Machine Learning for Complex Event Recognition

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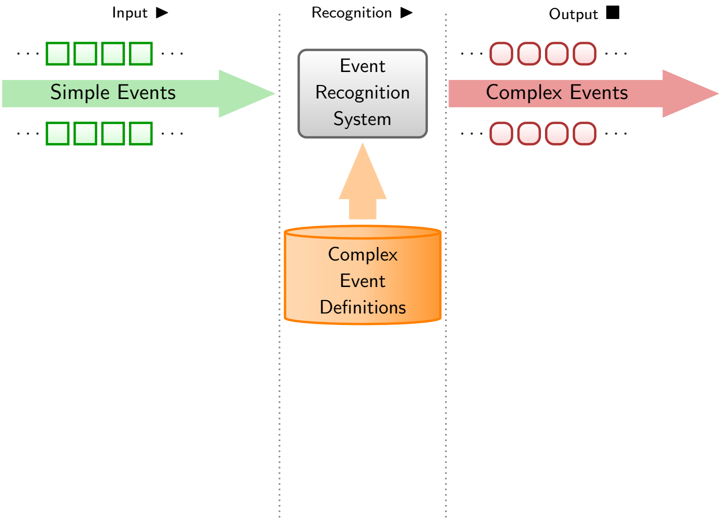
Complex Event Recognition



Complex Event Recognition

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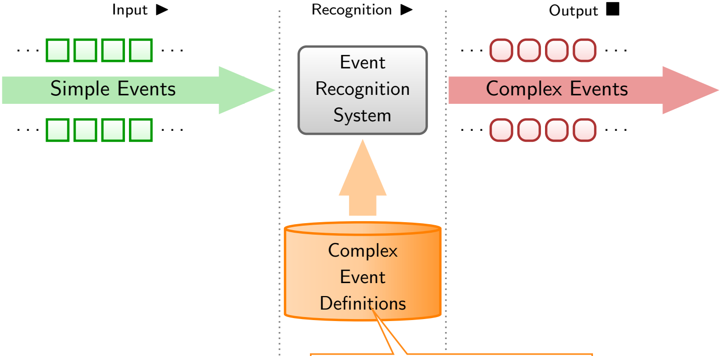
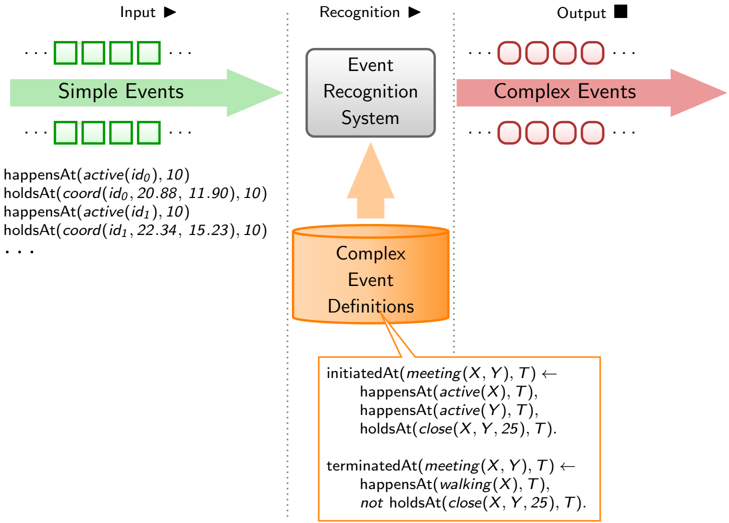


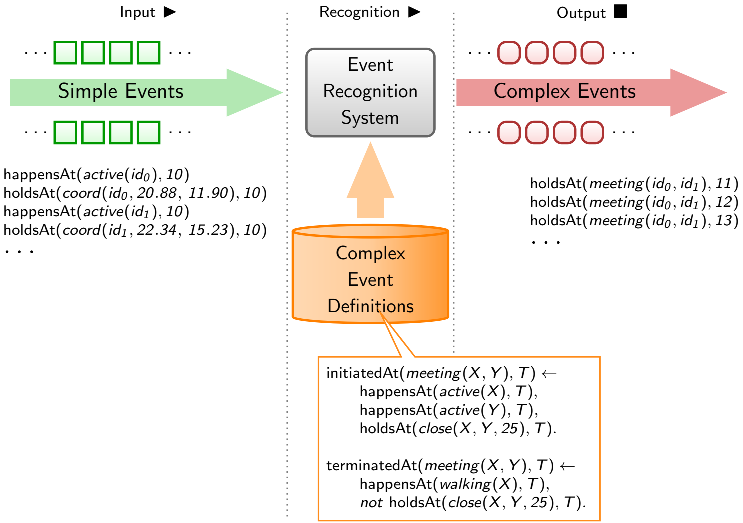
initiatedAt($meeting(X, Y)$, T) $\leftarrow$
happensAt($active(X)$, T),
happensAt($active(Y)$, T),
holdsAt($close(X, Y, 25)$, T).

