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AIICS Autonomous UAV Technologies

Stream Reasoning using Temporal Logic for Autonomous System

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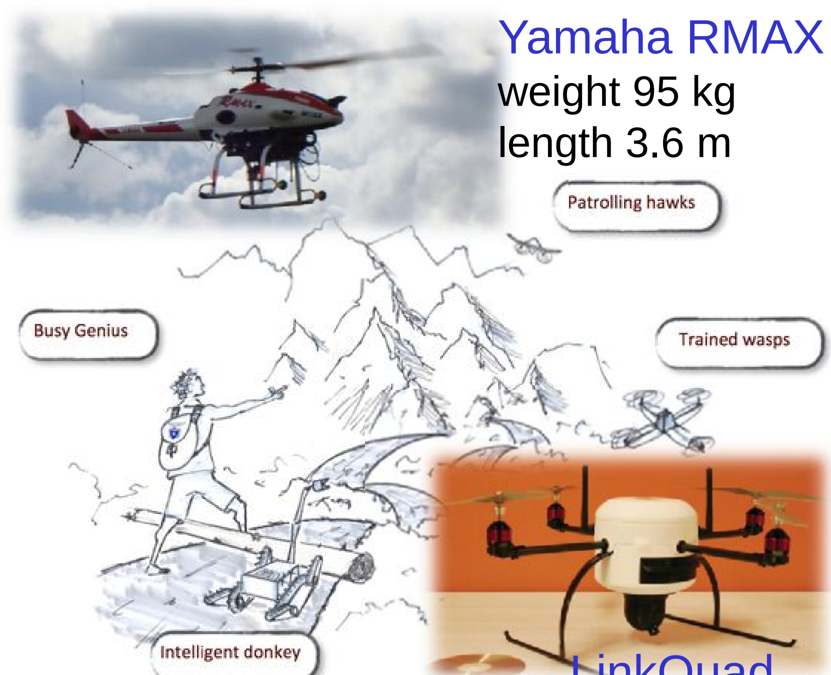
Collaborative Unmanned Aircraft Systems

A principled approach to building collaborative unmanned aircraft systems for complex missions.



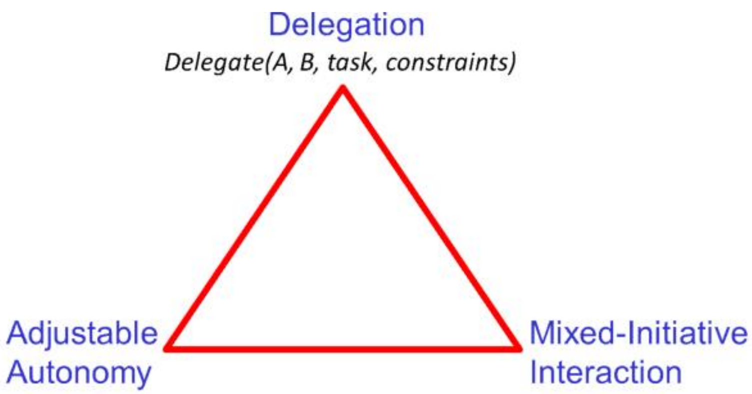
Yamaha RMAX
weight 95 kg
length 3.6 m

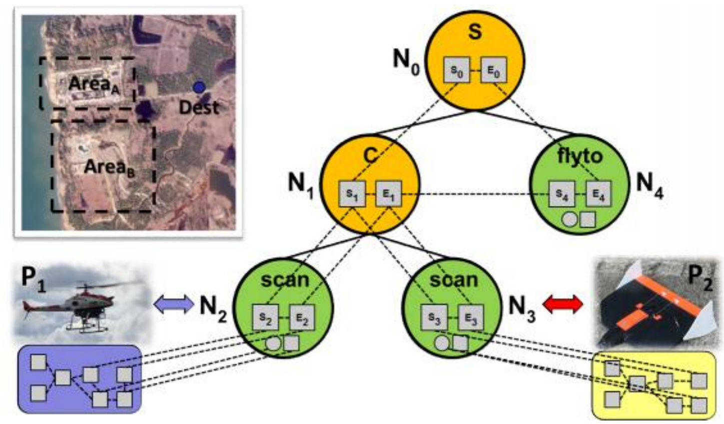
LinkQuad
weight ~1 kg
diameter ~70cm

SHERPA


SELECTED AUTONOMOUS FUNCTIONALITIES
LINKÖPING UNIVERSITY, SWEDEN
DEPARTMENT OF COMPUTER AND INFORMATION SCIENCE
AUTONOMOUS UNMANNED AERIAL VEHICLE TECHNOLOGIES LAB

