Context-enhanced Information Fusion

ADVANCED ALGORITHMS FOR EFFECTIVELY FUSING
HARD AND SOFT INFORMATION

NATO STO IST-155 Lecture Series

Dept. Mathematics, Computer Science and Physics
University of Udine, Italy

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Thanks

- Organizers
- Collegues and co-authors
  - L. Snidaro, J. Garcia and W. Koch, *special session* "**Multi-Level Fusion: issues in bridging the gap between high and low level fusion**"
  - J. Garcia, L. Snidaro, J. M. Molina, Dr. I. Visentini, *special session* "**Context-based Information Fusion**"
  - IST-132 / RTG-063 Research Task Group on "**Information Filtering and Multi Source Information Fusion**"
  - L. Snidaro, J. García, J. Llinas, E. Blasch (eds.),"**Context Enhanced Information Fusion**", Springer, 2016 [5]

Outline

- Lecture I:
  - – Introduction to context
  - – Contex for IF
  - – Terminology and fundamental concepts
  - – Middleware / Context-aware architectures
- Lecture II:
  - – Applications

INTRODUCTION TO DATA FUSION

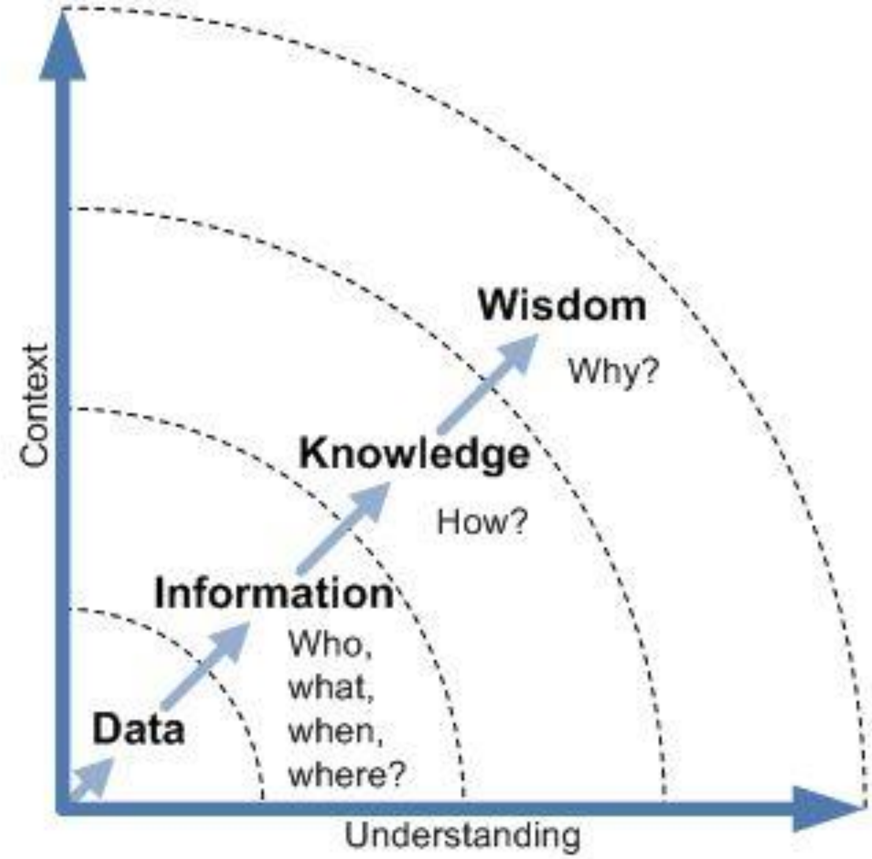
Many sources…

Nowadays IT systems have access to a large variety of inputs coming from…

- Sensors
- Databases / Repositories
- Internet
- Soft sources (humans!)
- …

What's Information?

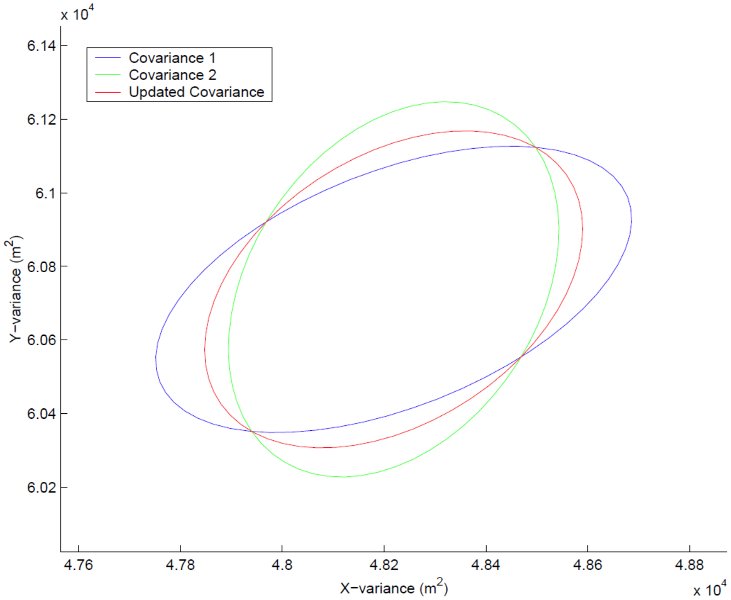
- Data is just signals, numbers, letters, strings, colors, etc.
- Information has higher semantic value …
- In many domains too much data and not enough information



Data Fusion

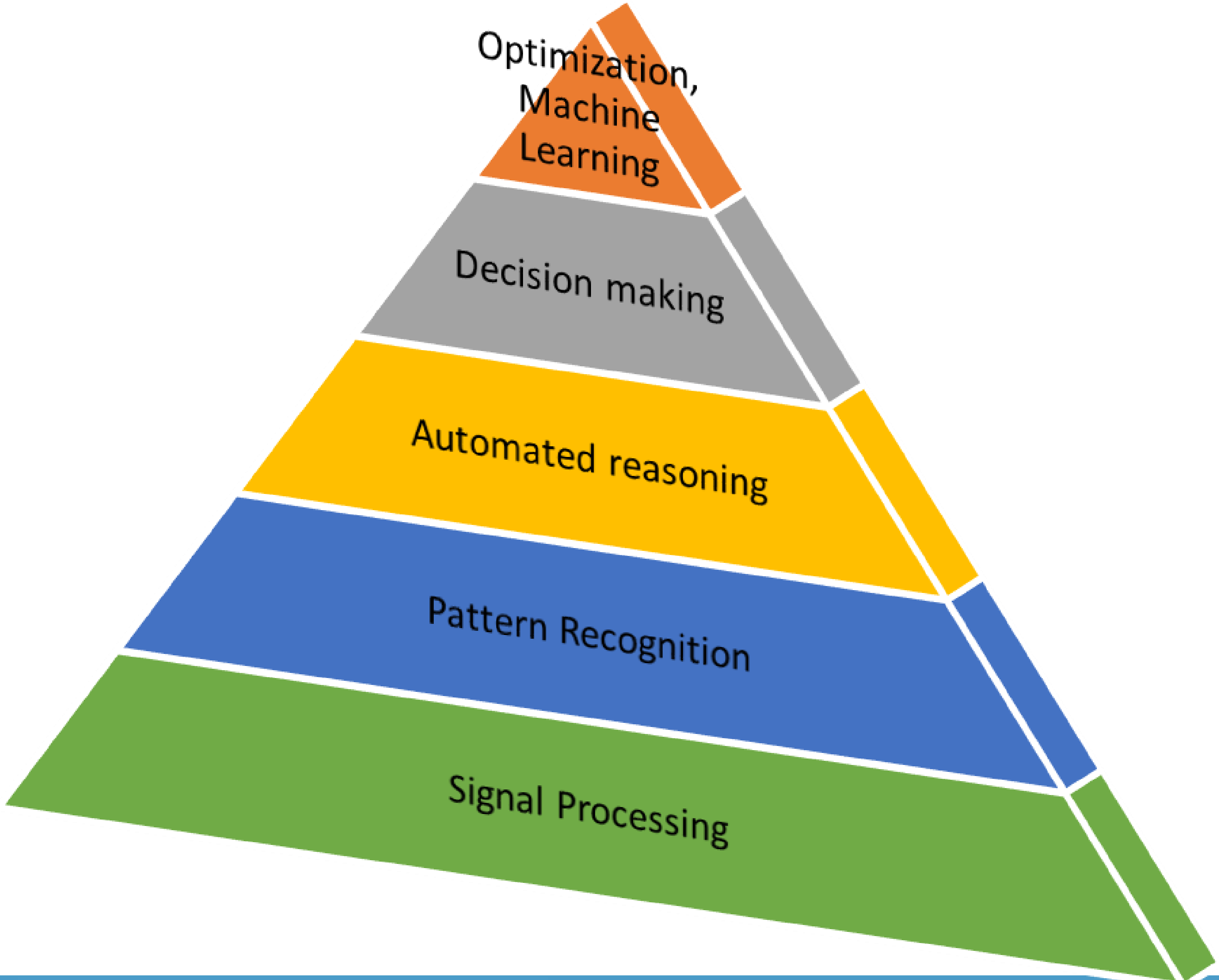
Data Fusion is the process for combining data to estimate entity states, where an entity can be any aspect of reality at any degree of abstraction [1]

…so that the fused result is, *in some sense* (e.g. on average), better than the single source



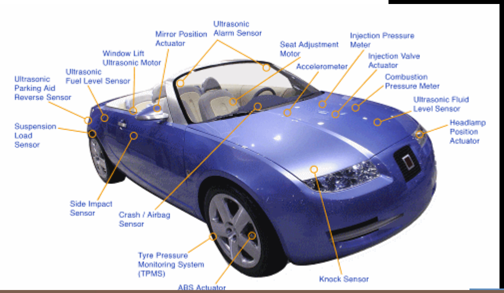
[1] Alan N. Steinberg, and Christopher L. Bowman, “Revisio [illegible] *Handbook of Multisensor Data Fusion*, ed. Martin E. Liggins, David L. Hall and James Llinas, CRC Press, London, 2009.