terminatedAt($meeting(X, Y)$, T) $\leftarrow$
happensAt($walking(X)$, T),
not holdsAt($close(X, Y, 25)$, T).

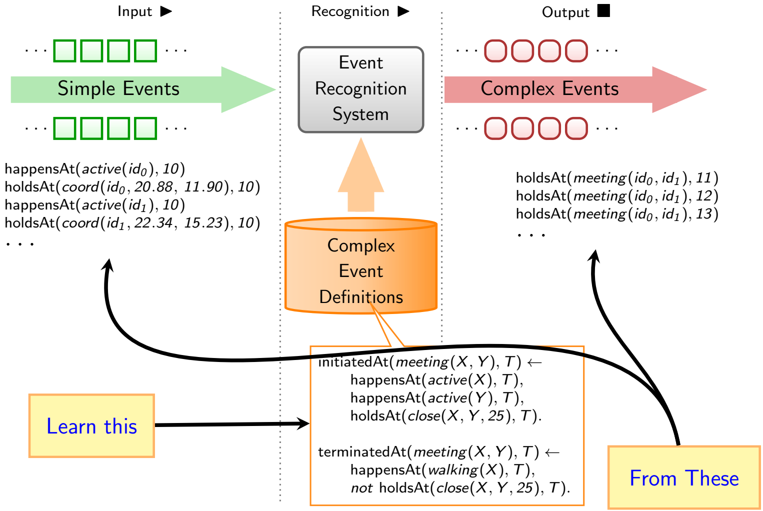
Complex Event Recognition



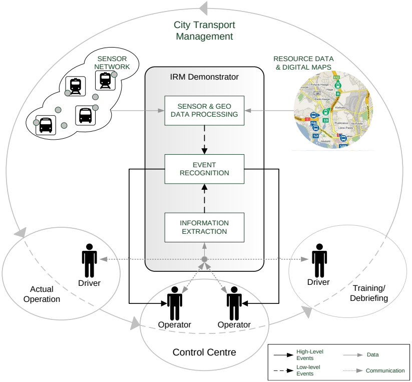
Complex Event Recognition



Learning for Complex Event Recognition



Applications



Complex Event Recognition using the Event Calculus

- Formal, declarative semantics.
- Representation of complex temporal phenomena.
- Representation of complex atemporal phenomena.
- Very efficient reasoning $\rightarrow$ RTEC.

Complex Event Recognition using the Event Calculus

- Formal, declarative semantics.
- Representation of complex temporal phenomena.
- Representation of complex atemporal phenomena.
- Very efficient reasoning $\rightarrow$ RTEC.
- Direct connections to machine learning $\rightarrow$ Inductive Logic Programming (ILP).

Inductive Logic Programming

- Input:
  - Positive and negative examples.
  - Background knowledge.
  - Language bias.
- Output:
  - A logical theory that entails as many positive and as few negative examples as possible.

Search Space for Rule Learning

Top Rule ⊤: initiatedAt(*meet*(*X*, *Y*), *T*) ←

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*).

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*inactive*(*Y*), *T*).

...

initiatedAt(*meet*(*X*, *Y*), *T*) ←
holdsAt(*orientation*(*X*, *Y*, *45*), *T*).

Rules generated by adding one condition from ⊥ to the body of ⊤

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
happensAt(*inactive*(*Y*), *T*).

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
holdsAt(*close*(*X*, *Y*, *25*), *T*).

... ...

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
happensAt(*inactive*(*Y*), *T*),
holdsAt(*close*(*X*, *Y*, *25*), *T*).

... ...

... ...