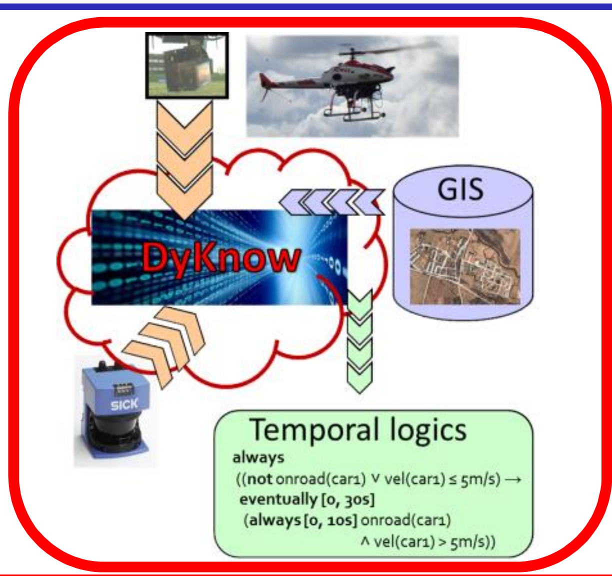
High-Level Research Overview



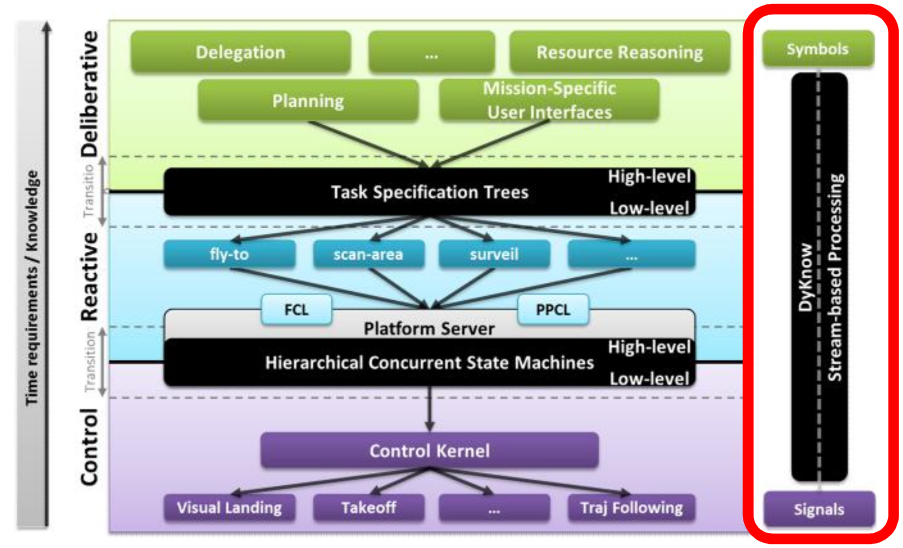


Delegation and task allocation through constraint satisfaction

Stream reasoning

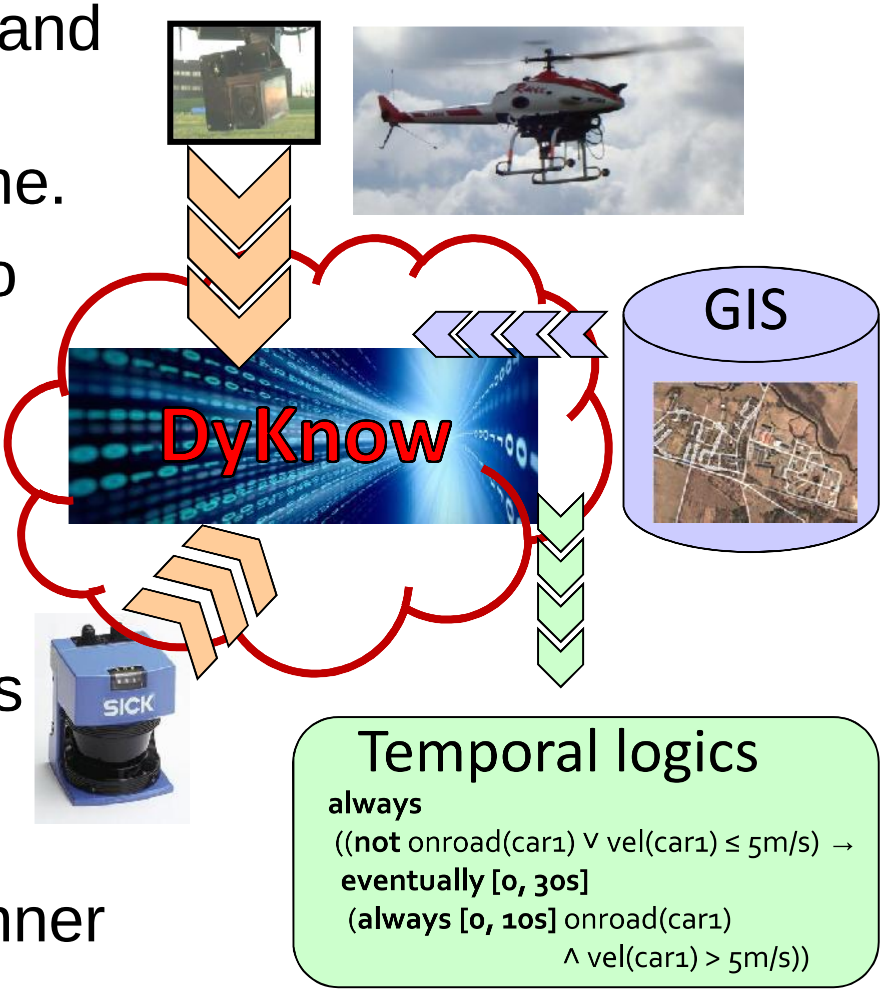


Architectures



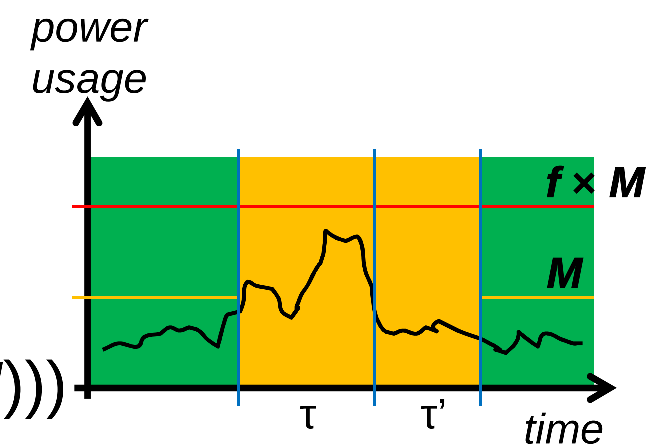
Stream Reasoning

- Autonomous systems produce and process sequences of values incrementally created at run-time.
- These sequences are natural to model as *streams*.
- *Stream reasoning* is incremental reasoning over streams.
- Stream reasoning approximates continuous reasoning with minimal latency necessary in order to react in a timely manner to changes in the environment.

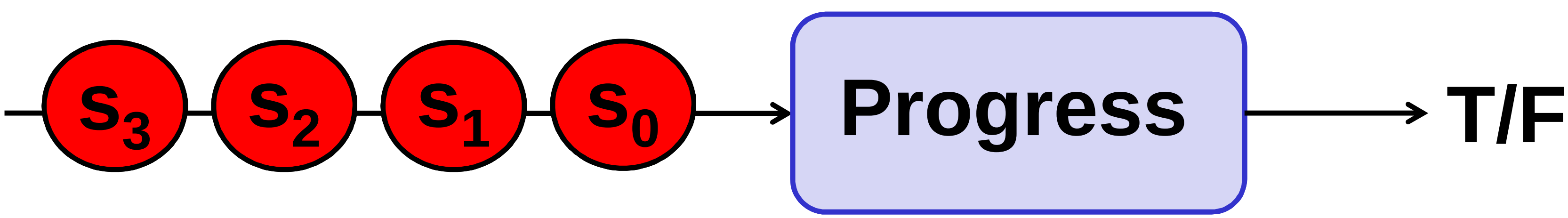


Stream Reasoning using Metric Temporal Logic

always $\forall$*uav*.((power_usage(*uav*) > *M*) →
((power_usage(*uav*) < *f* × *M*)
until[0, τ]
(**always**[0, τ’] power_usage(*uav*) ≤ *M*)))

