Representation and Processing of Instantaneous and Durative Temporal Phenomena

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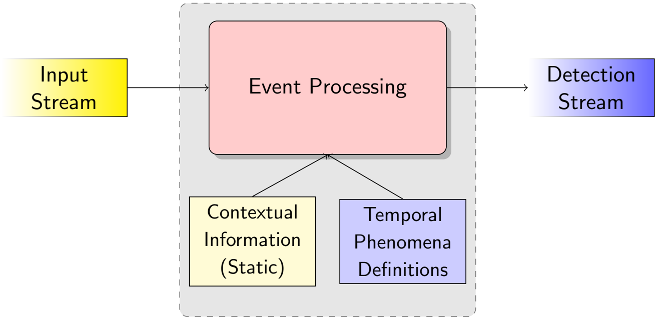
Event processing systems



Pattern definition languages

Currently:

- the majority of pattern languages use either an interval-based temporal model (e.g., ETALIS[1]) or a point-based temporal model (e.g., SASE+[2])
- some combine instants and intervals, but don't offer Allen's relations on intervals (Event Calculi[3])
- automata based languages focus on sequences of events (FlinkCEP[4])

There is a need for a language that allows the expression of instantaneous and durative entities and is expressive enough for the definition of hierarchical events e.g. maritime events.

[1] D. Anicic et al. ETALIS: Rule-Based Reasoning in Event Processing

[2] H. Kawashima et al. Complex event processing over uncertain data streams.

[3] A. Artikis et al. An Event Calculus for Event Recognition

[4] `https://ci.apache.org/projects/flink/flink-docs-release-1.13/docs/libs/cep/`

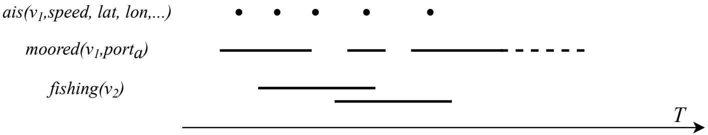
A temporal phenomena definition language

We present a logic based language that allows the specification of instantaneous and durative temporal phenomena.

The key elements of the language are:

- events: happen on instants of time,
- states: hold true on intervals,
- dynamic temporal phenomena: hold true on intervals.

Events, states and dynamic temporal phenomena are expressed as predicates of corresponding types, and can be either **user-defined** or **input**.



Syntax

Our language is described by the triplet $\langle \mathscr{P}, L, \Phi \rangle$

- $\mathscr{P}$ is a set of Predicates (atomic formulae); event, state or dynamic temporal phenomenon predicates;
- $L = \{\wedge, \vee, \neg\} \cup$
  $\{\rightarrowtail, \sqcup, \sqcap, \setminus\} \cup$
  $\{$before, meets, overlaps, finishes, starts, equals, contains$\} \cup$
  $\{\text{start}, \text{end}\}$.
- Φ is the set of formulae defined by the union of the formulae sets:
  - $\Phi^{\bullet}$ describe instantaneous temporal phenomena,
  - Φ^{-} describe durative temporal phenomena that hold (are true) in disjoint maximal intervals, and
  - $\Phi^{=}$ describe durative temporal phenomena that may hold in non-disjoint intervals.

Definitions: Events

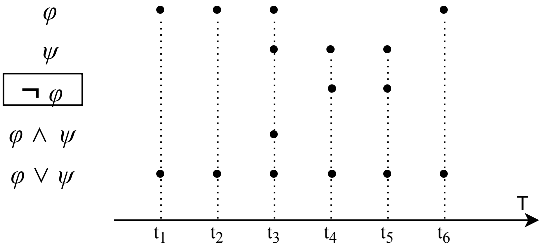
Events are true on instants of time and they can be defined using formulae of $\Phi^{\bullet}$ i.e., expressions on instants.