IF: a mix of reserch fields

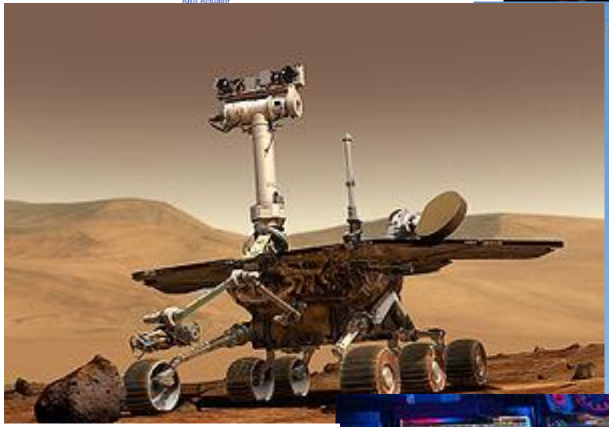


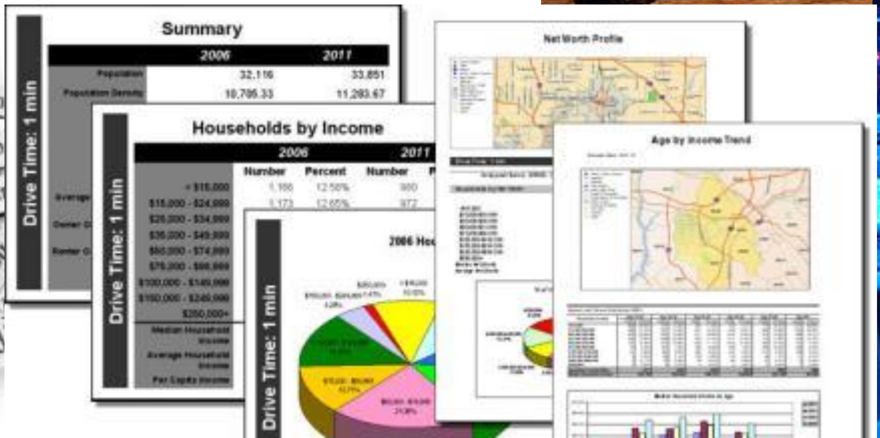
Applications

Extremely wide spectrum of application fields



- » Medicine
- » Robotics
- » Transportation
- » Security
- » Intelligence
- » …





(some) Advantages of Data Fusion

- Accuracy
- Redundancy
- Complementarity
- Robustenss
- Extended coverage

(some) Dirty secrets in DF

- *There is no substitute for a good sensor:*
  - no amount of data fusion can substitute for a single accurate sensor that measures the phenomena that you want to observe

- *Downstream processing cannot make up for errors (or failures) in upstream processing:*
  - data fusion processing cannot correct for errors in processing (or lack of pre-processing) of individual sensor data.

D. Hall, A. Steinberg «Dirty Secrets in Multisensor Data Fusion»

(some) Dirty secrets in DF (2)

- ***Sensor fusion can result in poor performance if incorrect information about sensor performance is used:***
  - A common failure in data fusion is to characterize the sensor performance in an *ad hoc* or convenient way. Failure to accurately model sensor performance will result in corruption of the fused results.

- *There is no such thing as a magic or golden data fusion algorithm:*
  - Despite claims to the contrary, there is no perfect algorithm that is optimal under all conditions. Often real applications do not meet the underlying assumptions required by data fusion algorithms (e.g., available prior probabilities or statistically independent sources).

D. Hall, A. Steinberg «Dirty Secrets in Multisensor Data Fusion»

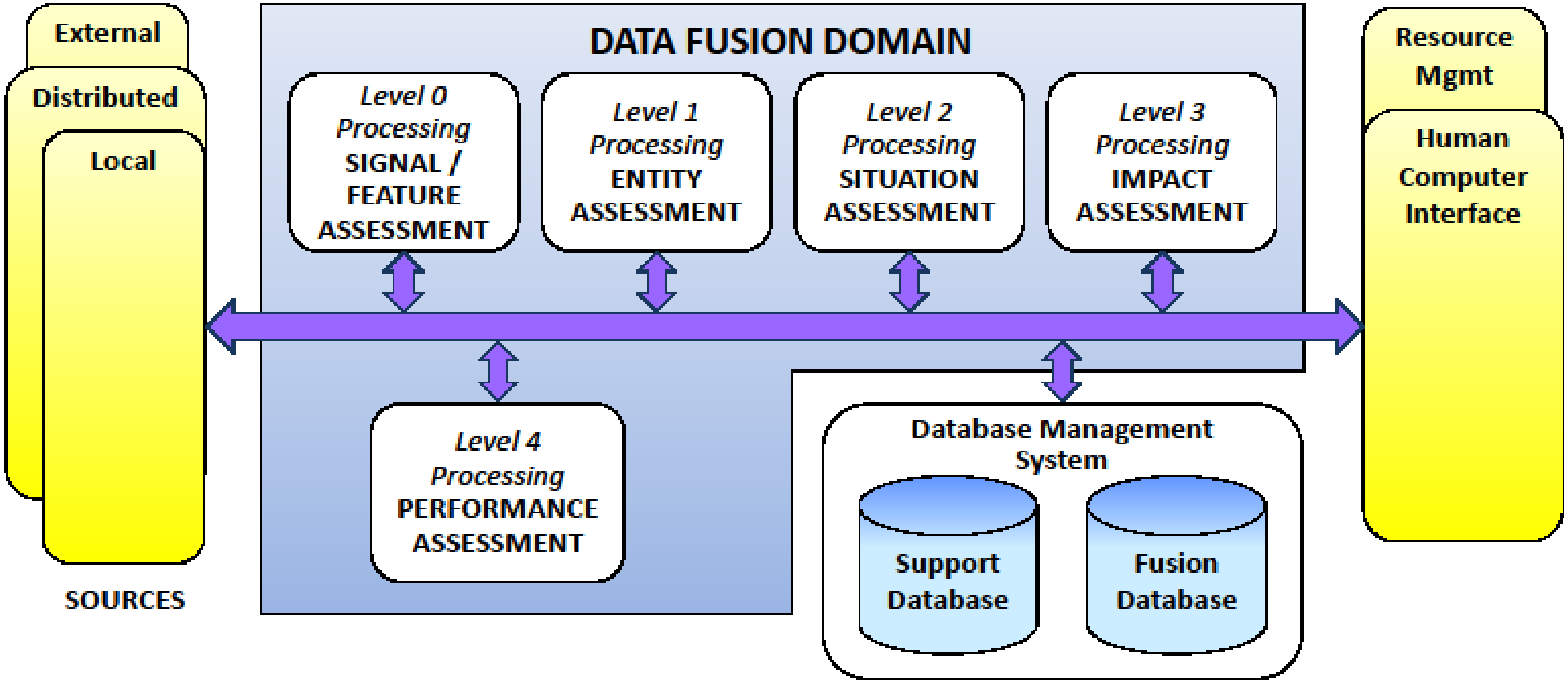
(some) Dirty secrets in DF (3)

- ***Fusion is not a static process:***
  - The data fusion process is not static, but rather an iterative dynamic process that seeks to continually refine the estimates about an observed situation or threat environment.

D. Hall, A. Steinberg «Dirty Secrets in Multisensor Data Fusion»

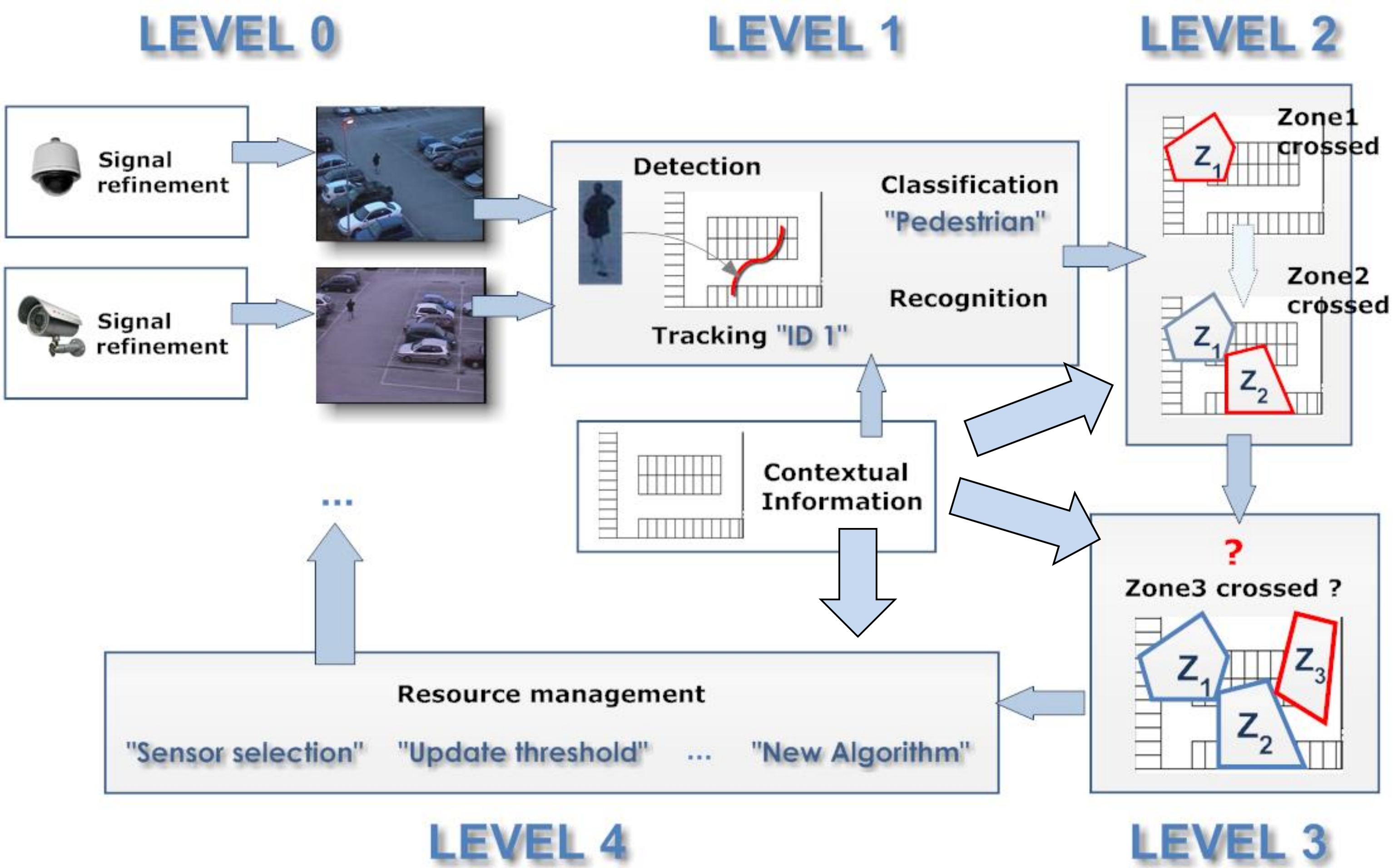
THE JDL MODEL

The JDL model



Joint Directors of Laboratories (JDL) Data Fusion Subgroup, mid 1980s

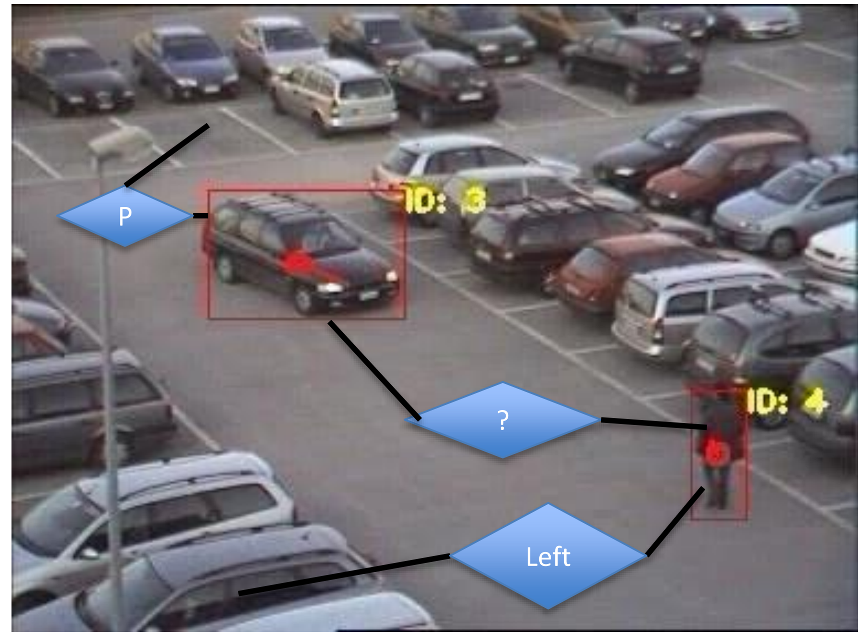
An example: VS system



Why Level 2 Data Fusion is challenging

Level 1

Level 2



- Level 1 is relatively low dimensional
- Level 2 inherently relational
- Many relations non directly observable
- Level 2 attributes/processes non well understood
- Desire to mimic human reasoning in Level 2 processes

Low/High: Is there a gap?