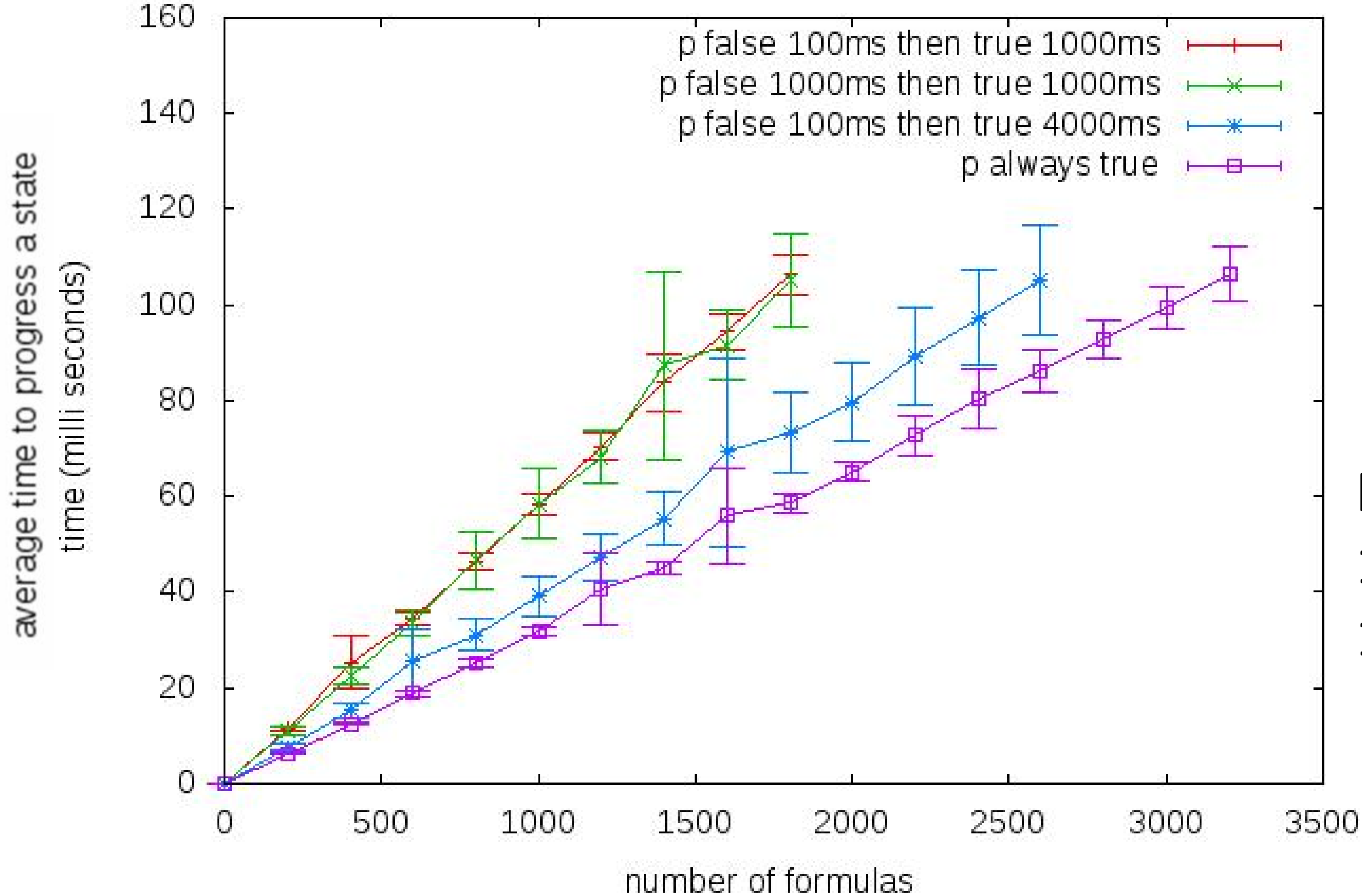


The semantics of these formulas is defined over infinite state sequences. Progression is one technique to check whether the current prefix is sufficient to determine the truth value of a formula.



Stream Reasoning using Metric Temporal Logic

always (¬p → **eventually** [0, 1000] **always** [0, 1000] p)



Pentium-M
1.4 GHz
1 GB RAM

Application: Execution Monitoring

If things can go wrong they probably will!

This implies the need for continual monitoring of an autonomous system and its environment in a principled, contextual, task specific manner which can be specified by the system itself!

always (eventually [0, t] (always [0,t'] speed(uav) < T))

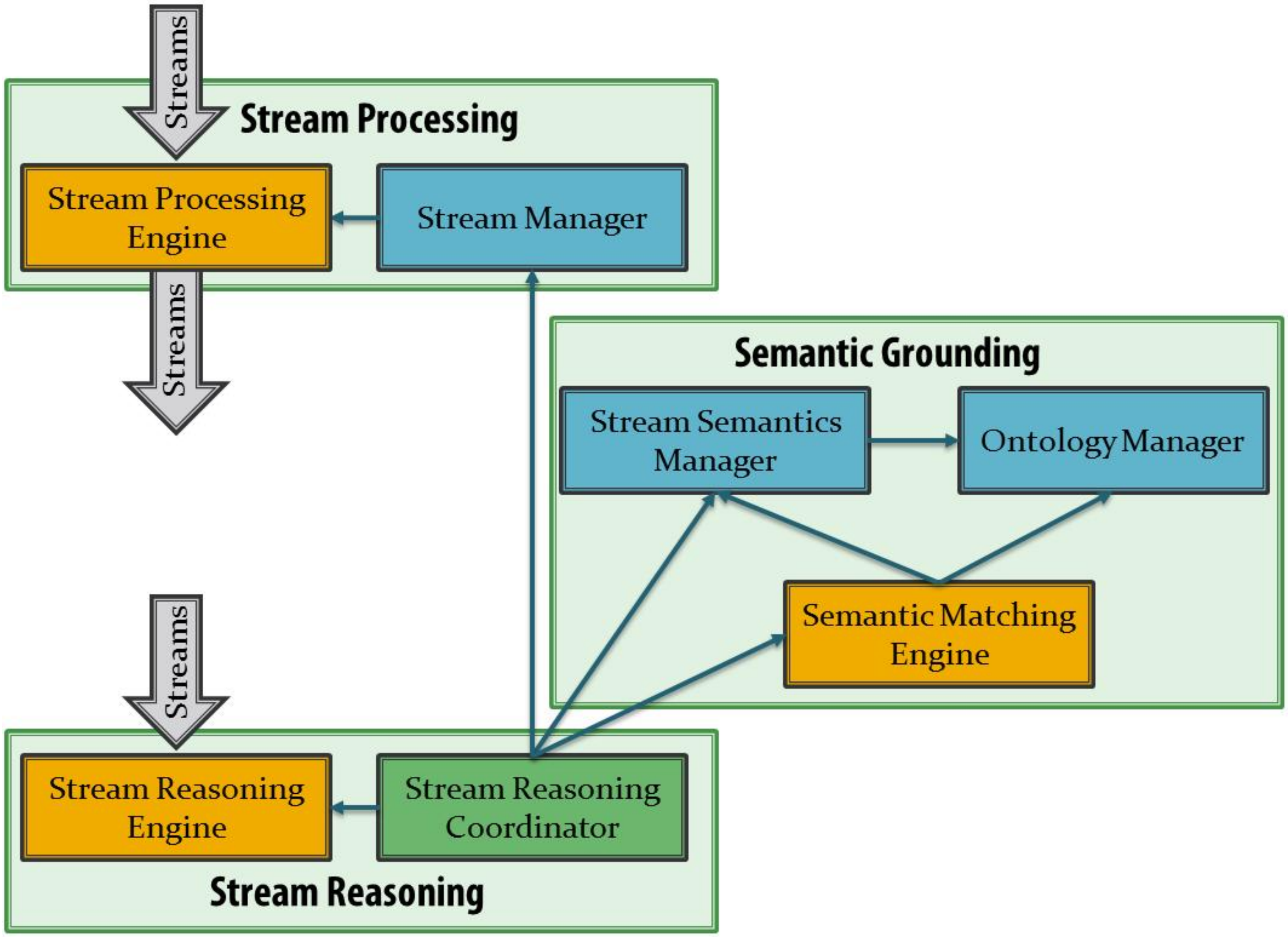
It should always be the case that within t time units from now, an interval of length t' should start where the UAV's speed stays below threshold T.