Bottom Rule ⊥ : initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*), happensAt(*inactive*(*Y*), *T*), holdsAt(*close*(*X*, *Y*, *25*), *T*),
holdsAt(*close*(*Y*, *X*, *25*), *T*), *not* happensAt(*inactive*(*X*), *T*), *not* happensAt(*abrupt*(*X*), *T*),
not happensAt(*running*(*X*), *T*), happensAt(*inactive*(*Y*), *T*), *not* happensAt(*active*(*Y*), *T*),
not happensAt(*running*(*Y*), *T*), *not* happensAt(*abrupt*(*Y*), *T*), holdsAt(*orientation*(*X*, *Y*, *45*), *T*).

Search Space for Rule Learning

Top Rule $\top$: initiatedAt(*meet*(X, Y), T) $\leftarrow$

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T).

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*inactive*(Y), T).

. . .

initiatedAt(*meet*(X, Y), T) $\leftarrow$
holdsAt(*orientation*(X, Y, *45*), T).

Rules generated by adding one condition from $\perp$ to the body of $\top$

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
happensAt(*inactive*(Y), T).

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
holdsAt(*close*(X, Y, *25*), T).

. . . . . .

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
happensAt(*inactive*(Y), T),
holdsAt(*close*(X, Y, *25*), T).

. . . . . .

Ordered by θ-subsumption $\preceq$:
If $r_1 \preceq r_2$ then
covers(r_2, e) $\Rightarrow$ covers(r_1, e) for all examples e

. . . .

Bottom Rule $\perp$: initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T), happensAt(*inactive*(Y), T), holdsAt(*close*(X, Y, *25*), T),
holdsAt(*close*(Y, X, *25*), T), *not* happensAt(*inactive*(X), T), *not* happensAt(*abrupt*(X), T),
not happensAt(*running*(X), T), happensAt(*inactive*(Y), T), *not* happensAt(*active*(Y), T),
not happensAt(*running*(Y), T), *not* happensAt(*abrupt*(Y), T), holdsAt(*orientation*(X, Y, *45*), T).

Learning a Rule: Search

Positives
not covered

Top Rule $\top$: initiatedAt($meet(X, Y), T$) $\leftarrow$

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($inactive(Y), T$).

...

...

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$),
happensAt($inactive(Y), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$),
holdsAt($close(X, Y, 25), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$),
happensAt($inactive(Y), T$),
holdsAt($close(X, Y, 25), T$).

...

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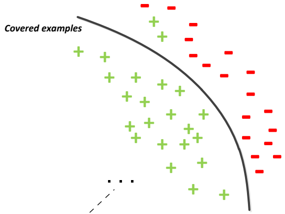

Bottom Rule $\perp$: initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$), happensAt($inactive(Y), T$), holdsAt($close(X, Y, 25), T$),
holdsAt($close(Y, X, 25), T$), *not* happensAt($inactive(X), T$), *not* happensAt($abrupt(X), T$),
not happensAt($running(X), T$), happensAt($inactive(Y), T$), *not* happensAt($active(Y), T$),
not happensAt($running(Y), T$), *not* happensAt($abrupt(Y), T$), holdsAt($orientation(X, Y, 45), T$).

Learning a Rule: Search

Generalization ↑

Top Rule ⊤: initiatedAt(*meet*(X, Y), T) ←

initiatedAt(*meet*(X, Y), T) ←
happensAt(*active*(X), T).

initiatedAt(*meet*(X, Y), T) ←
happensAt(*inactive*(Y), T).

. . .

. . .

initiatedAt(*meet*(X, Y), T) ←
happensAt(*active*(X), T),
happensAt(*inactive*(Y), T).

initiatedAt(*meet*(X, Y), T) ←
happensAt(*active*(X), T),
holdsAt(*close*(X, Y, 25), T).

initiatedAt(*meet*(X, Y), T) ←
happensAt(*active*(X), T),
happensAt(*inactive*(Y), T),
holdsAt(*close*(X, Y, 25), T).