- Is there a gap?
  - Unavoidable separation?
  - Lack of communication?
  - Lack of holistic approach?

- Different scientific communities working on different methods and solutions

- Not many «multi-level» fusion solutions

Sewing levels together…

CONTEXT?

Hard&Soft data

- Hard data/information: device-generated
- Soft data/information: human generated

- Both define the source type, not the observation uncertainty!

- Key differences:
  - Types of data/info that can be provided
    - Humans can better provide semantically rich relational info
  - encoding of quality/uncertainty of the source
    - «source model» is harder to define for humans

Hard&Soft ≠ Low&High

	Low-level	High-Level
Hard	Typically numerical data or classification labels	Sensor or system outputs with high semantic value such as detection of events or situations which are typically underpinned by relations holding between the elements involved in the detected pattern (e.g. relations among detected entities, relations between entities and context, etc.).
Soft	Typically numerical information (e.g. number of observed entities, distance, etc.) or text labels regarding entities.	Semantically rich observations describing a situation, typically expressed in natural language.

INTRODUCTION TO CONTEXT

What is context?

- Research interest in many diverse fields (Linguistics, Cognitive Psychology, AI, Ubiquitous computing, AmI, Pervasive Computing, etc.)

- Major challenges are generally:
  - how to formally define context
  - how to represent context
  - how to discover and reason about relevant contexts for particular applications.

Steinberg and G. Rogova, "Situation and context in data fusion and natural language understanding“, Fusion 2008

Much literature on contextual-awareness related to mobile devices!

- Centered on the user
  - initially just position
- Context-aware apps
- Many definitions in the literature!

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Contextual Information definitions

- Dey and Abowd (2001):
  - "Any information (either implicit or explicit) that can be used to characterize the situation of an entity"
- Henricksen (2003):
  - "The context of a task is the set of circumstances surrounding it that are potentially of relevance to its completion"
- Devlin (2005):
  - "a feature F is contextual for an action A if F constrains A, and may affect the outcome of A, but is not a constituent of A"

Contextual Information definitions (2)

Kandefer and Shapiro (2008): The structured set of variable, external constraints to some (natural or artificial) cognitive process that influences the behavior of that process in the agent(s) under consideration.

Contextual Information definitions (2)

- Snidaro et al. (2013) a collection of data of possibly wide-ranging types that can be said to be adjunct to certain focal conditions of interest, and depict the “setting” or “surroundings” in which the focal information unfolds

Contextual Information definitions (3)

- Steinberg & Rogova (2015): a ***context*** is a ***situation*** that provides information that can be used either
  - a) to condition expectations or
  - b) to improve the understanding of a given inference or planning/control problem

- A **situation** is a set of relationships
- <u>The particular concerns of some agent determine which situations are under consideration as contexts for those concerns</u>

See later ***Internal*** and ***External*** contexts

Some properties

Conventional electromechanical sensors (”physics-based or hard” sensors) fundamentally provide attributes of the various entities observed, they do not provide (are not capable of providing) first-order evidence about inter-entity relationships, which are the basis of situational compositions

- Local scope and validity
- Static and dynamic information
- Different info sources
  - Context gathering
  - Context discovery

Why context?

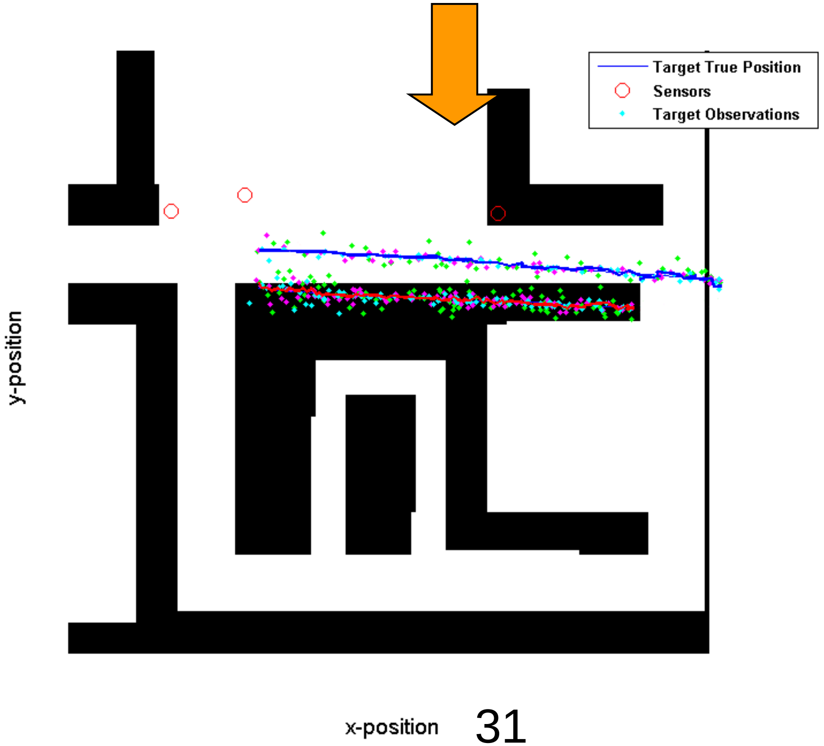
- Context awareness allows the possibility for a system to change and adapt to better react to unpredictable or potentially harmful events (i.e. partial occlusion of the target, unfavorable weather conditions, sun blinding, persistent reflections, etc.).

- Contextual information can play different roles at different levels, providing significant cues that can range from ancillary data to semantically rich goal-related information

Data refinement

- In real-world monitoring applications it often happens that a sensor provides a sequence of unreliable observations due to partial occlusion of the target, unfavorable weather conditions, sun blinding, persistent reflections, etc.

- E.g. checking the measurements against a map of the area - provide an insight on the reliability of the sensor in a specific situation.



Inference

- Context allows to draw inferences about the observed situation, events
  - Allows to reason about inter-entity relationships (not directly observable)
  - Rich semantics
  - A powerful way to semantically bind sensor measurements and real-world observables.