The set of formulae of $\Phi^{\bullet}$ is defined as follows:

- an event predicate is a formula of $\Phi^{\bullet}$
- iff $\phi \in \Phi^{\bullet}$ then $\neg\phi$ is a formula of $\Phi^{\bullet}$
- iff $\phi, \psi \in \Phi^{\bullet}$ then $\phi[\wedge, \vee]\psi$ is a formula of $\Phi^{\bullet}$
- iff $\phi \in \Phi^{-}$ then $\mathsf{start}/\mathsf{end}(\phi)$ is a formula of $\Phi^{\bullet}$

Logical connectives

$\phi, \psi \in \Phi^{\bullet}$



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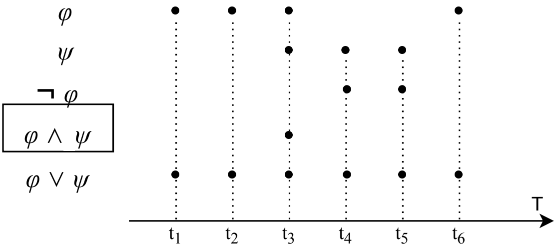

Logical connectives

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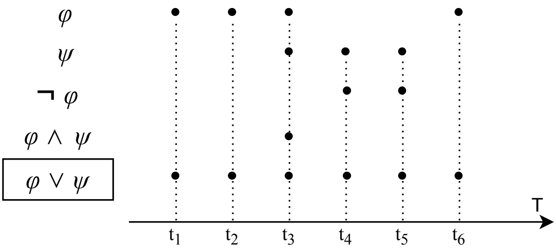


Definitions: States

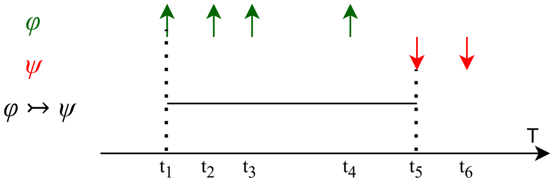
States are inertive and hold true for maximal intervals. States are defined in terms of Φ^- formulae i.e., with the use of the maximal range operator or with the use of the $\sqcup, \sqcap, \setminus$ interval operations.

The set of Φ^- formulae is defined as follows:

- a state predicate is formula of Φ^-
- iff $\phi, \psi \in \Phi^\bullet$ then $\phi \rightarrowtail \psi$ is formula of Φ^-
- iff $\phi, \psi \in \Phi^-$ then $\phi[\sqcup, \sqcap, \setminus]\psi$ is formula of Φ^-

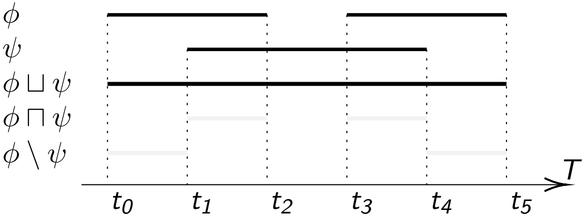
Maximal range operator

$\phi \rightarrowtail \psi$ where $\phi, \psi \in \Phi^{\bullet}$



Interval operations

- Temporal union ($\sqcup$),
- temporal intersection ($\sqcap$),
- temporal complement ($\setminus$).



Interval operations

- Temporal union ($\sqcup$),
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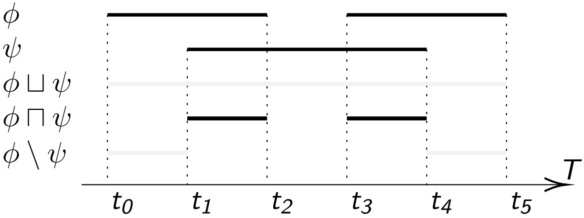

Interval operations

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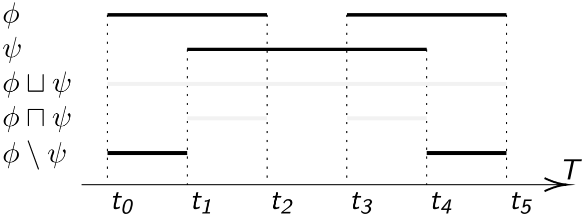


Definitions: Dynamic temporal phenomena

Dynamic temporal phenomena are defined in terms of temporal relations ($\square$) between events, states or activities (i.e., formulae of $\Phi^{=}$).