EXEC until [0, 5000] (¬EXEC ∧ altitude(uav) > 7)

The command should take less than 5 seconds to execute and when the execution is finished the altitude of the UAV should be above 7 meters.

DyKnow Semantically Grounded Stream Reasoning in ROS

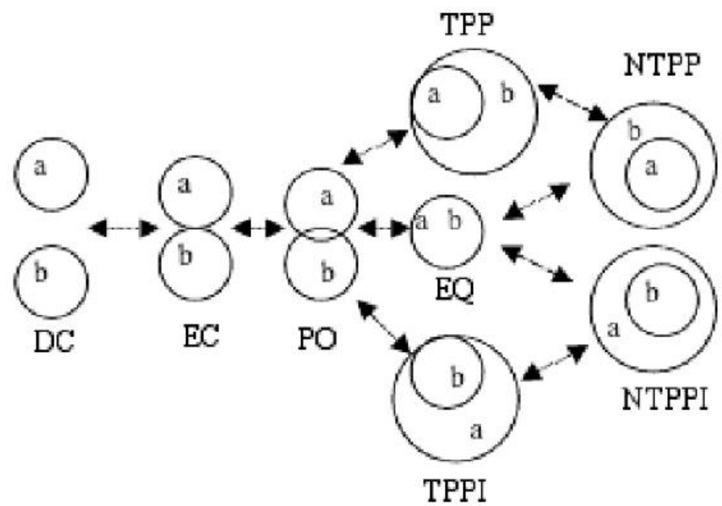
[Heintz IROS 2014]



Spatio-Temporal Stream Reasoning in DyKnow

[Heintz and de Leng ECAI 2014]

- The temporal reasoning is extended with spatial reasoning using for example RCC-8. RCC-8 defines 8 primitive relations and a composition table for qualitative constraint reasoning based on path consistency.
- Allows expressing conditions such as:
  - ∀*uav, restricted_area* **always** DC(*uav*, *restricted_area*)
  - ∀*uav, urban_area* **always** (PO(*uav*, *urban_area*) → **eventually** [0, 2min] altitude(*uav*) > 100m)



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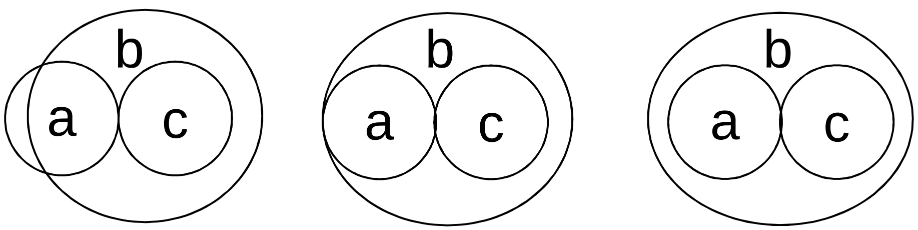
DC(urban_area1, restricted_area1)
DC(urban_area1, restricted_area2)
DC(urban_area1, urban_area2)
DC(urban_area1, road1)
DC(urban_area1, road2)
EC(road1, restricted_area1)
EC(road1, restricted_area2)
PO(road1, urban_area2)
DC(road1, road2)
PO(uav1, road2)
PO(uav1, urban_area2) …

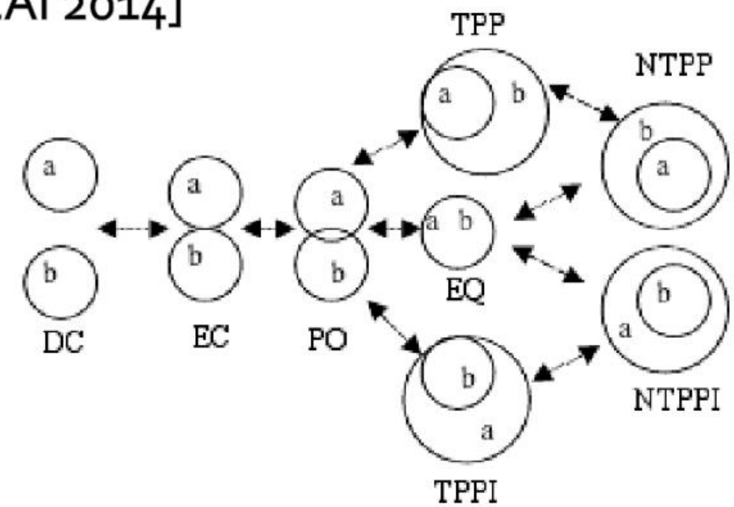
Spatio-Temporal Stream Reasoning in DyKnow

[Heintz and de Leng ECAI 2014]

Known: EC(a,c) $\wedge$ NTPP(c,b)

Deduced: PO(a,b) $\vee$ TPP(a,b)
$\vee$ NTPP(a,b)





DC(urban_area1, restricted_area1)
DC(urban_area1, restricted_area2)
DC(urban_area1, urban_area2)
DC(urban_area1, road1)
DC(urban_area1, road2)
EC(road1, restricted_area1)
EC(road1, restricted_area2)
PO(road1, urban_area2)
DC(road1, road2)
PO(uav1, road2)
PO(uav1, urban_area2) …

Spatio-Temporal Stream Reasoning in DyKnow

[Heintz and de Leng ECAI 2014]

- To handle incomplete spatial information we extend the first order logic to a three valued strong Kleene logic.

A and B	T	F	U
T	T	F	U
F	F	F	F
U	U	F	U

A or B	T	F	U
T	T	T	T
F	T	F	U
U	T	U	U

not A	
T	F
F	T
U	U

- The truth value of a spatial predicate P(a,b) given a set S of disjunctive base relations that hold between a and b is:
  - P(a,b) is true if $P \in S$ and $|S|=1$
  - P(a,b) is unknown if $P \in S$ and $|S|>1$
  - P(a,b) is false if $P \notin S$

always (PO(a,b) $\rightarrow$ **eventually** [0,2] DC(a,b))

always (PO(a,b) $\rightarrow$ **eventually** [0,2] DC(a,b))
$\wedge$ (U $\vee$ **eventually** [0,2] DC(a,b))

