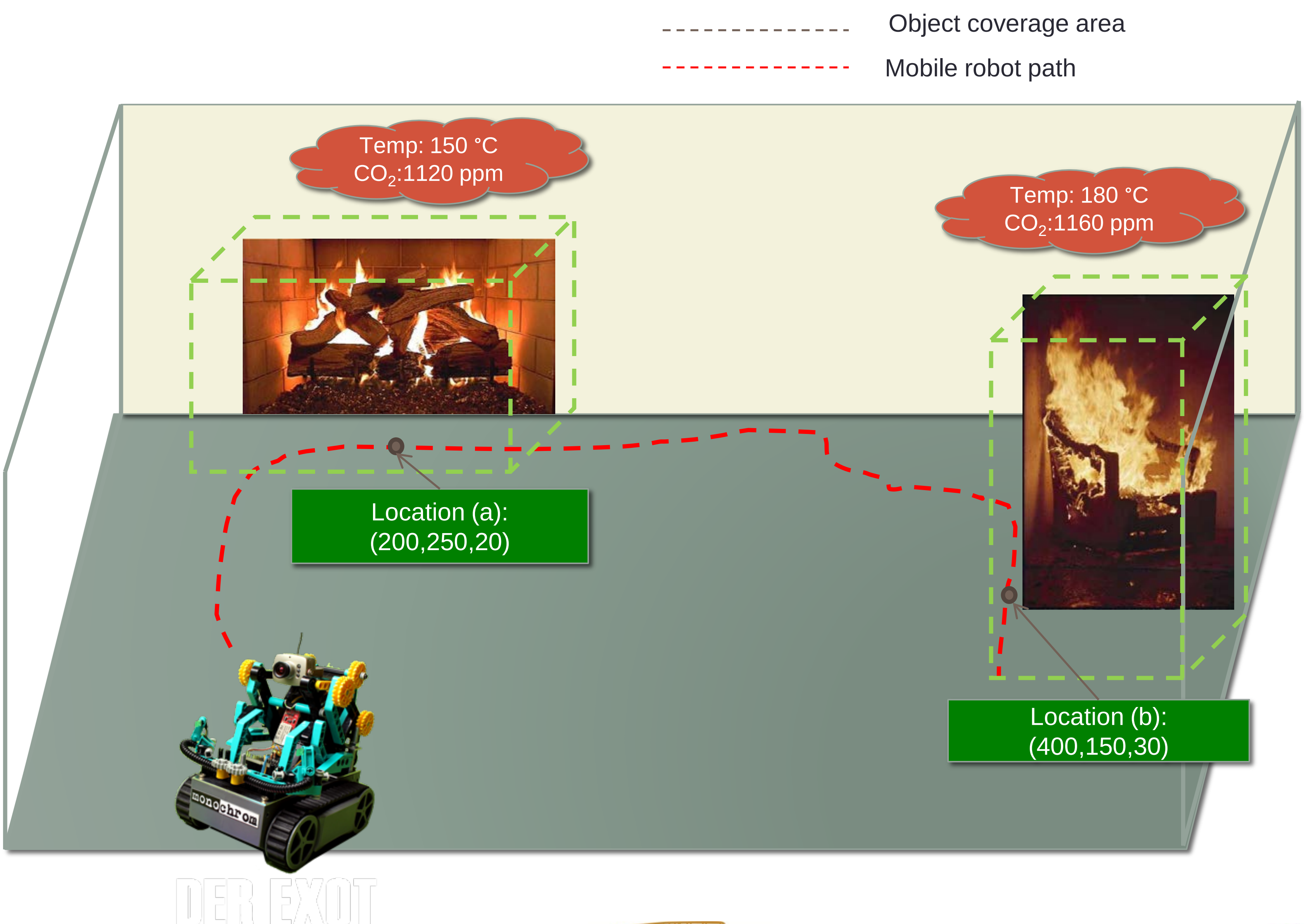
Comprehensive Framework