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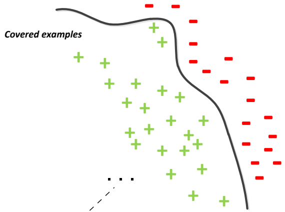

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Bottom Rule ⊥ : initiatedAt(*meet*(X, Y), T) ←
happensAt(*active*(X), T), happensAt(*inactive*(Y), T), holdsAt(*close*(X, Y, 25), T),
holdsAt(*close*(Y, X, 25), T), *not* happensAt(*inactive*(X), T), *not* happensAt(*abrupt*(X), T),
not happensAt(*running*(X), T), happensAt(*inactive*(Y), T), *not* happensAt(*active*(Y), T),
not happensAt(*running*(Y), T), *not* happensAt(*abrupt*(Y), T), holdsAt(*orientation*(X, Y, 45), T).

Learning a Rule: Search

Negatives covered

Top Rule $\top$: initiatedAt(*meet*(X, Y), T) $\leftarrow$

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T).

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*inactive*(Y), T).

...

...

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
happensAt(*inactive*(Y), T).

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
holdsAt(*close*(X, Y, *25*), T).

...

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T),
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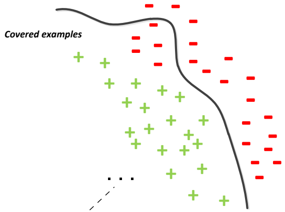
holdsAt(*close*(X, Y, *25*), T).

...



...

...

Bottom Rule $\perp$: initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T), happensAt(*inactive*(Y), T), holdsAt(*close*(X, Y, *25*), T),
holdsAt(*close*(Y, X, *25*), T), *not* happensAt(*inactive*(X), T), *not* happensAt(*abrupt*(X), T),
not happensAt(*running*(X), T), happensAt(*inactive*(Y), T), *not* happensAt(*active*(Y), T),
not happensAt(*running*(Y), T), *not* happensAt(*abrupt*(Y), T), holdsAt(*orientation*(X, Y, *45*), T).

Learning a Rule: Search

Specialization ↓

Top Rule ⊤: initiatedAt(*meet*(*X*, *Y*), *T*) ←

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*).

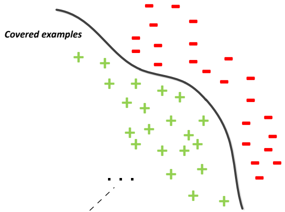
initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*inactive*(*Y*), *T*).

. . .

. . .

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
happensAt(*inactive*(*Y*), *T*).

initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
holdsAt(*close*(*X*, *Y*, *25*), *T*).



initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*),
happensAt(*inactive*(*Y*), *T*),
holdsAt(*close*(*X*, *Y*, *25*), *T*).

. . .

. . .

. . .

. . .

Bottom Rule ⊥ : initiatedAt(*meet*(*X*, *Y*), *T*) ←
happensAt(*active*(*X*), *T*), happensAt(*inactive*(*Y*), *T*), holdsAt(*close*(*X*, *Y*, *25*), *T*),
holdsAt(*close*(*Y*, *X*, *25*), *T*), *not* happensAt(*inactive*(*X*), *T*), *not* happensAt(*abrupt*(*X*), *T*),
not happensAt(*running*(*X*), *T*), happensAt(*inactive*(*Y*), *T*), *not* happensAt(*active*(*Y*), *T*),
not happensAt(*running*(*Y*), *T*), *not* happensAt(*abrupt*(*Y*), *T*), holdsAt(*orientation*(*X*, *Y*, *45*), *T*).

Online Inductive Logic Programming

Challenge:

- Inductive Logic Programming algorithms are batch learners.
  - Each candidate in the search space is evaluated on the entire dataset.

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Goal:

- Online learning:
  - Examples arrive in a stream.
  - Each example is "seen" once.

Online Inductive Logic Programming

Challenge:

- Inductive Logic Programming algorithms are batch learners.
  - Each candidate in the search space is evaluated on the entire dataset.

Goal:

- Online learning:
  - Examples arrive in a stream.
  - Each example is "seen" once.

Approach:

- Make decisions from subsets of the stream:
  - Decisions are optimal "locally".
  - Decisions are optimal "globally"...
    - within an error margin ϵ,
    - with probability $1-\delta$.

The Hoeffding Bound

- X is a random variable.
- $X_1, \ldots, X_N$ are N independent observations of X's values.
- Let $\bar{X}$ be the known, observed mean of X.
- Let $\hat{X}$ be the unknown, true mean of X.