CONTEXT FOR IF

Context-aware IF: expected benefits

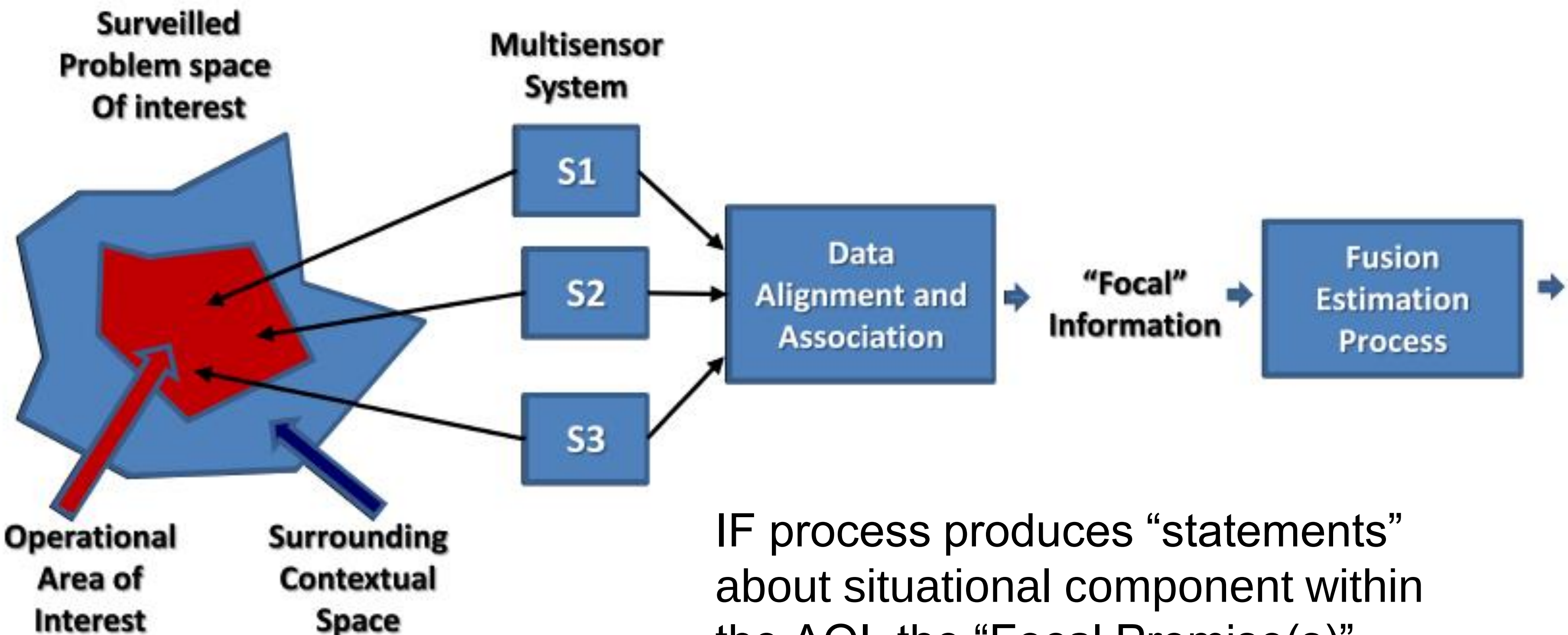
1) Constrain processing

2) Refine estimates

3) Explain observations

4) Adapt the fusion process

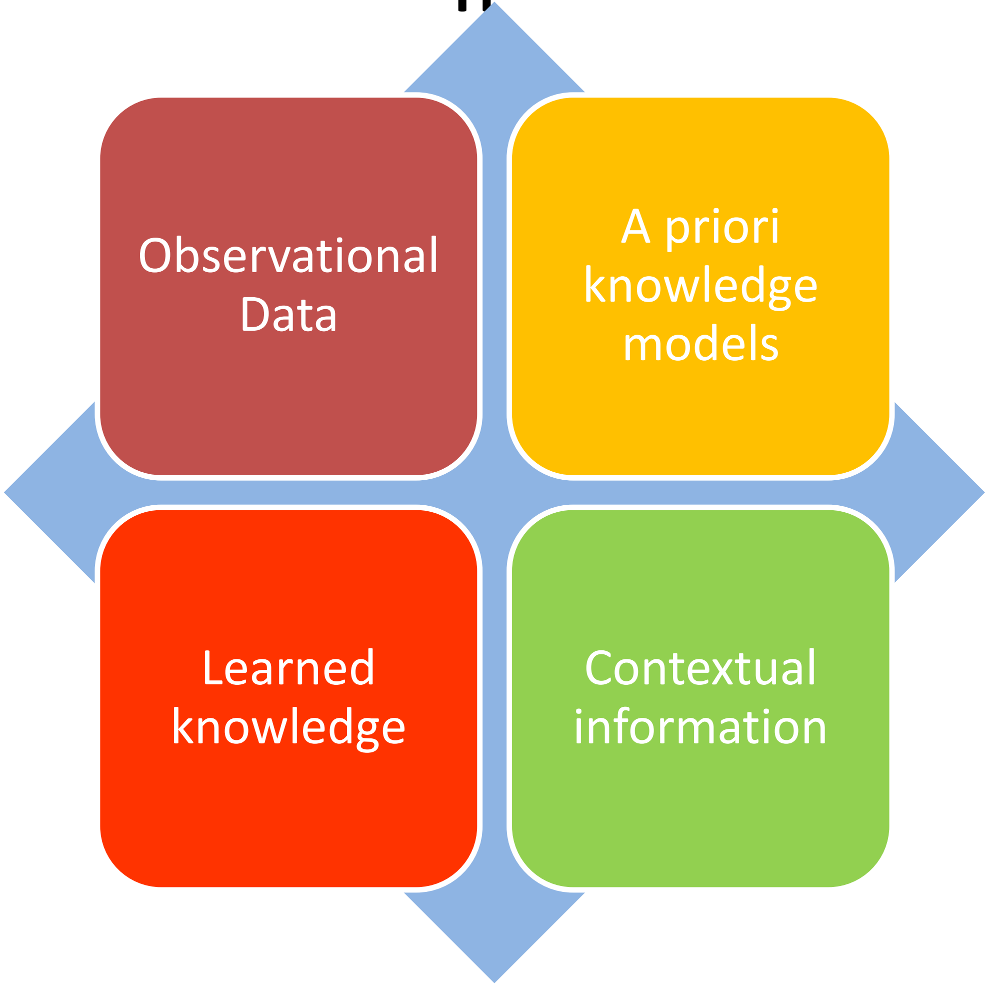
Context in IF



IF process produces "statements" about situational component within the AOI, the "Focal Premise(s)".

[1]

Generally understood categories of data in IF



Categories of data in IF

- Four categories of information can be applied to any IF problem:
  - **Observational data**

    Data collected from the world of interest with sensors

    It may include human inputs

    Attribute and feature data about entities, but also relationships
  - A priori knowledge models
  - Learned knowledge
  - Contextual information

Categories of data in IF

- Four categories of information can be applied to any IF problem:
  - Observational data
  - **A priori knowledge models**

    Predefined models to infer relations between entities at more abstract level

    Ontologies that formally represent the domain of interest with axioms defined in terms of concepts, relations, and instances
  - Learned knowledge
  - Contextual information

Categories of data in IF

- Four categories of information can be applied to any IF problem:
  - Observational data
  - A priori knowledge models
  - **Learned knowledge**

    Knowledge obtained through machine learning techniques operating on observational and other data: relationships, behaviors, etc.

    It is usually combined with a priori models
  - Contextual information

Categories of data in IF

- Four categories of information can be applied to any IF problem:
  - Observational data
  - A priori knowledge models
  - Learned knowledge
  - **Contextual information (CI)**

    Information that "surrounds" an entity/situation of interest in the world

    Conditioning factors to a reasoning process about an entity/situation

Context at different levels

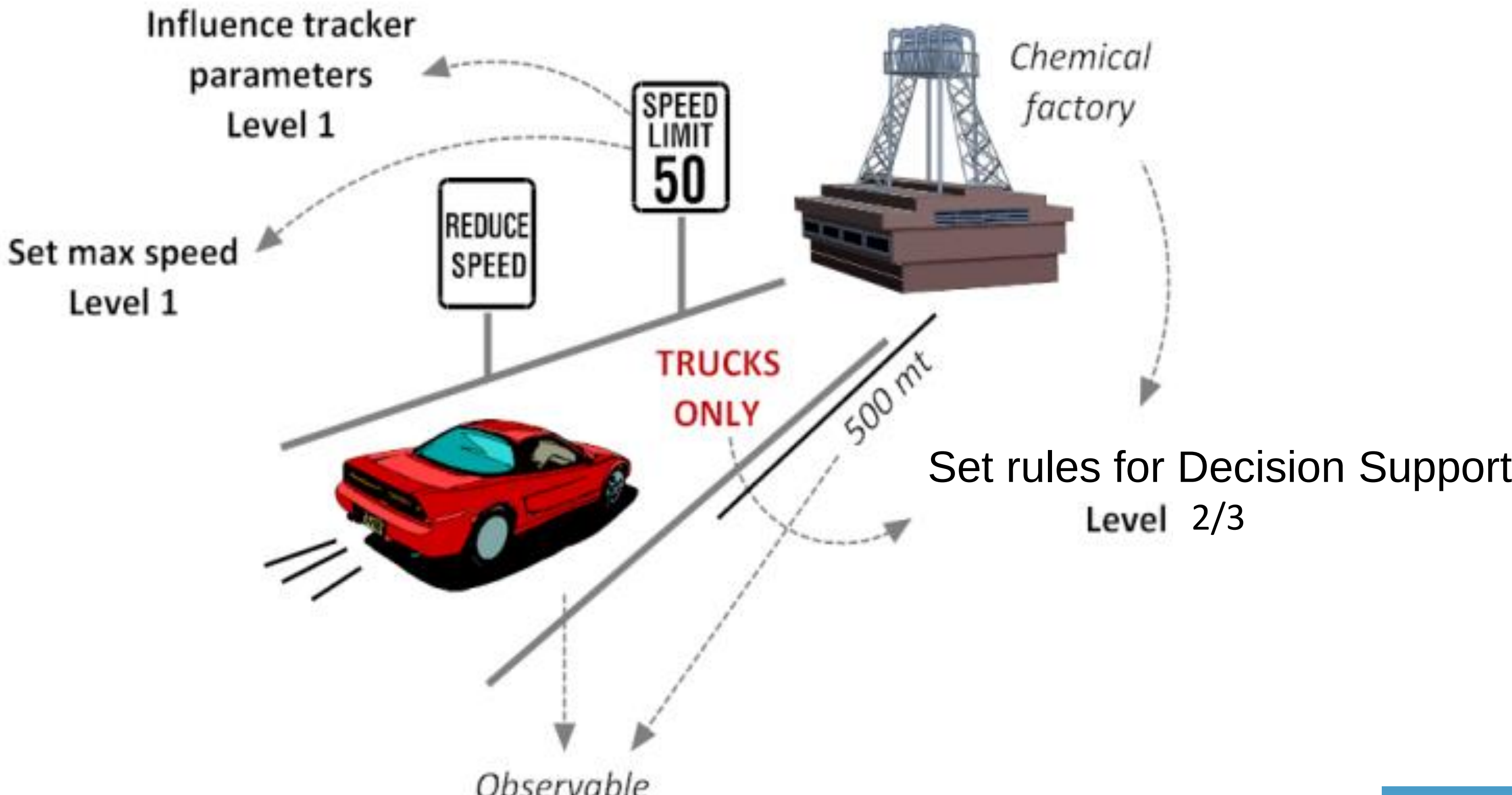
- Context can be exploited in fusion at different levels
- Influences on features, relations, behaviours and events

Level	Context	Effect
0	Rainy / Darkness	Reduced camera signal quality
1	Rainy weather	Reduced objects' speed
2	Rainy weather	Traffic more intense
3	Clear / full daylight	Reduced likelihood of car thefts

[4]

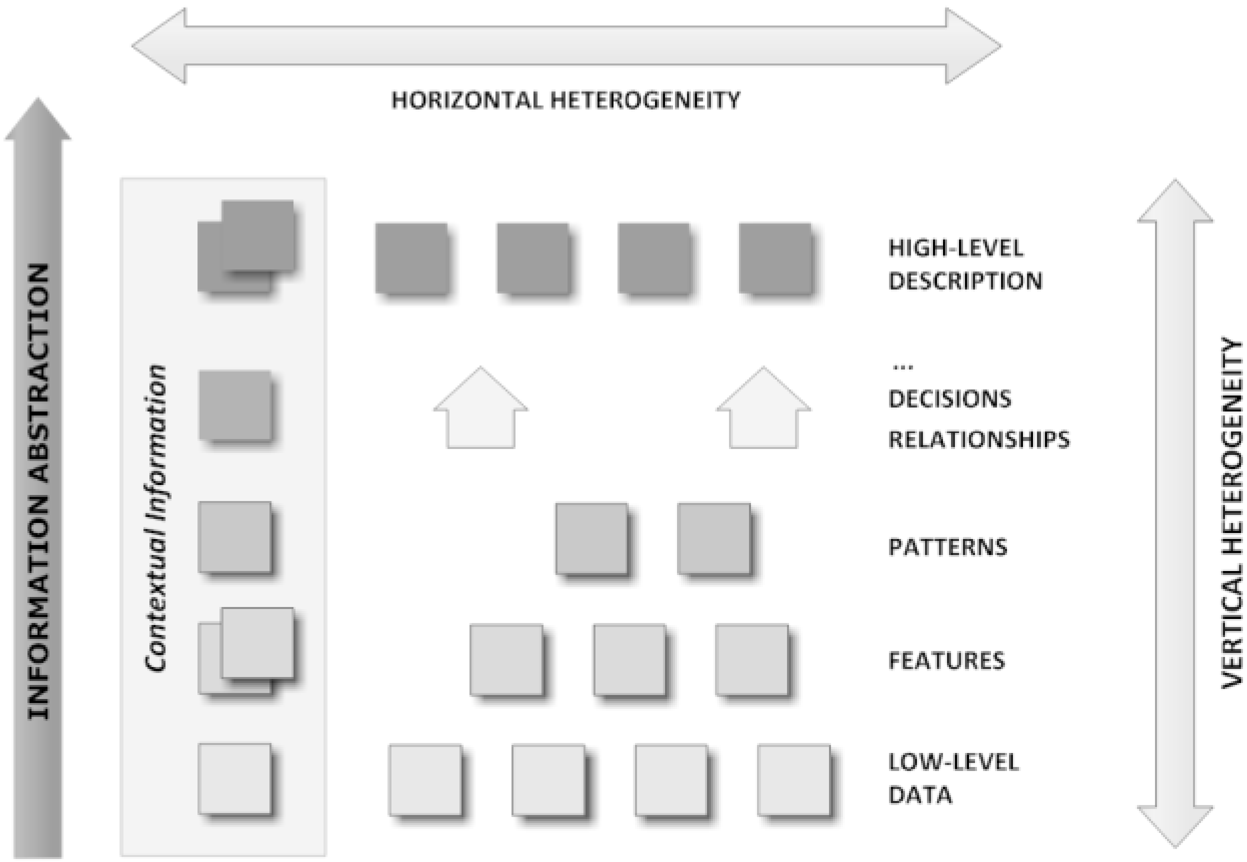
Context at different levels (2)

- Influences on features, relations, behaviours and events



Multi-sensor multi-cue context

- Context follows the same "abstraction" as fusion: multi-cue (vertical), multi-sensor (horizontal) information.