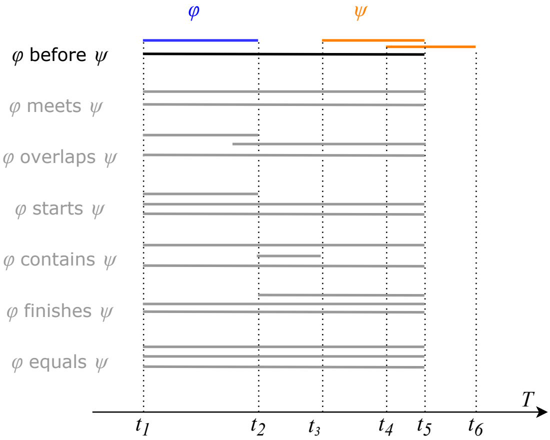
The set of $\Phi^{=}$ formulae is defined as follows:

- a dynamic temporal phenomenon predicate is a formula of $\Phi^{=}$
- and...

Relation	Formulae sets			
	$a \in \Phi^{-} \cup \Phi^{=}$ $b \in \Phi^{-} \cup \Phi^{=}$	$a \in \Phi^{\bullet}$ $b \in \Phi^{-} \cup \Phi^{=}$	$a \in \Phi^{-} \cup \Phi^{=}$ $b \in \Phi^{\bullet}$	$a \in \Phi^{\bullet}$ $b \in \Phi^{\bullet}$
a before b	✓	✓	✓	✓
a overlaps b	✓	-	-	-
a meets b	✓	-	-	-
a finishes b	✓	✓	-	-
a starts b	✓	✓	-	-
a contains b	✓	-	✓	-
a equals b	✓	-	-	-

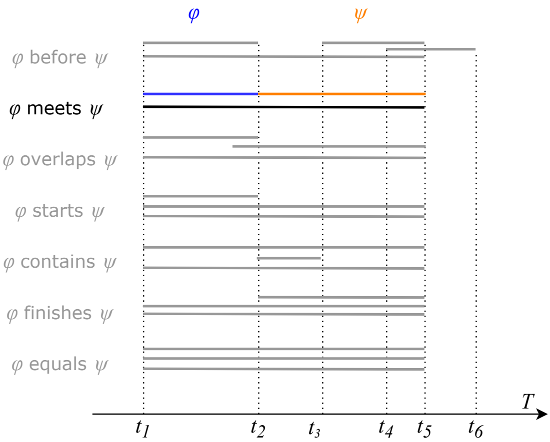
Temporal relations: interval - interval

$\phi, \psi \in \Phi^{-} \cup \Phi^{=}$



Temporal relations: interval - interval

$\phi, \psi \in \Phi^- \cup \Phi^=$



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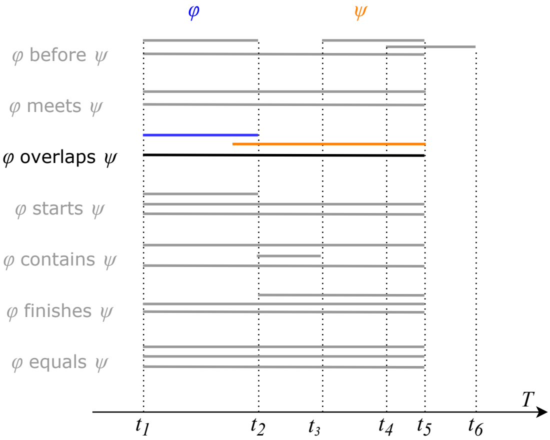

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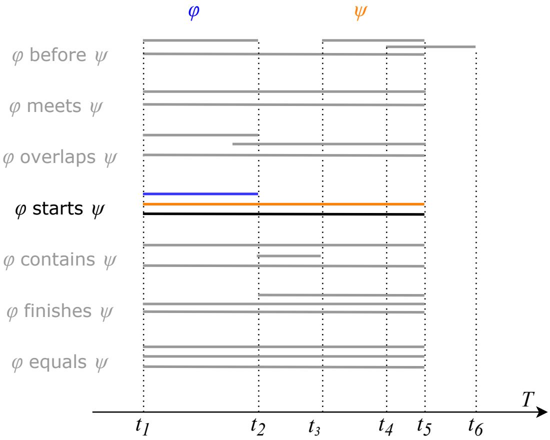