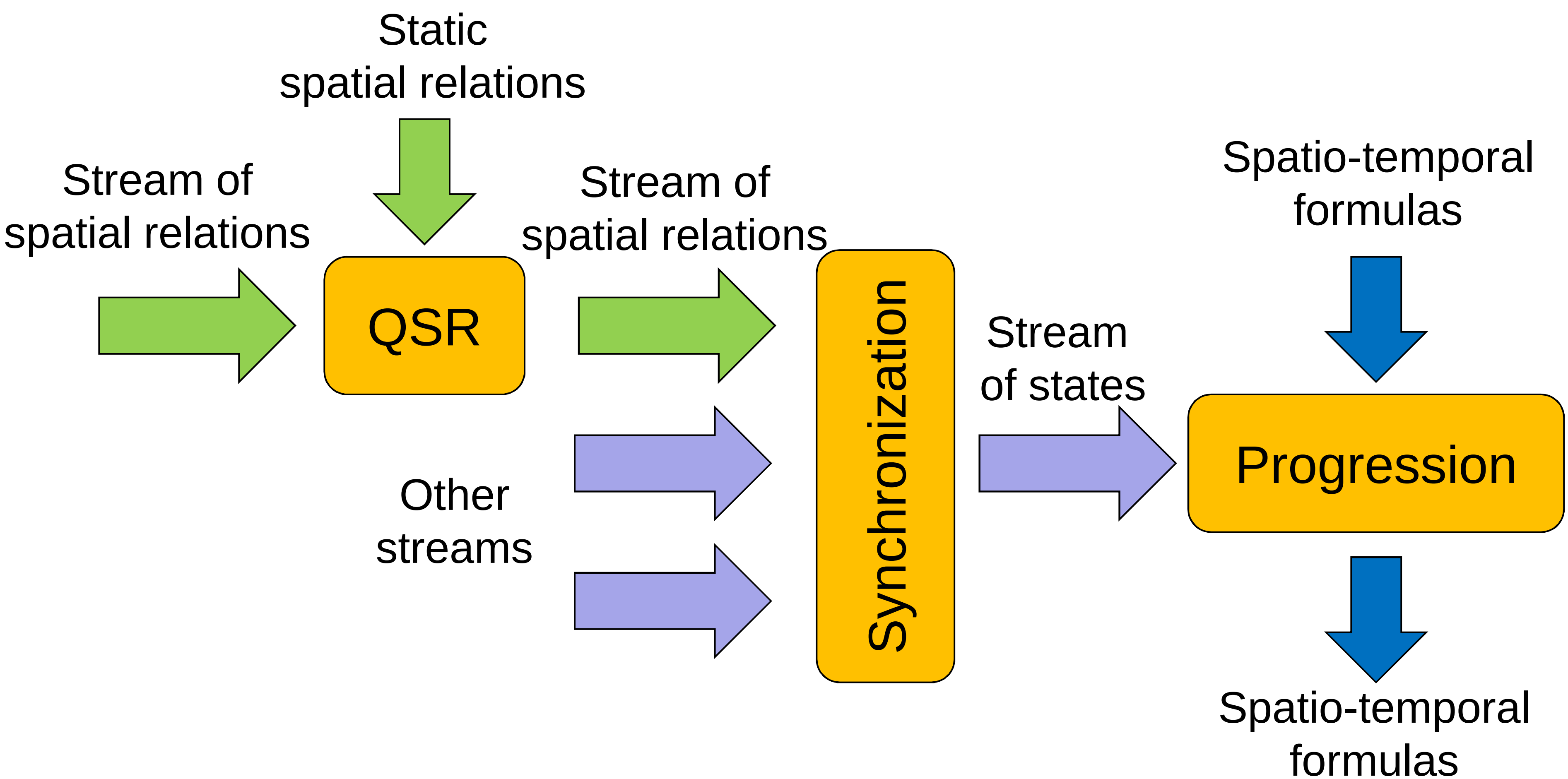
Known: EC(a,c) $\wedge$ NTPP(c,b)

Deduced: PO(a,b) $\vee$ TPP(a,b)
$\vee$ NTPP(a,b)

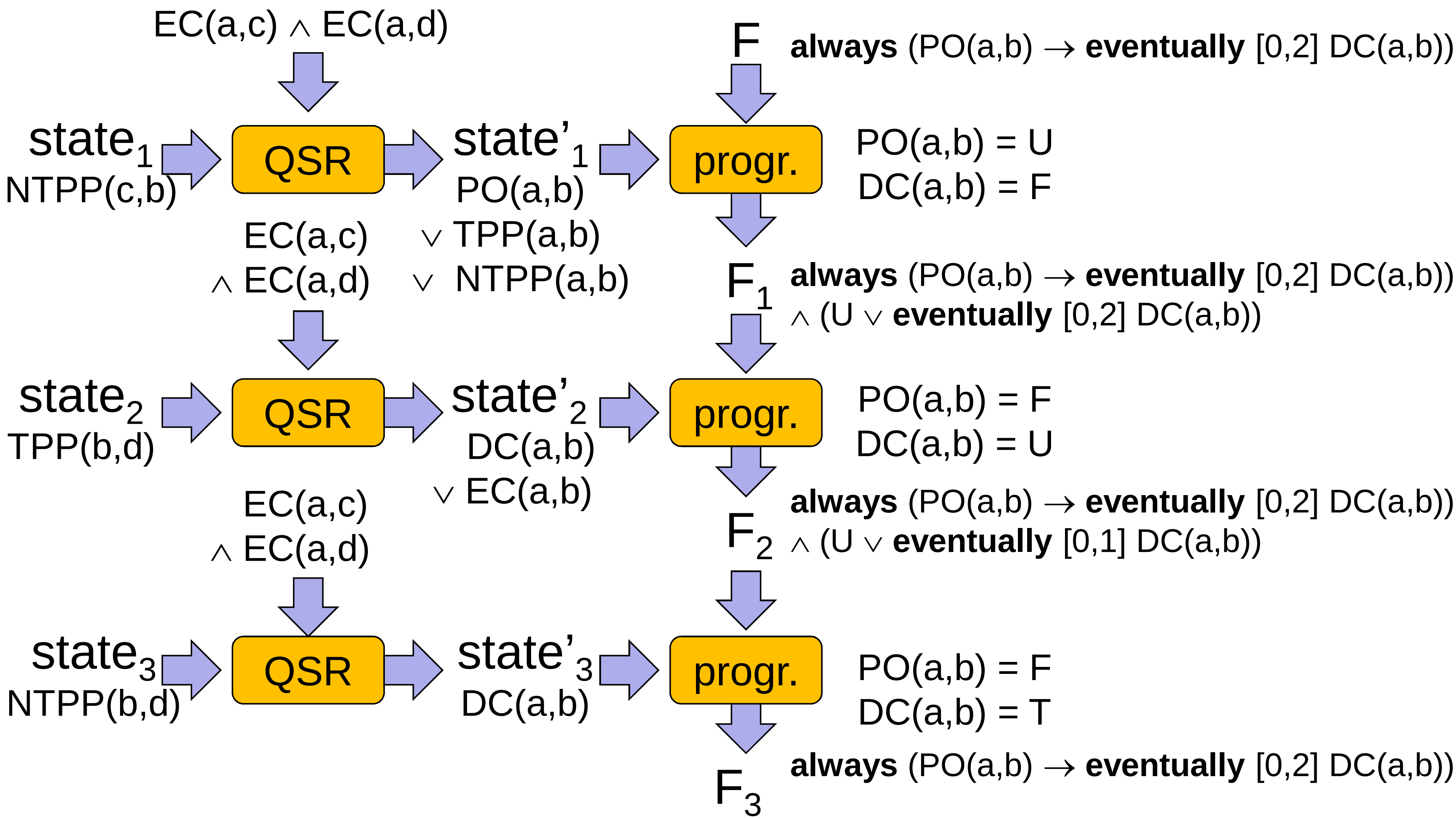
PO(a,b) = U and DC(a,b) = F

Spatio-Temporal Stream Reasoning in DyKnow

[Heintz and de Leng ECAI 2014]