Multiple information tokens have different levels of granularity and abstraction

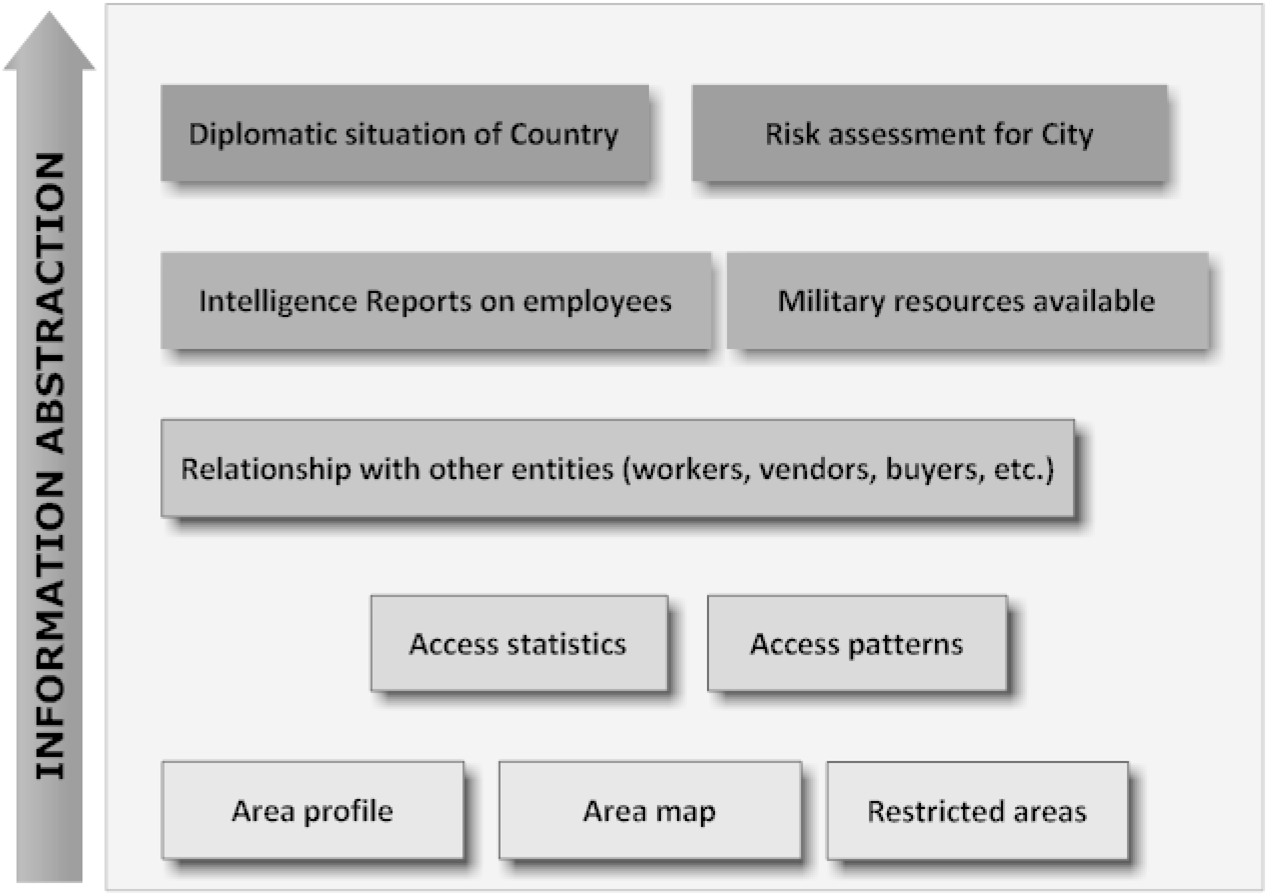
(coarse-to-fine, general-to-particular, bottom-up, etc.)

[4]

Multiple sources of information provide different context

Heterogeneity in contextual information

- An example: context on a nuclear plant

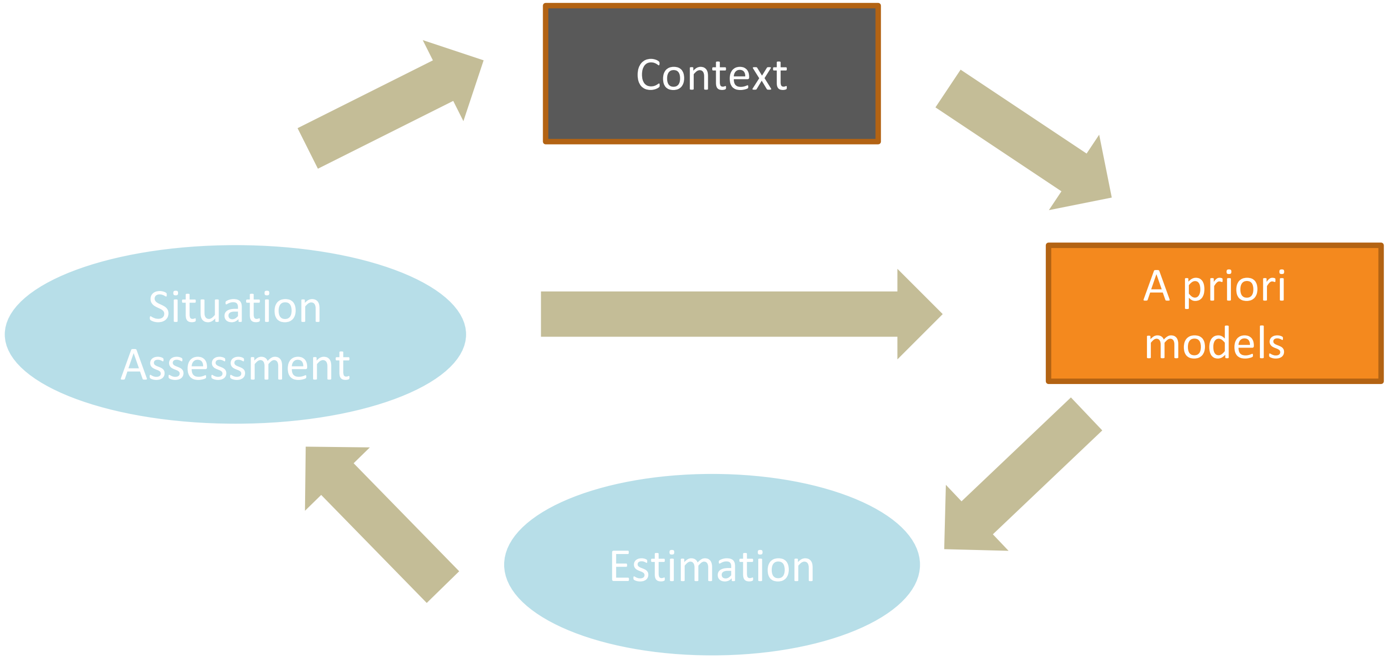


High-level information

Low-level information

Context as binding element

- Context allows for improving the associability between problem-space knowledge and models and observational data, increasing fusion performance.

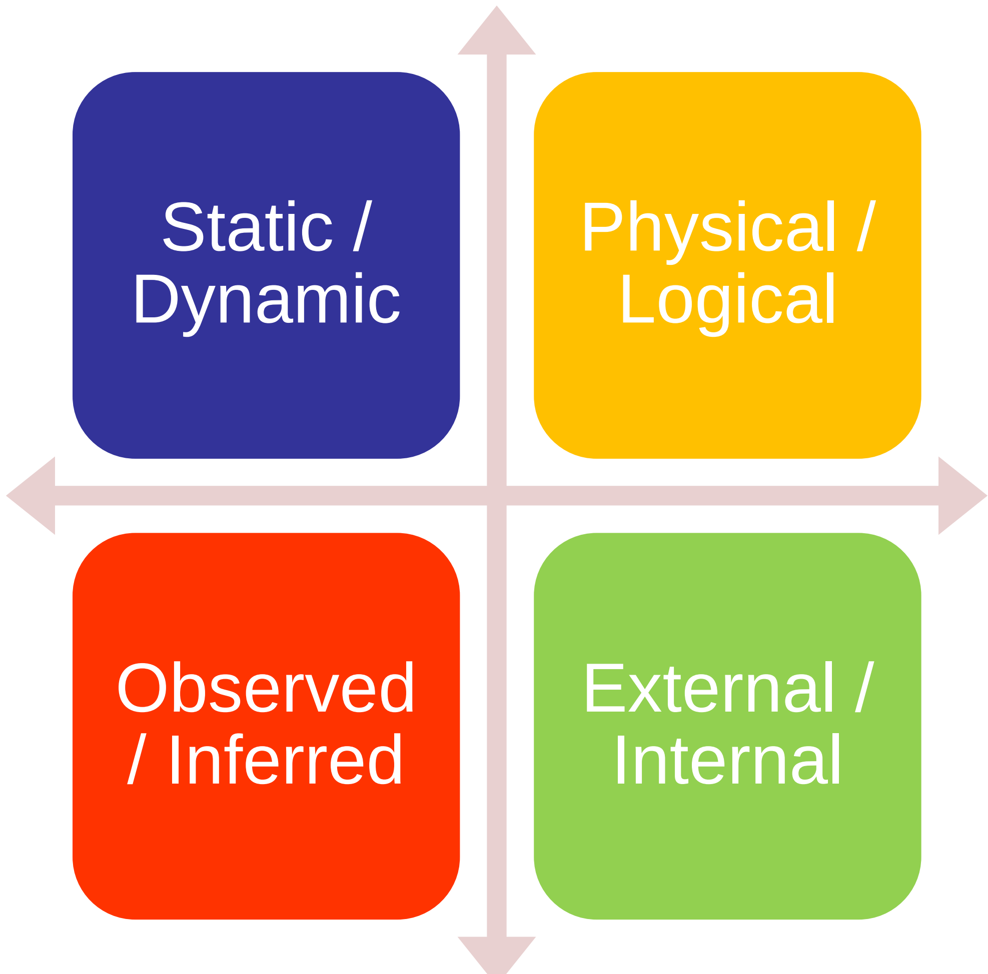


Context and JDL Level4

- Context awareness allows the possibility for a system to change and adapt to the surrounding environment

CONTEXT TERMINOLOGY AND CONCEPTS

Context types in IF



[3]

Context sources taxonomy

- Three dimensions:
  - PHYSICAL / LOGICAL
  - OBSERVED / INFERRED
  - STATIC / DYNAMIC

[3]

STATIC context	PHYSICAL context	LOGICAL context
OBSERVED context	Maps, GIS	Traffic regulations, hierachical relations, …
INFERRED context	Map refinements (obstacles, occlusions, roadworks…)	Patterns of life, social norms, buildings use, …