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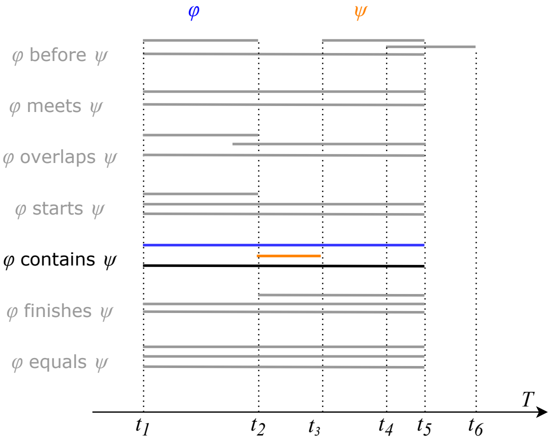

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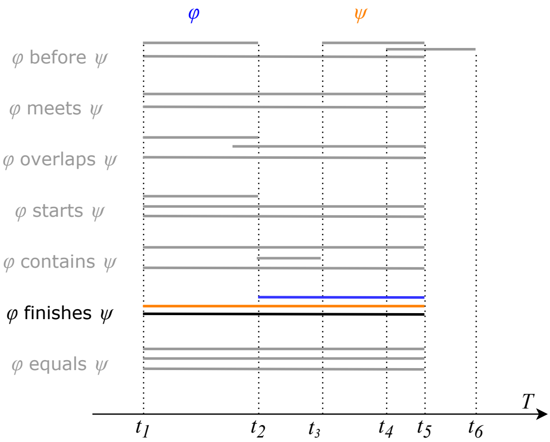

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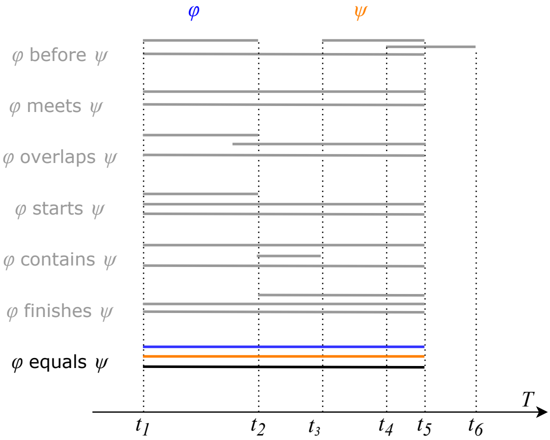

Temporal relations: instant - interval

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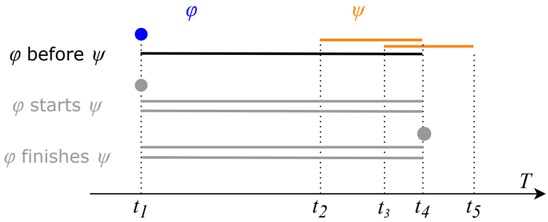

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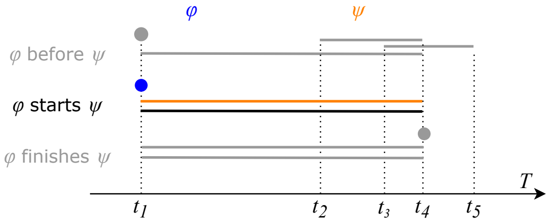

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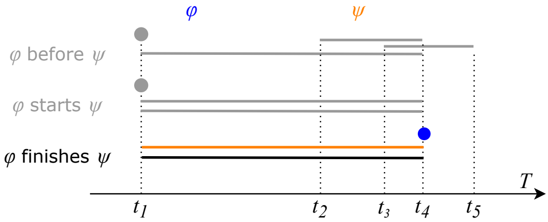

Temporal relations: interval - instant

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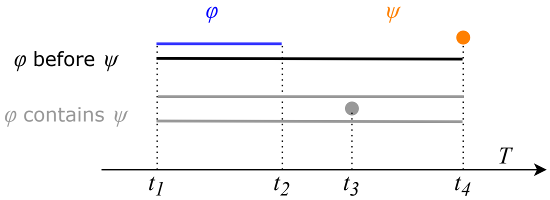

Temporal relations: interval - instant

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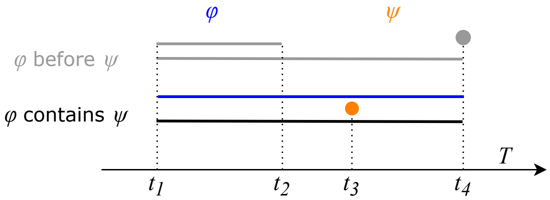