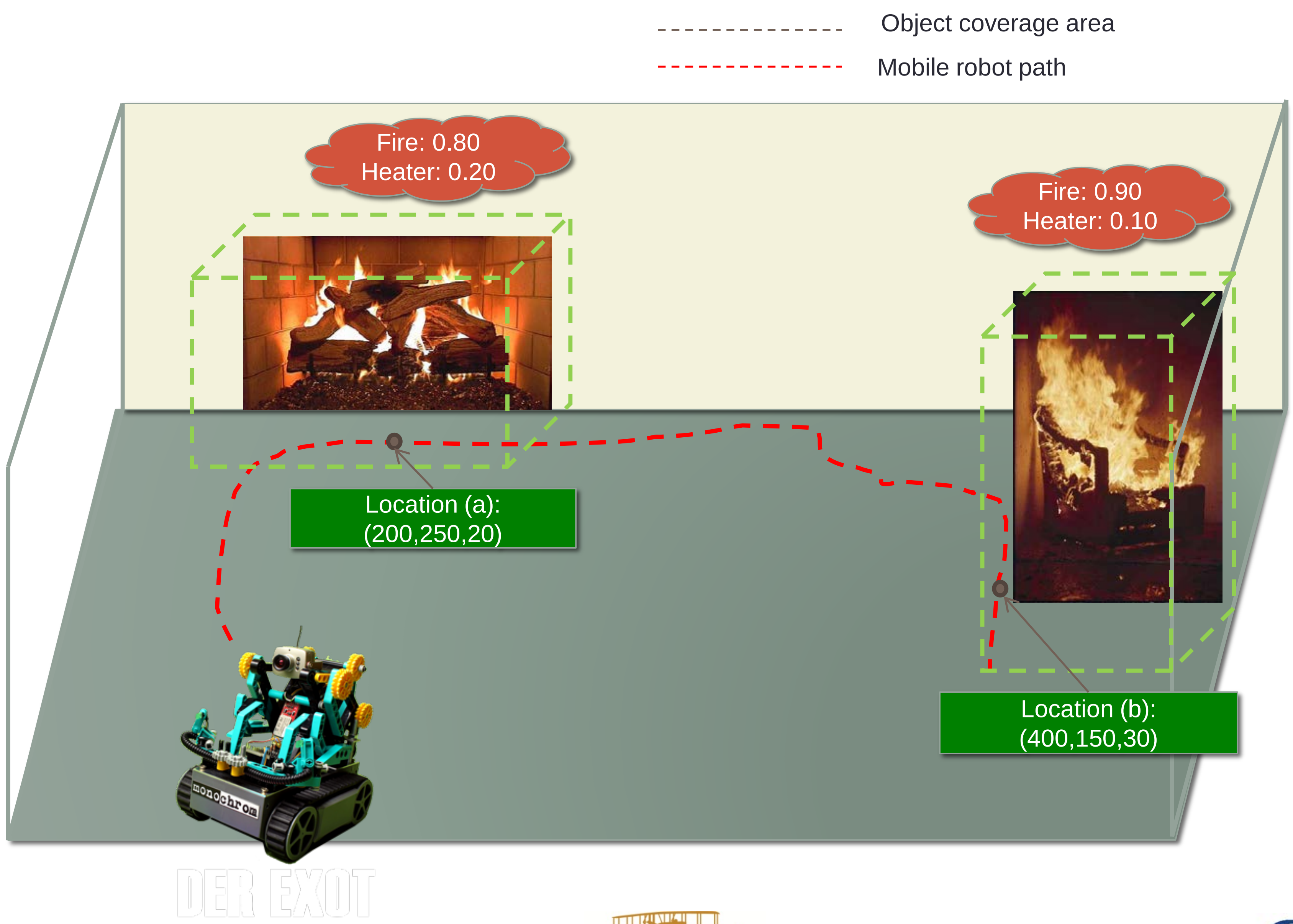
Comprehensive Framework (System level)