Context sources taxonomy

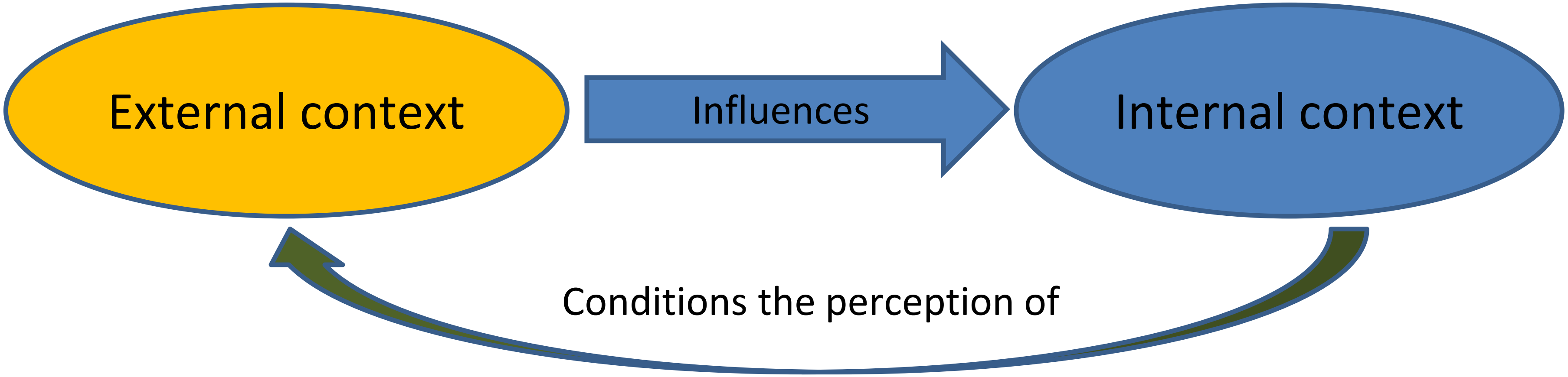
- Three dimensions:
  - PHYSICAL / LOGICAL
  - OBSERVED / INFERRED

[3]

DYNAMIC context	PHYSICAL context	LOGICAL context
OBSERVED context	Weather reports, Battery level	Traffic configuration User agenda, …
INFERRED context	Wind (sea state) trafficability	Loyalty, User's emotion, …

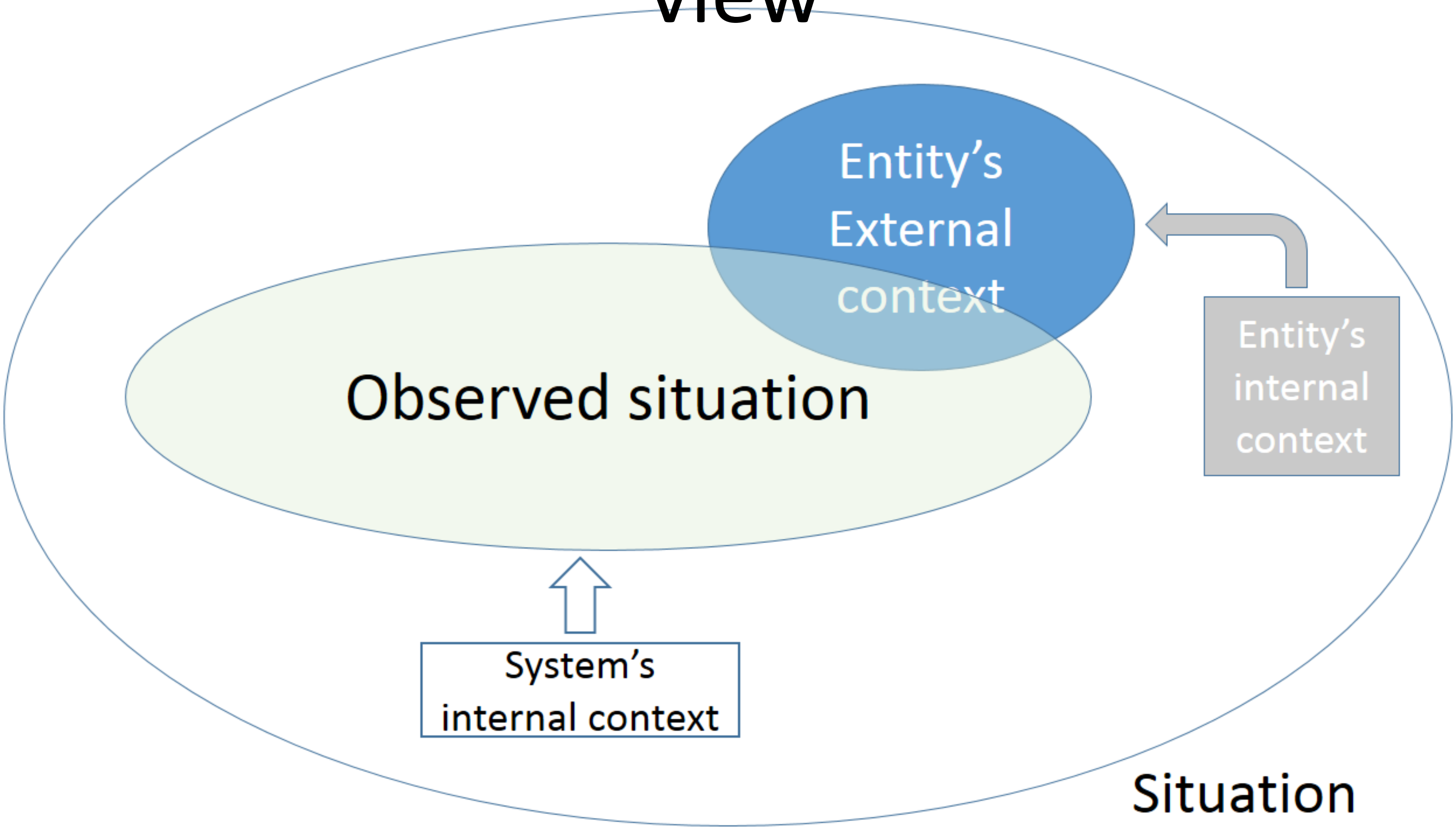
Internal and **external** context: cognitive view

- **External context** refers to the physical and social environment or the setting within which the subject's behavior is generated.
- **Internal context** refers to subject's current mental state driving the subject's behaviour



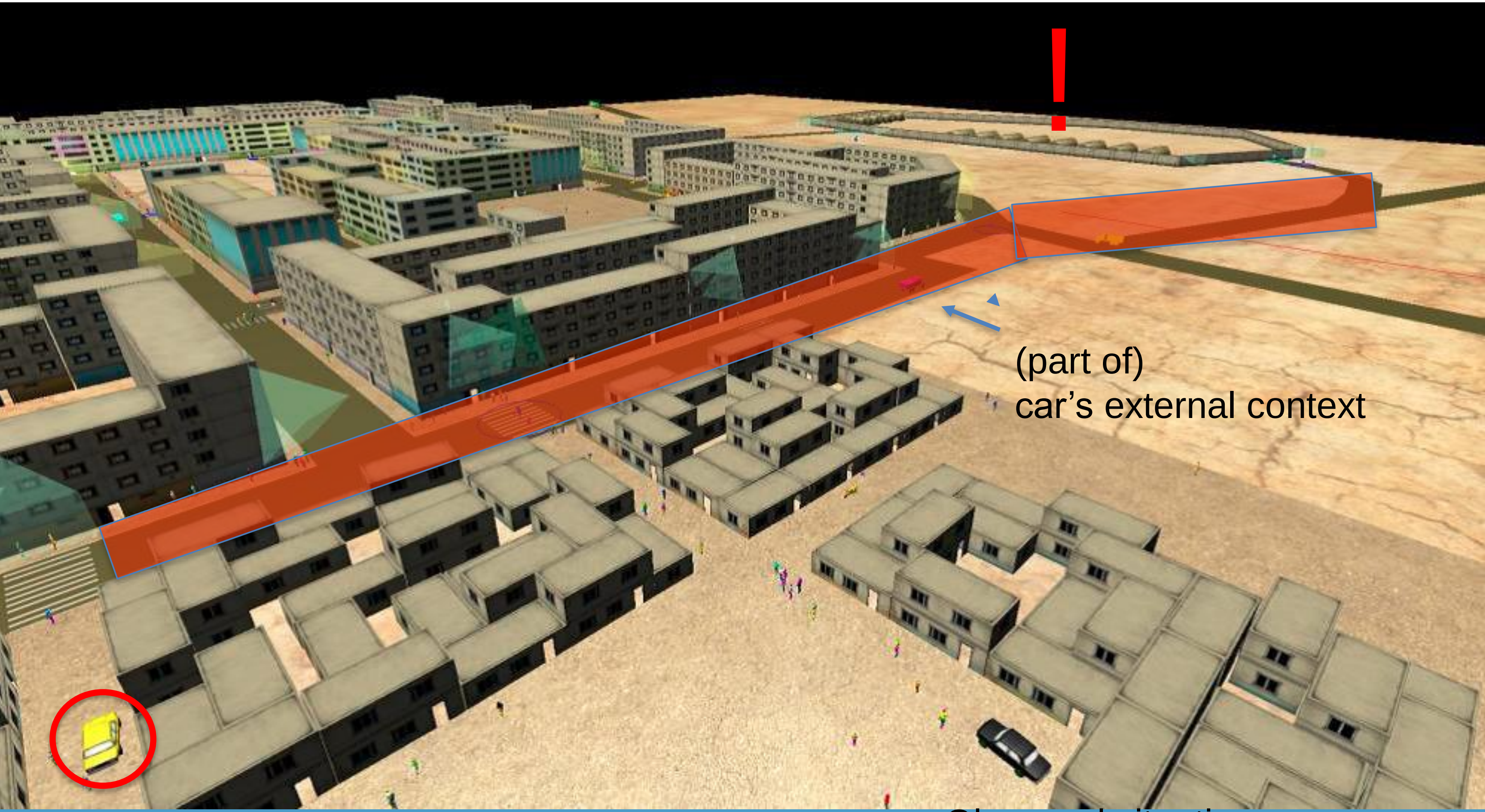
[2]