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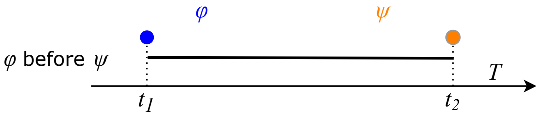


Maritime use case: available data

Dynamic data:

- Automatic Identification System (AIS) ✓
- RADAR (stream)
- Weather (stream)
- CCTV video (stream)

Static data:

- Area polygons, points of ports etc ✓
- Depth information (static)
- Vessel images (IHS)
- Vessel characteristics (IHS/AIS) ✓

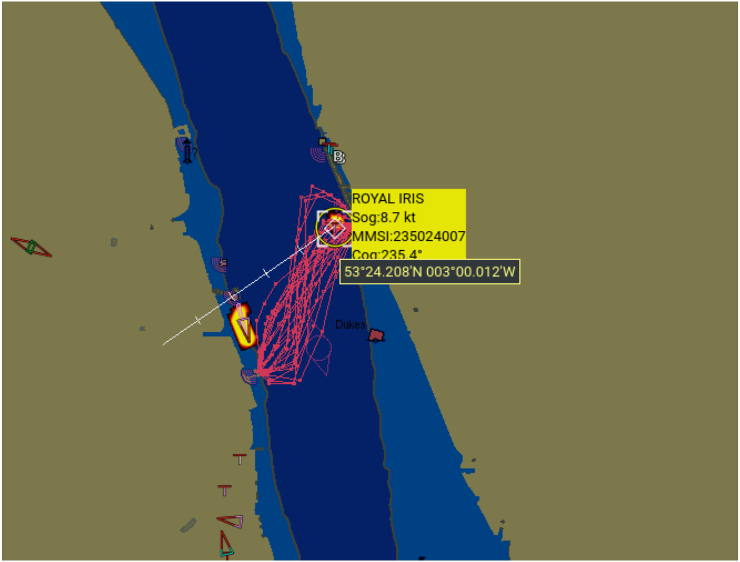
Automatic Identification System (AIS)

The Automatic Identification System is an extensively used autonomous tracking system that allows transmission of dynamic and static vessel information.

Transmitted Data:

- **Dynamic information** Every 2-10 sec while under way, every 6 min while anchored (speed, location, heading etc)
- **Static & Voyage related information:** Every 6 min (Vessel type, dimensions, destination, eta)

AIS track


ROYAL IRIS
Sog:8.7 kt
MMSI:235024007
Cog:235.4°
53°24.208'N 003°00.012'W
Dukes

Maritime examples: stopped & underway

A *Vessel* is stopped for the **maximal** time intervals its speed is less than a user defined threshold e.g., 0.5 knots.

$$
\begin{aligned}
&\text{event } \mathit{stop\_start}(\mathit{Vessel}) : \\
&\quad \mathit{ais}(\mathit{Vessel}, \mathit{Speed}, \ldots) \land \mathit{Speed} \leq 0.5 \ . \\
&\text{event } \mathit{stop\_end}(\mathit{Vessel}) : \\
&\quad \mathit{ais}(\mathit{Vessel}, \mathit{Speed}, \ldots) \land \mathit{Speed} > 0.5 \ .
\end{aligned}
$$

$$
\begin{aligned}
&\text{state } \mathit{stopped}(\mathit{Vessel}) : \\
&\quad \mathit{stop\_start}(\mathit{Vessel}) \rightarrowtail \mathit{stop\_end}(\mathit{Vessel}).
\end{aligned}
$$

A *Vessel* is underway for the **maximal** time intervals its speed is greater than a user defined threshold e.g., 2.7 knots.

$$
\begin{aligned}
&\text{state } \mathit{underway}(\mathit{Vessel}) : \\
&\quad \mathit{ais}(\mathit{Vessel}, \mathit{Speed}, \ldots) \land \mathit{Speed} > 2.7 \rightarrowtail \\
&\quad \mathit{ais}(\mathit{Vessel}, \mathit{Speed}, \ldots) \land \mathit{Speed} < 2.7.
\end{aligned}
$$