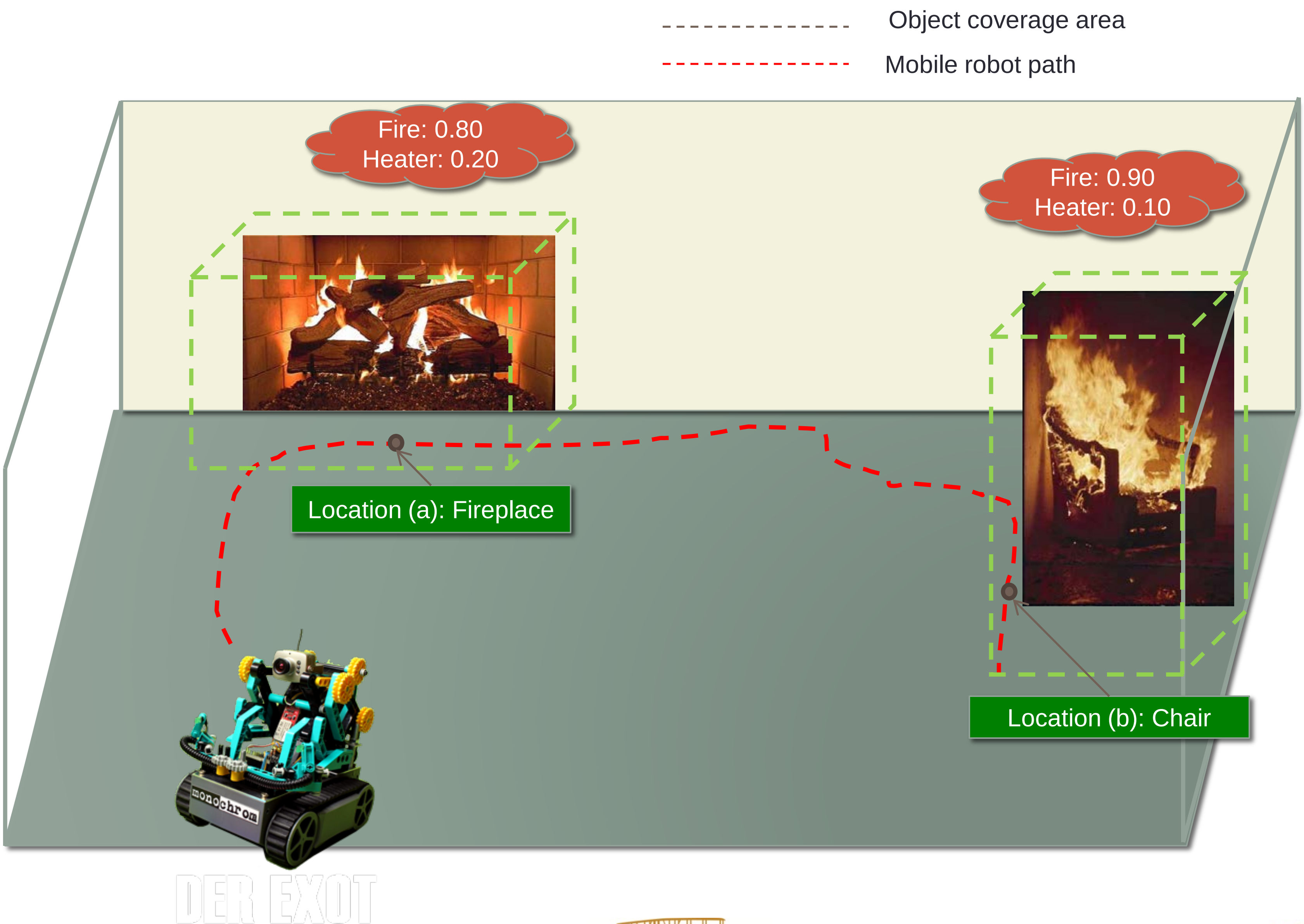


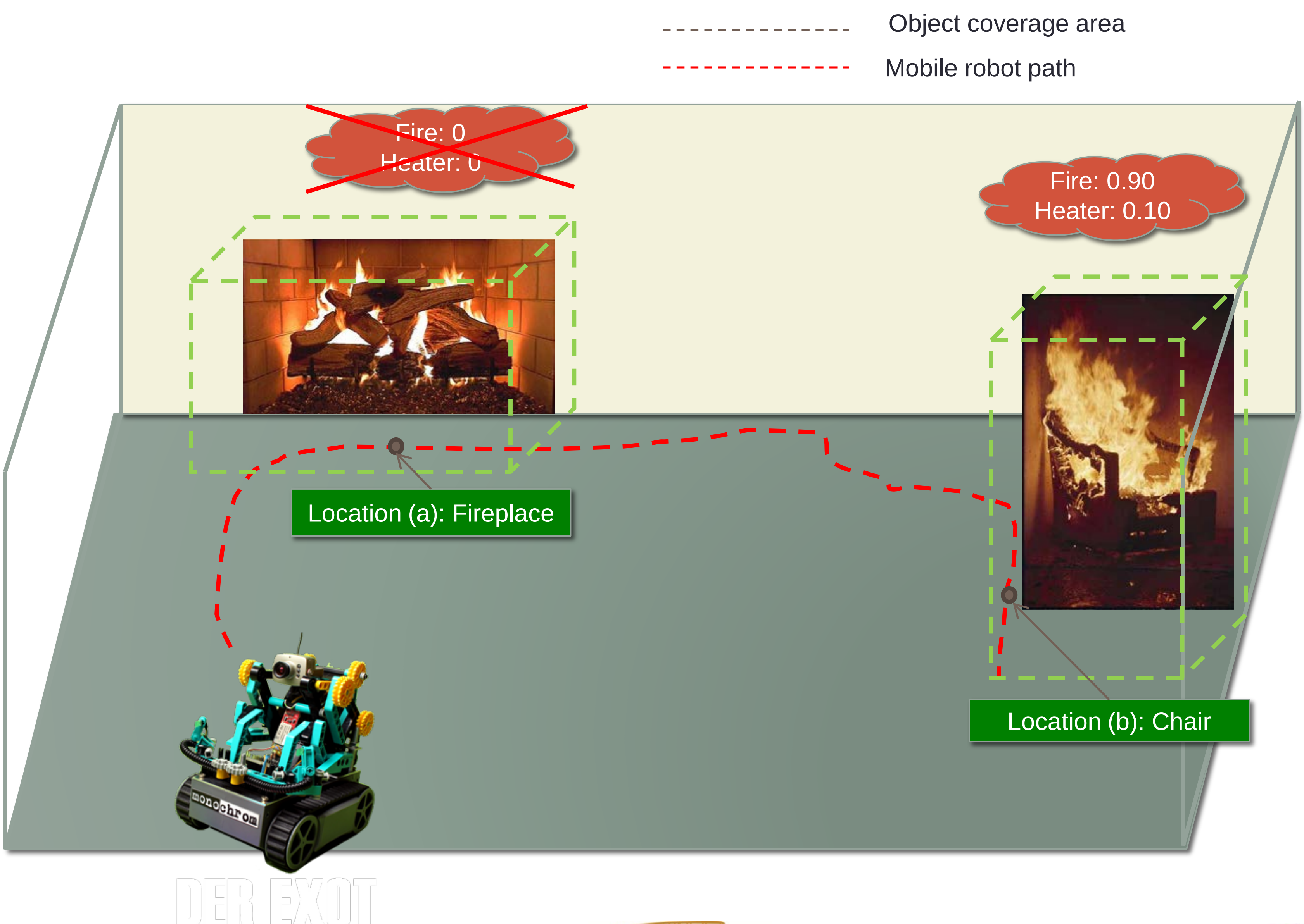
Comprehensive Framework (Semantic modeling)