Internal and external context: fusion view

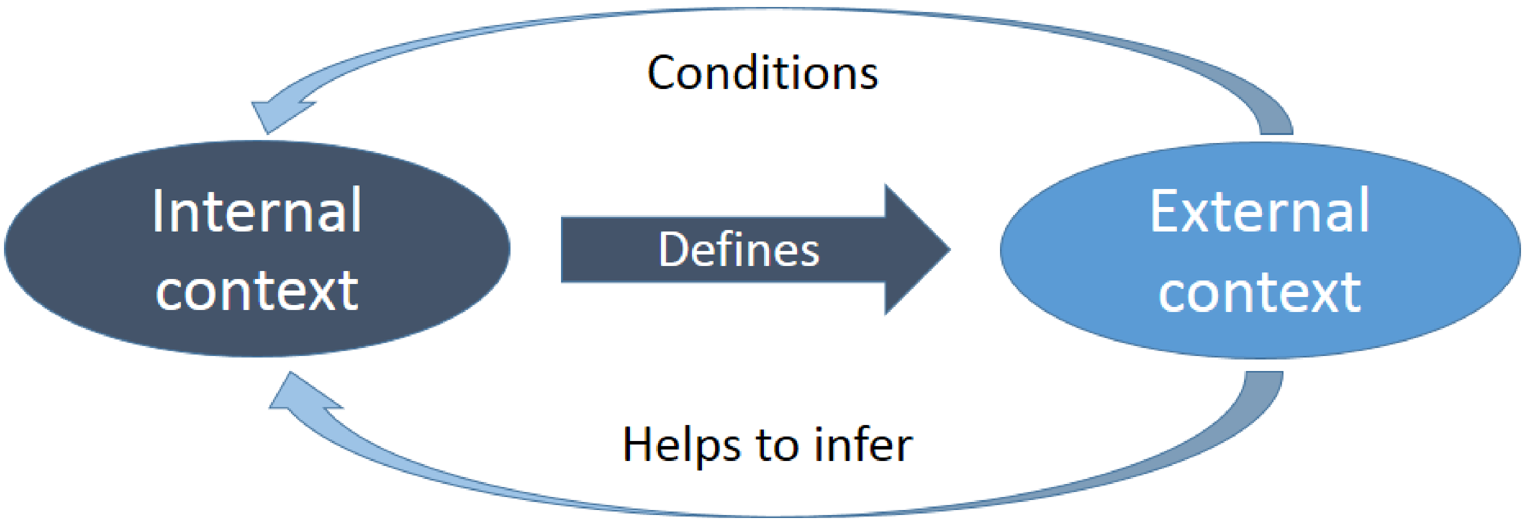


[2]

Internal and external context: fusion view



Internal and external context: fusion view



[2]

Context representation

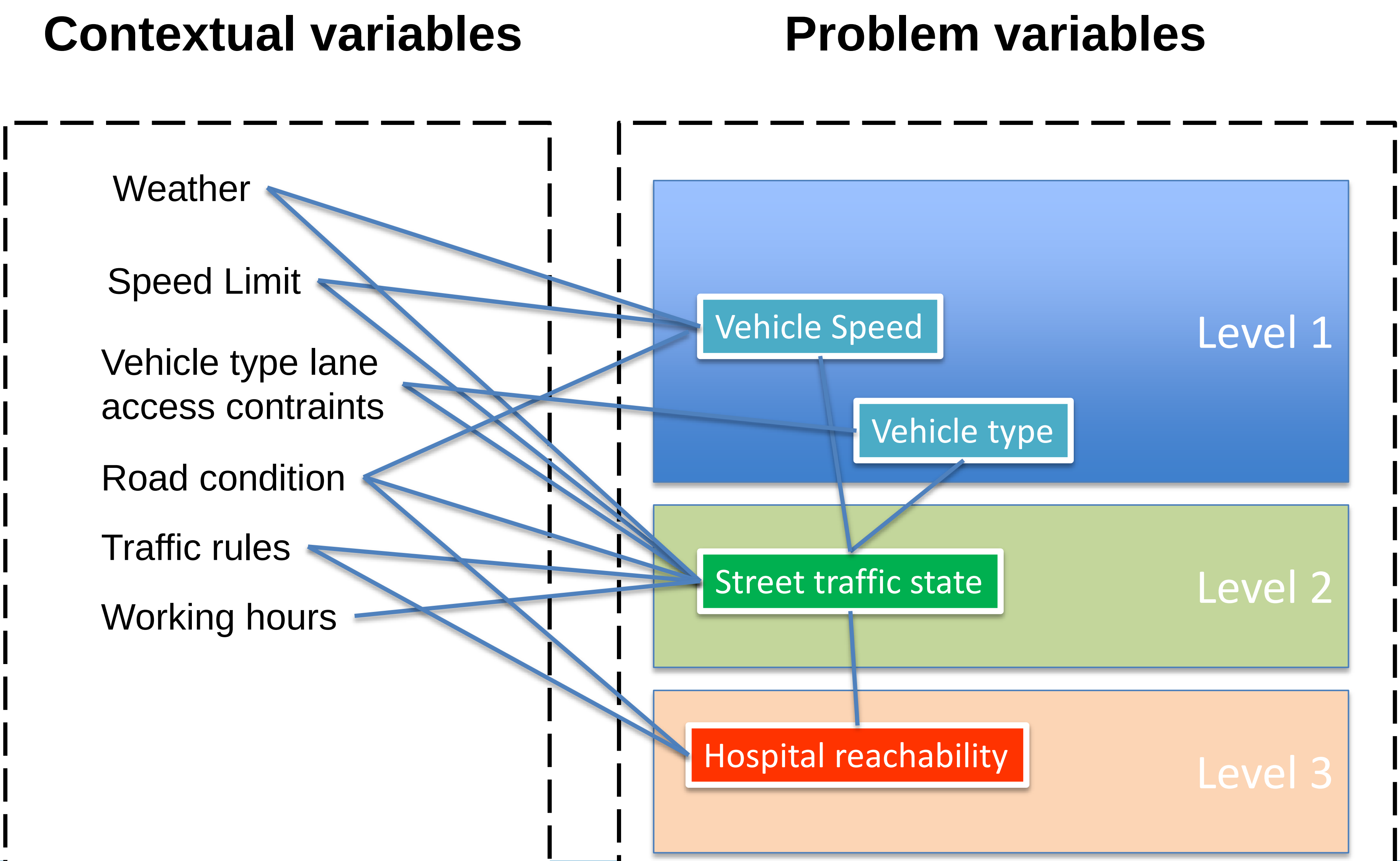
- **Embedded**: meaningful sensory features that characterize particular situations.
  - works at a perceptive level, typical of reactive systems
- **Logic-based**: declarative knowledge representation languages, ranging from ontologies to first order logic
  - main advantage is symbolic framework and inference tools (supports planning and reasoning)
- **Probabilistic**: formalize relations between context and problem variables through probabilistic structures, e.g., Bayesian Networks.
  - Handling of uncertainty

[2]

Formalizing CI – IF interaction

- **CI** can be characterized by "***Contextual Variables***"
- **Problem variables** are the focus of the fusion process
- Problem variable *X* can serve as a context variable for a problem variable *Y*

[1]

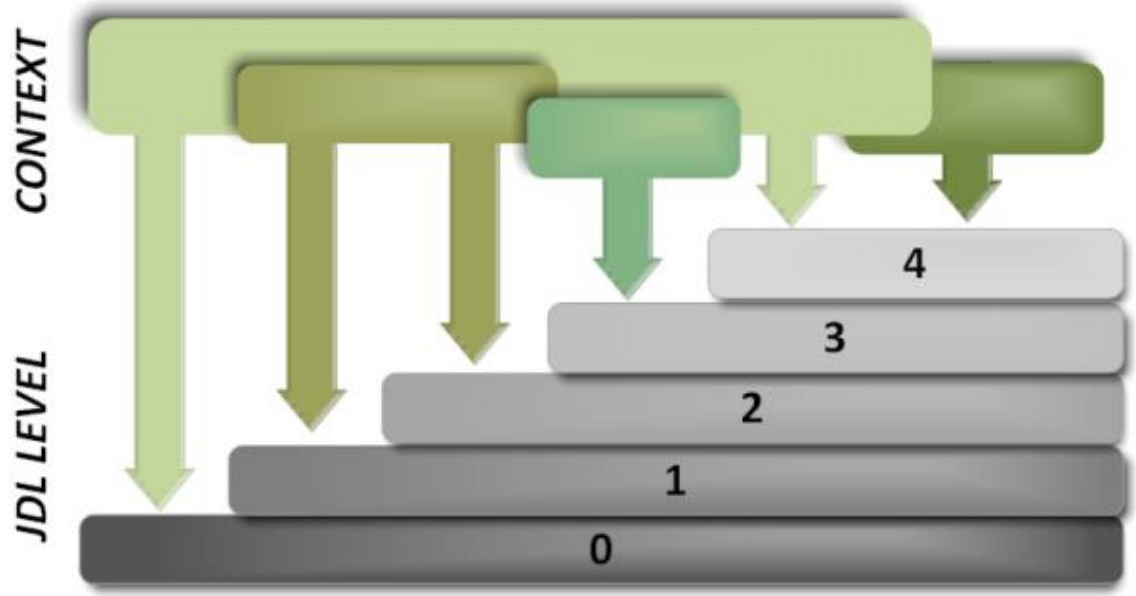

Contextual variables
Problem variables
Weather
Speed Limit
Vehicle type lane
access contraints
Road condition
Traffic rules
Working hours
Vehicle Speed
Vehicle type
Level 1
Street traffic state
Level 2
Hospital reachability
Level 3

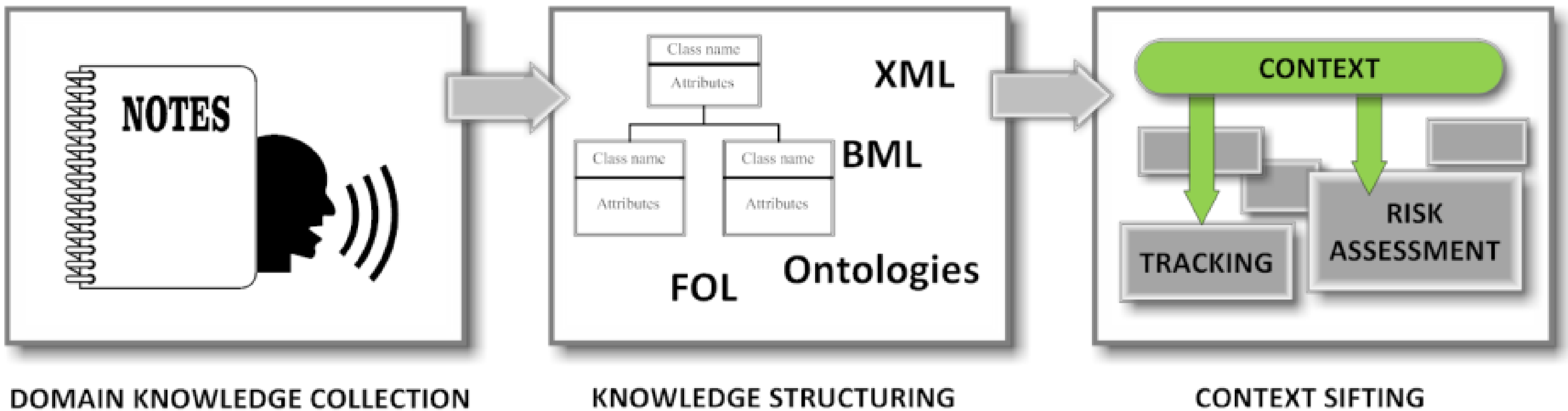
Context Sifting

Design issue: understanding how contextual information should be channeled and exploited at different levels