Maritime examples: in port/fishing area & moored

In port. (In fishing area is defined in a similar manner)

$$\text{state } \mathit{in\_port}(\mathit{Vessel}, \mathit{Port}) : \\ \mathit{enters\_port}(\mathit{Vessel}, \mathit{Port}) \rightarrowtail \mathit{leaves\_port}(\mathit{Vessel}, \mathit{Port}).$$

A *Vessel* is moored when it is stopped inside a port (*Port*).

$$\text{state } \mathit{moored}(\mathit{Vessel}, \mathit{Port}) : \\ \mathit{stopped}(\mathit{Vessel}) \sqcap \\ \mathit{in\_port}(\mathit{Vessel}, \mathit{Port}).$$

Maritime examples: trip & fishing trip

A trip of a Vessel from a PortA to a PortB can be defined as follows:

$$
\begin{array}{l}
\text{dynamic } \mathit{trip}(\mathit{Vessel}, \mathit{PortA}, \mathit{PortB}) : \\
\quad \text{end}(\mathit{moored}(\mathit{Vessel}, \mathit{PortA})) \text{ before} \\
\quad (\mathit{underway}(\mathit{Vessel}) \\
\quad\; \text{before start}(\mathit{moored}(\mathit{Vessel}, \mathit{PortB})).
\end{array}
$$

A fishing trip starts from a *PortA* and ends at a *PortB*, during the trip the vessel is underway and during that period it passed through a fishing area *FArea*.

$$
\begin{array}{l}
\text{dynamic } \mathit{fishing\_trip}(\mathit{Vessel}, \mathit{PortA}, \mathit{AreaID}, \mathit{PortB}) : \\
\quad \text{end}(\mathit{moored}(\mathit{Vessel}, \mathit{PortA})) \text{ before} \\
\quad\quad ((\mathit{underway}(\mathit{Vessel}) \text{ contains } \mathit{in\_fishing\_area}(\mathit{Vessel}, \mathit{AreaID})) \\
\quad\quad\; \text{before start}(\mathit{moored}(\mathit{Vessel}, \mathit{PortB}))).
\end{array}
$$

Maritime examples: pilotage in Liverpool

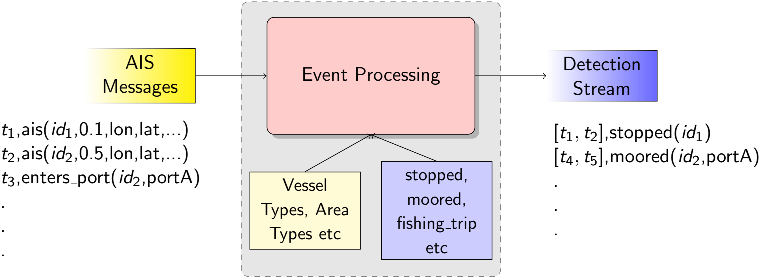
Description of pilotage from a VTS expert:

- The vessel will initially be anchored in the anchorage area 1.
- The pilot will join the vessel reasonably close to "The Bar". Around 15 minutes before the pilot arrives, the vessel will get underway and be travelling 5-8 knots when the pilot joins the vessel.
- The pilot will then navigate the vessel into port (Seaforth, Garston Dock, Pier Head or elsewhere). The fast pilot boat will probably go in ahead of it.

A prototype formalisation of this activity in our language would be:

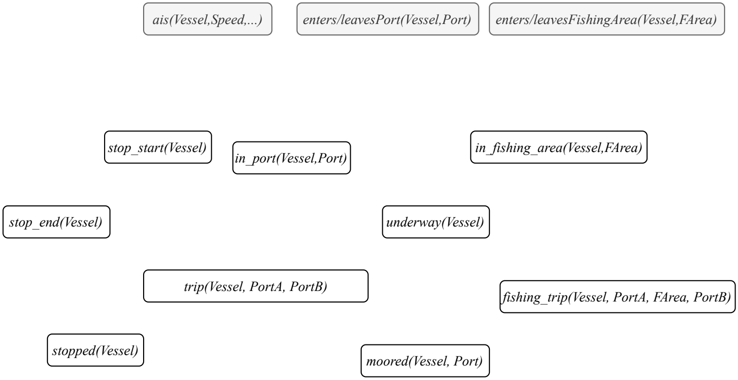
$$
\begin{array}{l}
\text{dynamic } \mathit{pilotage}(\mathit{Vessel}, \mathit{Pilot}) : \\
\quad \mathit{end}(\mathit{anchored}(\mathit{Vessel}, \mathit{anchorage\_1})) \text{ before} \\
\qquad (((\mathit{underway}(\mathit{Vessel}) \text{ contains} \\
\qquad\quad (\mathit{in\_area}(\mathit{Vessel}, \mathit{theBar}) \cap \mathit{in\_area}(\mathit{Pilot}, \mathit{theBar}))) \text{ overlaps} \\
\qquad\ \ \mathit{in\_proximity}(\mathit{Vessel}, \mathit{Pilot})) \text{ before} \\
\qquad \mathit{start}(\mathit{moored}(\mathit{Vessel}, \mathit{Port})) \ \wedge \ \mathit{Port} \in [\mathit{Seaforth}, ...]).
\end{array}
$$

Maritime use case



Processing: Evaluation order

Processing of the user defined temporal phenomena requires a valid evaluation order. For example:



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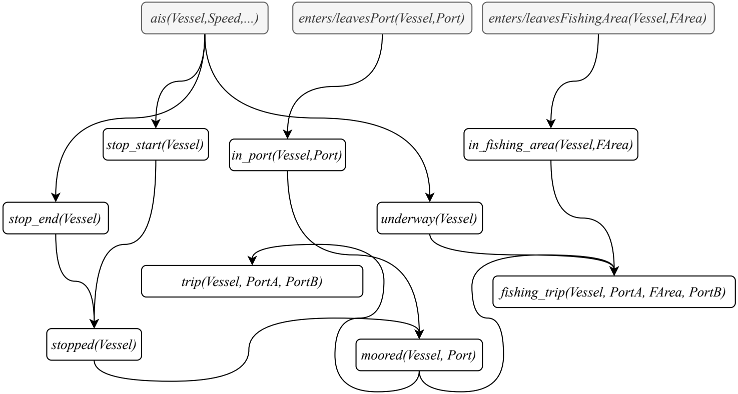

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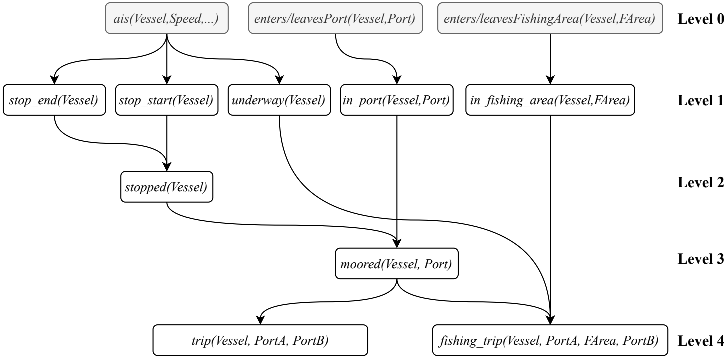
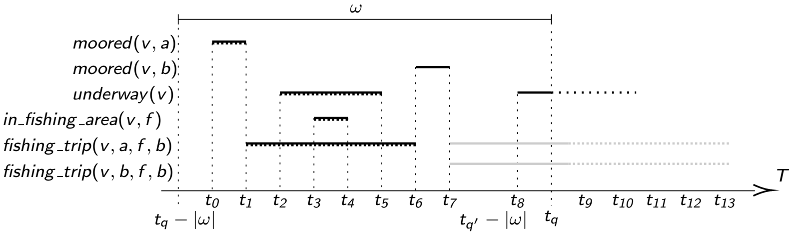


Topological sort of the dependency graph (DAG) provides a valid evaluation order.

Processing: Streams

Processing happens at equally spaced, with a step s, query times t_q and a temporal window ω.



As the window slides, elements that fall outside should be discarded **unless** they have been classified as ‘non-redundant’.