Progression of Metric Spatio-Temporal Logic



The Sense-Reasoning Gap

Sense-Reasoning Gap

Reasoning

Qualitative models

Knowledge fusion

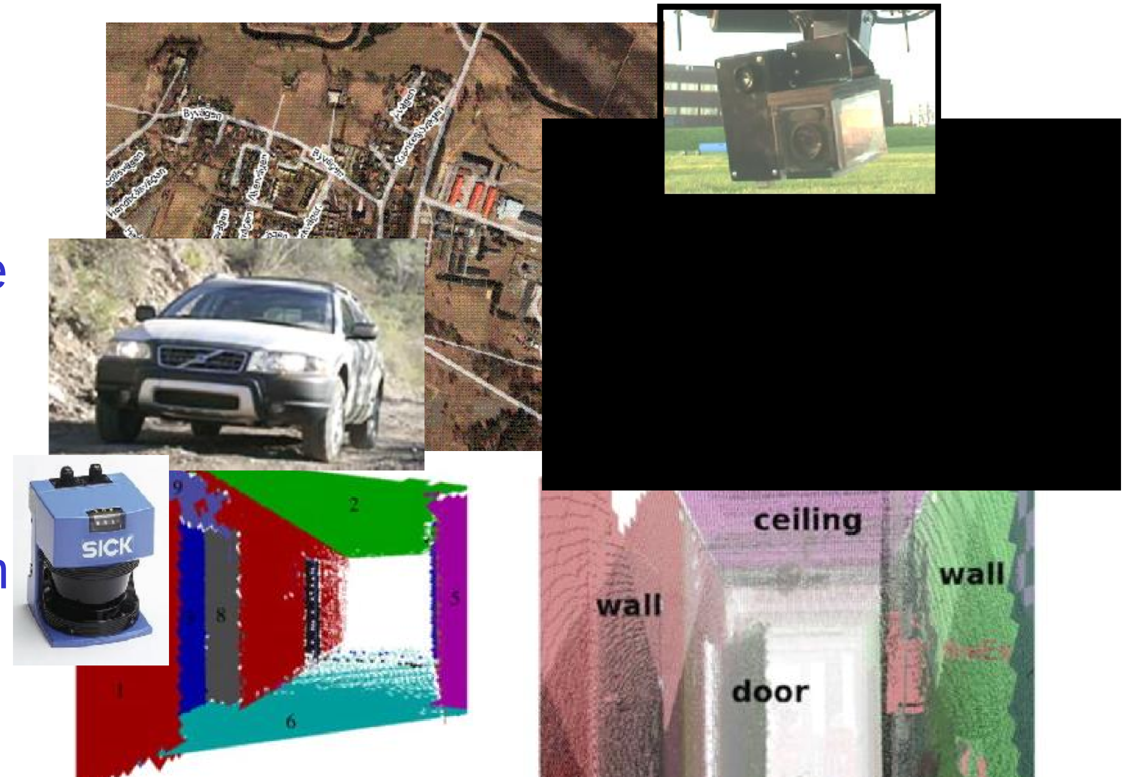
Mixed quantitative and qualitative models

Information fusion

Quantitative models

Sensor fusion

Sensing



The ***sense-reasoning gap*** is the gap between the noisy numerical data directly generated by sensors and the crisp symbolic information that reasoning functionalities normally assume to be available.