Online-> System running

Offline-> Design Time



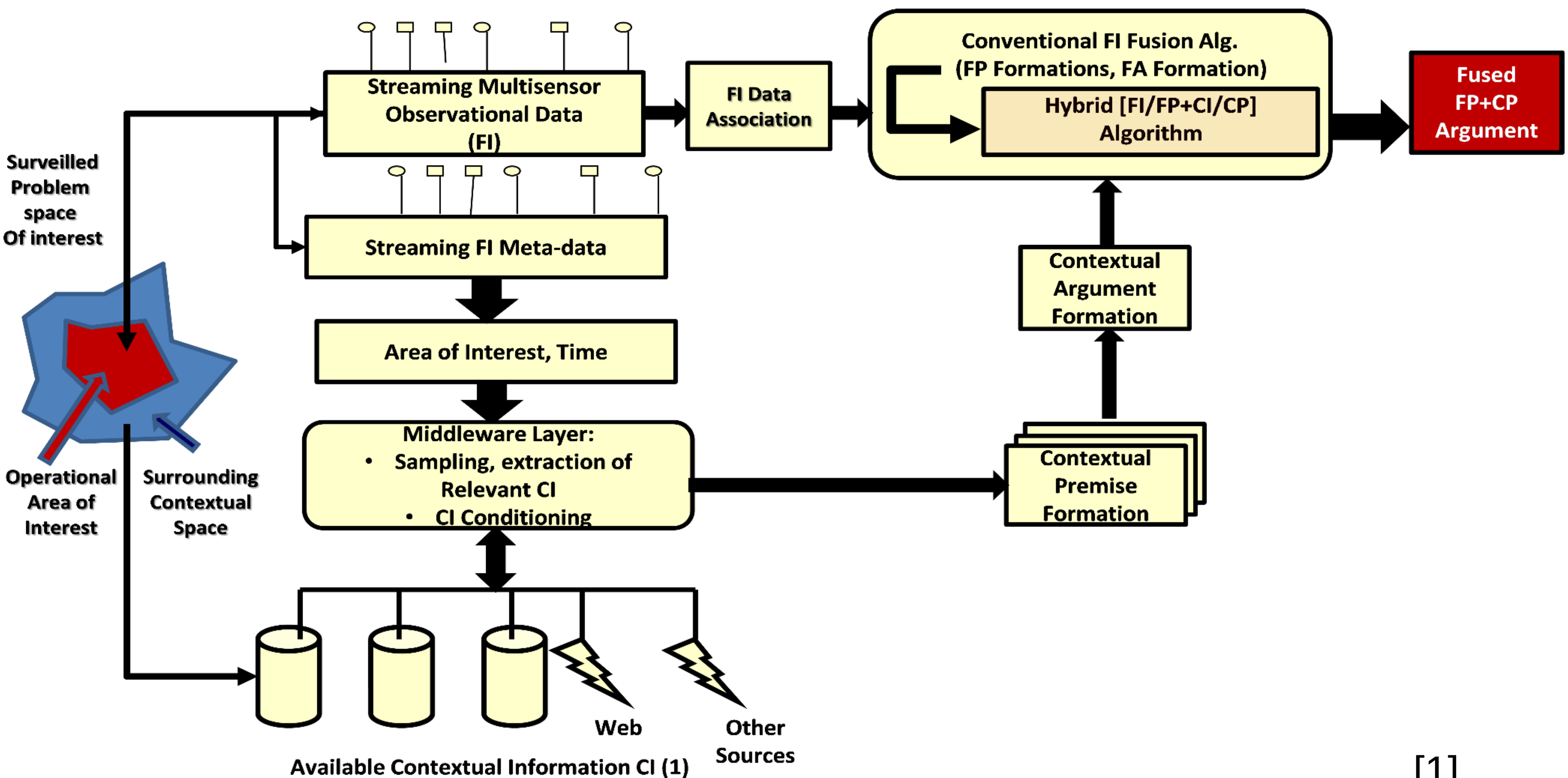


Strategies for CI exploitation

- “A priori” framework
  - Accounts for the effect on situational estimation of that CI that is known **at design time (“a priori”)**
  - This CI should be easily **incorporated to the fusion procedures** (*hard-wired*)
  - It produces hybrid fusion methods, maybe numerical/symbolical

[1]

“A priori” framework



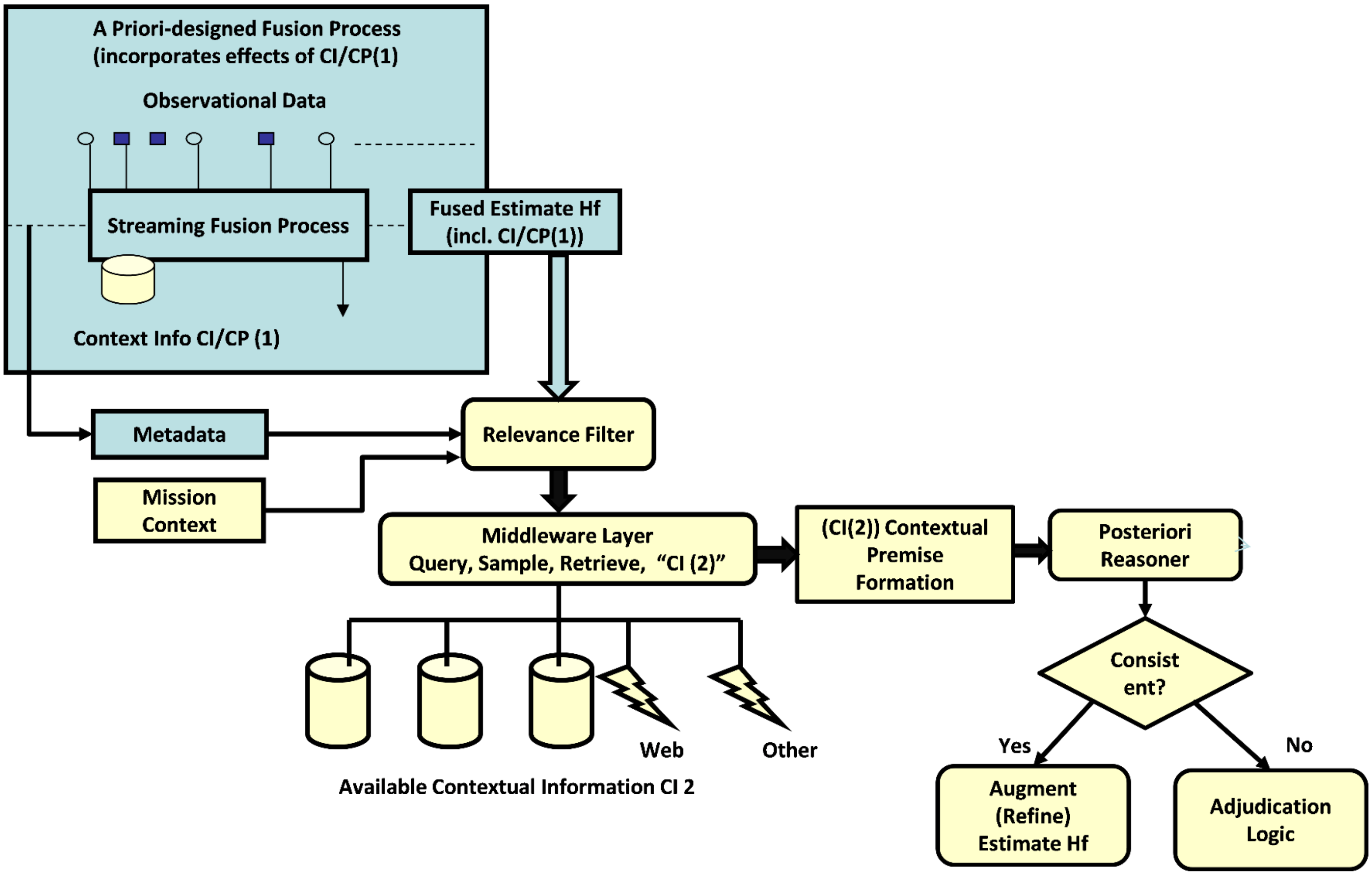
[1]

Strategies for CI exploitation

- "A posteriori" framework
  - Sometimes, the **integration of all CI** in the IF algorithm/system **is not possible**:
    - All relevant CI may not be known or available at system/algorithm design time
    - CI may not be of a type integrated into the system/algorithm at design time
  - CI exploitation is an additional process that performs:
    - Retrieval of *relevant* CI from available sources
    - Consistency checking (fusion hypothesis and relevant CI)
    - Augment, embellish fused results
    - Supports possible L4 adaptive operations: **problem-space reconfiguration**

[1]

"A posteriori" framework



[1]

Difficulties

- Dynamic: difficult to anticipate, open and hard to model how it affects the problem

- Ambiguities, redundancies and implications: the same idea can be expressed from different points of view or at different abstraction levels.

  → *Heavy rain (over 25mm/h) for the last 72 hours around 47º25'N – 125º03'W.*

  → *Dirty roads around Townville are impassable.*

- Full characterization of CI may not be possible to be known at design time, except in very closed worlds
  - *Middleware* is a possible solution

[1][2]

Conclusions

- Concepts and issues for developing context-aware fusion system
- Middleware approach for interface between data/information sources and fusion functions, brokering all relevant contextual data sources to the correct data sinks
- International collaboration investigating the role of CI in fusion systems
  - NATO Task Group on Information Filtering and Multi-source Information Fusion (IST-106-RTG-051) 2011-14, 2015-17
  - Design and architecture of Adaptive Information Fusion/Information Integration (IF/II) Office Naval Resarch Global ONR-G, program NICOP 2014 Grant N62909-14-1-N061
  - Edited book on "Context Enhanced Information Fusion", Springer, 2016 [5]

Context Enhanced Information Fusion.

Boosting real world performance with domain knowledge

Lauro Snidaro, Jesús García, James Llinas, Erik Blasch 2016

Springer

Book on Context-enhanced Information Fusion

Thank you!

References

[1] J. Llinas, L. Snidaro, J. García, and E. Blasch, “Context and fusion: Definitions, terminology”, in L. Snidaro et al. (eds.), Context-Enhanced Information Fusion, Advances in Computer Vision and Pattern Recognition, Ch. 1, pp. 3-23, 2016, doi:10.1007/978-3-319-28971-7_1

[2] L. Snidaro, J. Garcia, J. Llinas, “Context-based information fusion: a survey and discussion”, Information Fusion, Vol.25, September 2015, pp.16-31, doi:10.1016/j.inffus.2015.01.002

[3] J. García, L. Snidaro, J. Llinas, “Architectural Aspects for Context Exploitation in Information Fusion”, in L. Snidaro et al. (eds.), Context-Enhanced Information Fusion, Advances in Computer Vision and Pattern Recognition, Ch. 8, pp. 187-205, 2016, doi:10.1007/978-3-319-28971-7_8

[4] L. Snidaro, I. Visentini, “Context for dynamic and multi-level fusion”, in L. Snidaro et al. (eds.), Context-Enhanced Information Fusion, Advances in Computer Vision and Pattern Recognition, Ch. 16, pp. 433-453, 2016, doi:10.1007/978-3-319-28971-7_16

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[5] L. Snidaro, J. García, J. Llinas and E. Blasch (eds.), Context-Enhanced Information Fusion - Boosting Real-World Performance with Domain Knowledge, Advances in Computer Vision and Pattern Recognition series, , Springer International Publishing, 2016, doi: 10.1007/978-3-319-28971-7