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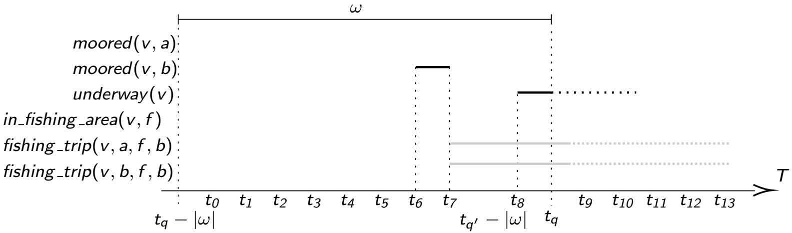

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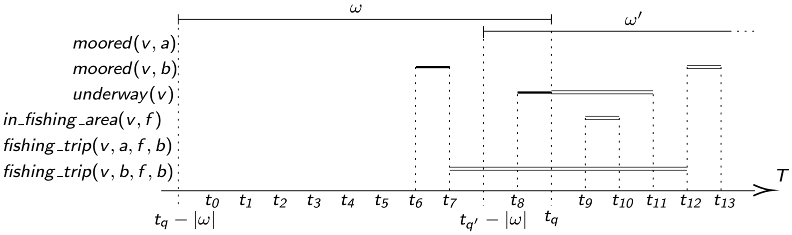
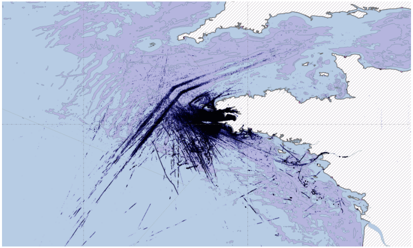


As the window slides, elements that fall outside should be discarded **unless** they have been classified as 'non-redundant'.

Preliminary evaluation: dataset

Attribute	**Brest, France**
Period (months)	6
Vessels	5K
AIS signals	18M
Fishing areas	263
Ports	222
Spatio-temporal events	160K

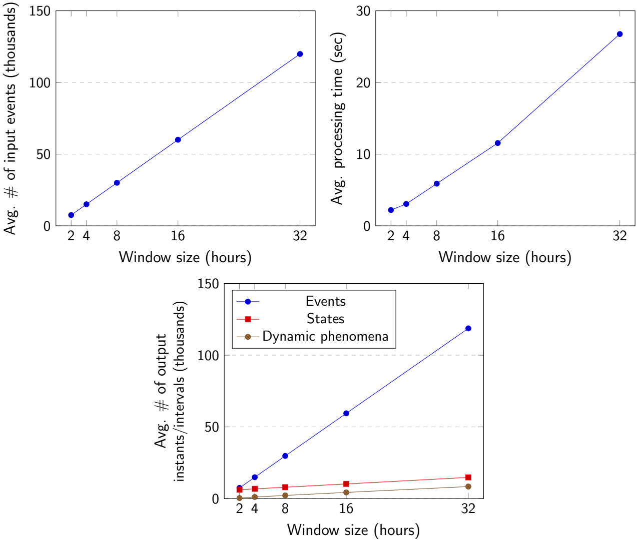


- **Source:** Cyril Ray et. al. Heterogeneous integrated dataset for Maritime Intelligence, surveillance, and reconnaissance. Data in Brief, Volume 25, 2019.
- **Preprocessing:** M. Pitsikalis et. al. Composite Event Recognition for Maritime Monitoring. DEBS ’19

Preliminary evaluation: User defined phenomena

User defined phenomena
$stop\_end/start(Vessel)$
$underway(Vessel)$
$in\_port(Vessel, Port)$
$in\_fishing\_area(Vessel, Port)$
$stopped(Vessel)$
$moored(Vessel, Port)$
$trip(Vessel, PortA, PortB)$
$fishing\_trip(Vessel, PortA, FArea, PortB)$

Preliminary evaluation: efficiency (2h step)



Intel(R) Core(TM) i7-3612QM CPU @ 2.10GHz, SWI-Prolog 7.6.4

Summary

We offer:

- a language that allows the description of phenomena that happen on instants and intervals, the relations between them and hierarchical definitions,
- a formal description of the semantics,
- the operational semantics for stream processing, and
- an open source implementation `https://github.com/manospits/Phenesthe`.

Although we presented examples inspired from the maritime domain, the language can be used in a wide set of applications.

Future work:

- integrate temporal stream processing with process mining techniques for the discovery of dynamic temporal phenomena,
- make the implementation scalable.

Thank you!