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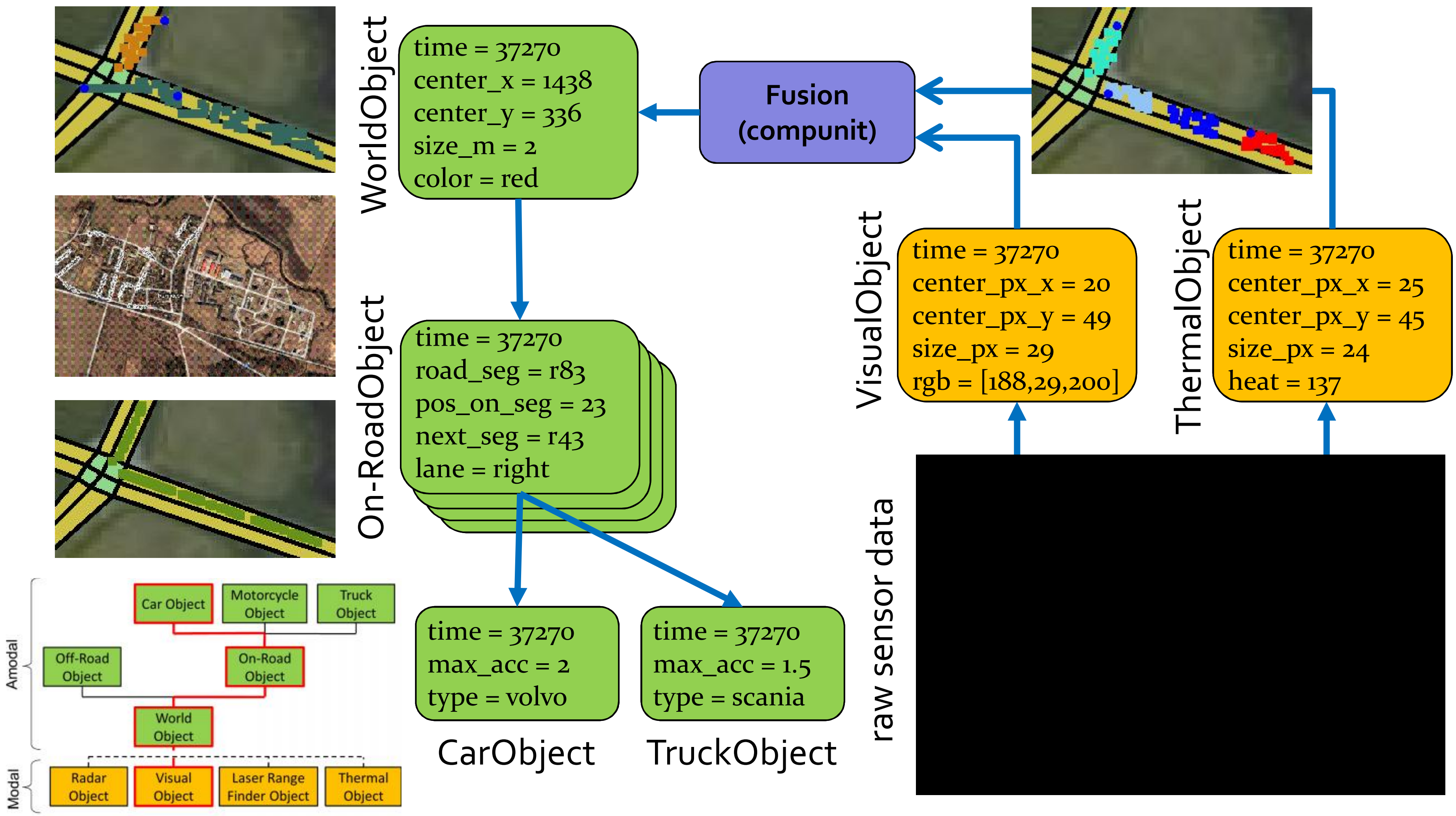
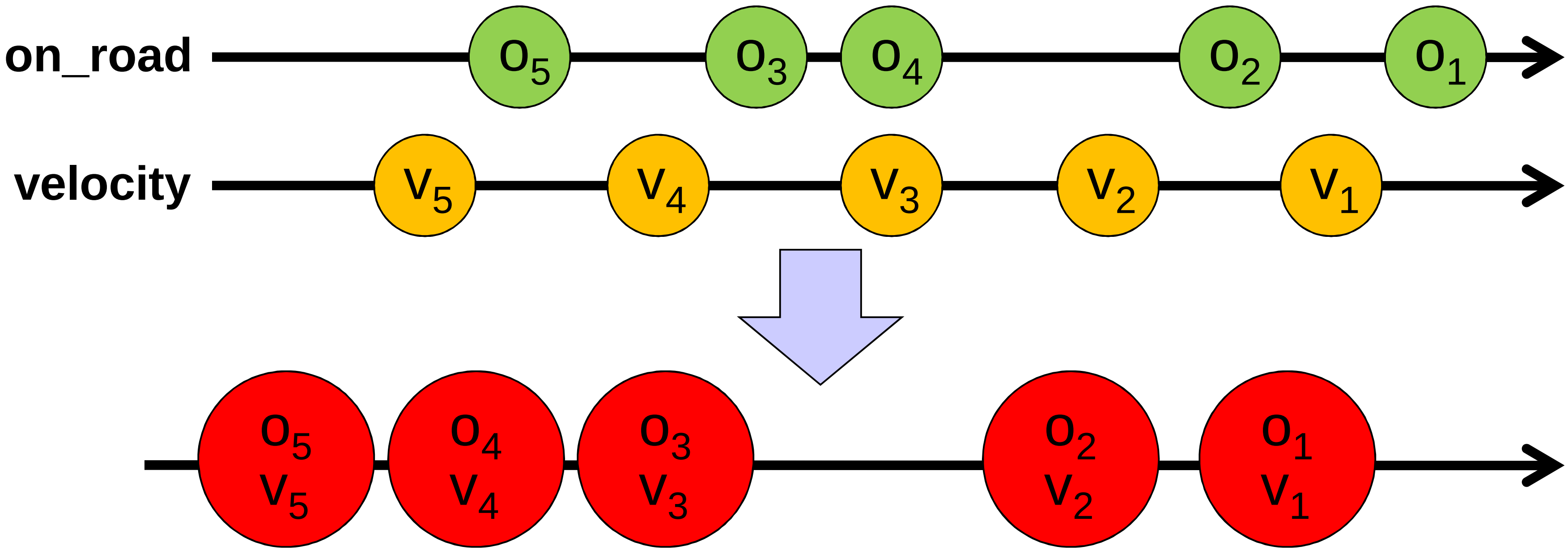
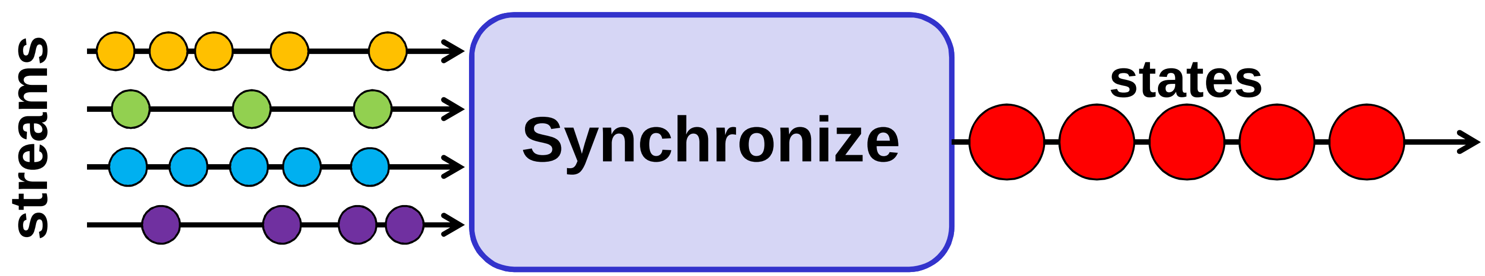
Bridging the Sense-Reasoning Gap



Generating State Streams





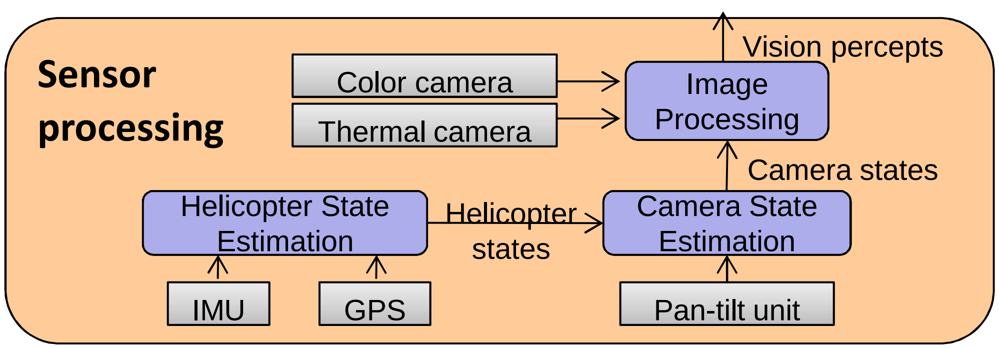
Grounding Stream Reasoning in Robotic Systems

[de Leng and Heintz FOfAI 2015, Heintz IROS 2014; de Leng and Heintz FUSION 2013]

- A temporal logical formula contains a number of symbols representing variables whose values over time must be collected and synchronized in order to determine the truth value of the formula.

  forall *x* in UAV **always**(Speed[*x*] < 60)

- Given a functional system, such as a robot, producing streams the grounding problem for logic-based stream reasoning is to *connect symbols in formulas to streams in the functional system so that the symbols get their intended meaning*.



Syntactic and Semantic Grounding

[de Leng and Heintz FOfAI 2015, Heintz IROS 2014; de Leng and Heintz FUSION 2013]

- *Syntactic grounding*: Use a direct mapping between symbols and streams, for example by using stream names in the formulas. A formula such as

  forall *x* in UAV **always**(Speed [x] < 60)