Object coverage area
Mobile robot path
Temp: 150 °C
CO2:1120 ppm
Temp: 180 °C
CO2:1160 ppm
Location (a):
(200,250,20)
Location (b):
(400,150,30)
DER EXOT


Object coverage area
Mobile robot path
Fire: 0.80
Heater: 0.20
Fire: 0.90
Heater: 0.10
Location (a):
(200,250,20)
Location (b):
(400,150,30)
monochrom
DER EXOT


Object coverage area
Mobile robot path
Fire: 0.80
Heater: 0.20
Fire: 0.90
Heater: 0.10
Location (a): Fireplace
Location (b): Chair
monochrom
DER EXOT


Object coverage area
Mobile robot path
Fire: 0
Heater: 0
Fire: 0.90
Heater: 0.10
Location (a): Fireplace
Location (b): Chair
monochrom
DER EXOT

Key Contributions

- Developed a fusion based indoor localization algorithm to achieve accurate spatial information of the sensing platform.
  - Accurate indoor localization algorithm.
  - Surveillance and tracking of mobile robots in indoor environments.
  - Integration of indoor positioning results with virtual world environment.

Related papers:

- P. Desai, N. Baine, and K. S. Rattan, "Fusion of RSSI and TDoA Measurements from Wireless Sensor Network for Robust and Accurate Indoor Localization," in *International Technical Meeting of The Institute of Navigation*, 2011, pp. 223–230.
- P. Desai, N. Baine, and K. S. Rattan, "Indoor localization for global information service using acoustic wireless sensor network," in *Proceedings of SPIE*, 2011, vol. 8053, no. 1, pp. 805304–805304–10.
- P. Desai and K. S. Rattan, "System Level Approach for Surveillance Using Wireless Sensor Networks and PTZ Camera," in *2008 IEEE National Aerospace and Electronics Conference*, 2008, pp. 353–357.
- P. Desai and K. S. Rattan, "Indoor localization and surveillance using wireless sensor network and Pan/Tilt camera," in *Proceedings of the IEEE 2009 National Aerospace Electronics Conference NAECON*, 2009, pp. 1–6.
- An invited journal paper in preparation.

Key Contributions

- Introduced fuzzy abstraction and inference technique to comprehend events via handling the uncertainty in the context information & the ambiguity in the domain knowledge.
  - P. Desai, C. Henson, P. Anatharam, and A. Sheth, "SECURE: Semantics Empowered resCUe Environment (Demonstration Paper)," in *4th International Workshop on Semantic Sensor Networks (SSN 2011)*, 2011, pp. 110–113.
  - A journal paper in preparation.

- Developed semantic mapping technique for indoor objects to aid the situational context awareness results via further discriminating not applicable events.
- Developed and deployed a comprehensive situation awareness framework for cyber-physical system.
  - A journal paper in preparation.

Future work

- Richer spatio-temporal relation modeling between indoor objects and entities
- Efficient coverage space for the indoor objects
- Accurate indoor localization via smartphones

Acknowledgements





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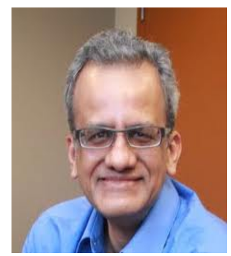




Questions?