  would then have to be written something like

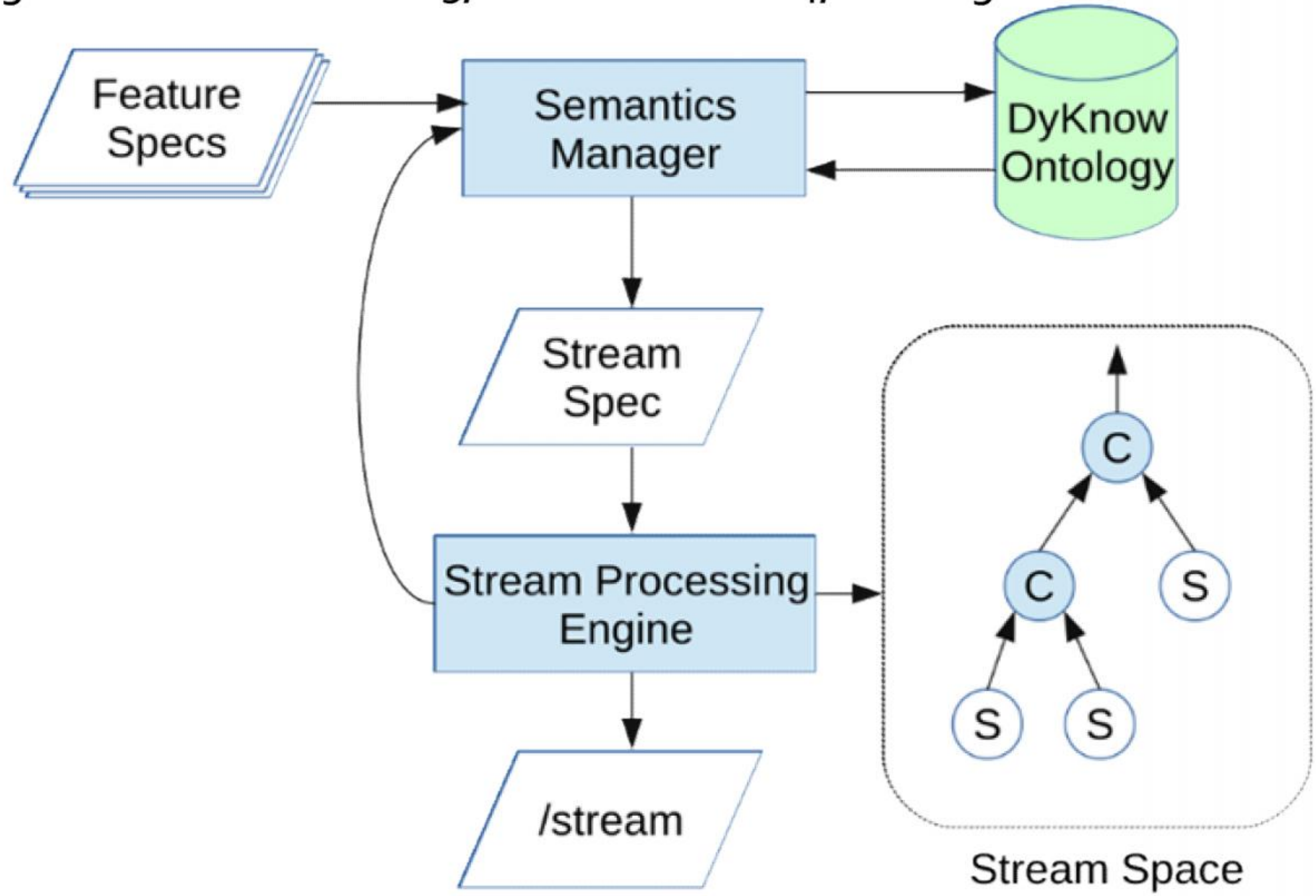
  always((/uav1/uavstate.spd < 60) ∧ (/uav2/uavstate.spd < 60))

- *Semantic grounding*: Annotate streams with their semantic content and reason about how to connect symbols to streams using semantic web technologies. We call this reasoning for *semantic matching*. It finds the relevant streams by matching the ontological concepts used in a formula to the ontological concepts associated with the streams.

Semantic Web

Semantically Grounded Stream Reasoning

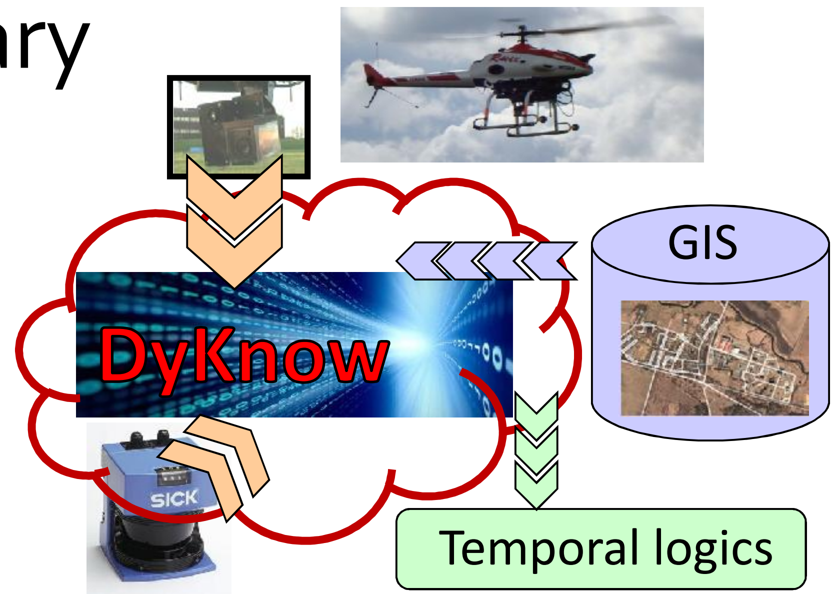
[de Leng and Heintz FOfAI 2015, Heintz IROS 2014; de Leng and Heintz FUSION 2013]



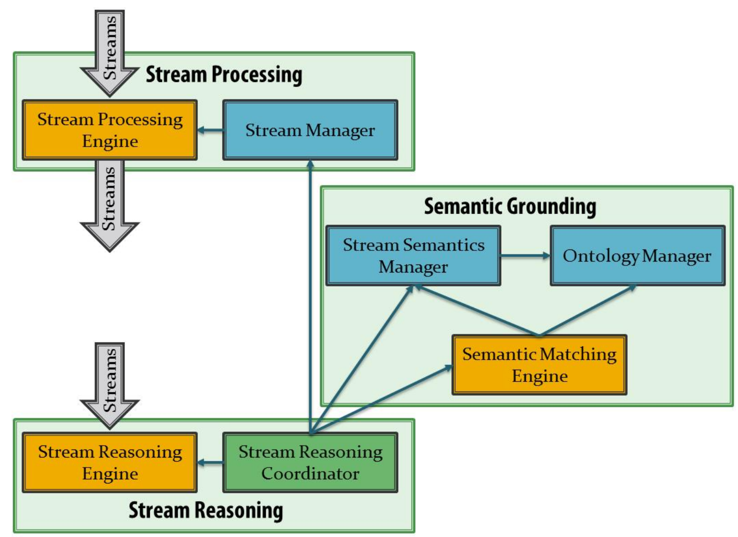
Discussion

- A stream can be seen as a partial view of a conceptual central KB. One important and interesting special case is to view a stream as temporal information, where each stream element is conceptually a separate time-point.
- Windows are an explicit construct to create independent parts
- Event processing vs Stream Reasoning.
- Separating stream processing and stream reasoning.
- Determining the truth value of a formula over a given stream or finding all substitutions which make the formula true.
- Finding all substreams which satisfies a formula.
- Combine formula evaluation (path checking) with theorem proving (model checking).

Summary



- High level incremental reasoning over streaming information is essential to autonomous systems.
- DyKnow is a practical framework for grounded stream reasoning including support for spatio-temporal reasoning.
- The reasoning is semantically grounded through a common ontology and a specification of the semantic content of streams relative to the ontology.
- Through DyKnow, ROS is extended with a powerful stream reasoning capability available to a wide range of robotic systems.



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