The Hoeffding Bound

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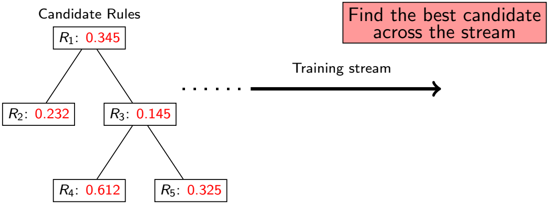
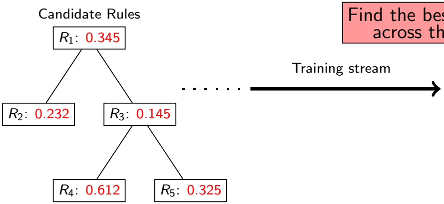
- $X_1, \ldots, X_N$ are N independent observations of X's values.
- Let $\bar{X}$ be the known, observed mean of X.
- Let $\hat{X}$ be the unknown, true mean of X.
- Then:
  $\bar{X} - \epsilon \leq \hat{X} \leq \bar{X} + \epsilon$, with probability $1 - \delta$, where $\epsilon = \sqrt{\frac{ln(1/\delta)}{2N}}$

Online Rule Learning



Online Rule Learning

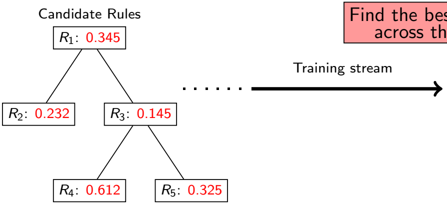
Find the best candidate across the stream



As examples stream in...

Monitor $\bar{X} = \overline{score}_{BestRule} - \overline{score}_{SecondBestRule}$

Online Rule Learning



Find the best candidate across the stream

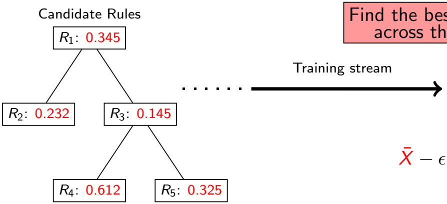
As examples stream in...

Monitor $\bar{X} = \overline{score}_{BestRule} - \overline{score}_{SecondBestRule}$

Continue until the number N of examples

makes $\bar{X} > \epsilon = \sqrt{\dfrac{ln(1/\delta)}{2N}}$

Online Rule Learning



Find the best candidate across the stream

$$\bar{X} - \epsilon \leq \hat{X} \leq \bar{X} + \epsilon, \text{ where } \epsilon = \sqrt{\frac{ln(1/\delta)}{2N}}$$

As examples stream in...

Monitor $\bar{X} = \overline{score}_{BestRule} - \overline{score}_{SecondBestRule}$

Continue until the number N of examples makes $\bar{X} > \epsilon = \sqrt{\frac{ln(1/\delta)}{2N}}$

Then

$\bar{X} - \epsilon > 0 \Rightarrow$

$\hat{X} > 0 \Rightarrow$

BestRule is indeed the best rule, with probability $1-\delta$.

Online Rule Learning

initiatedAt(*meet*(X, Y), T)
score: 0.987

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(Y), T).
score: 0.312

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T).
score: 0.534

initiatedAt(*meet*(X, Y), T) $\leftarrow$
holdsAt(*close*(X, Y, *25*), T).
score: 0.023

Input stream

Online Rule Learning

initiatedAt(*meet*(X, Y), T)
score: 0.732

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(Y), T).
score: 0.307

initiatedAt(*meet*(X, Y), T) $\leftarrow$
happensAt(*active*(X), T).
score: 0.568

initiatedAt(*meet*(X, Y), T) $\leftarrow$
holdsAt(*close*(X, Y, *25*), T).
score: 0.048

Input stream

Online Rule Learning

initiatedAt($meet(X, Y)$, T)
score: 0.216

initiatedAt($meet(X, Y)$, T) $\leftarrow$ happensAt($active(Y)$, T).
score: 0.418

initiatedAt($meet(X, Y)$, T) $\leftarrow$ happensAt($active(X)$, T).
score: 0.632

initiatedAt($meet(X, Y)$, T) $\leftarrow$ holdsAt($close(X, Y, 25)$, T).
score: 0.122

Input stream

● ● ●

Online Rule Learning

initiatedAt($meet(X, Y), T$)

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
holdsAt($close(X, Y, 25), T$).

Best rule so far

Used $\mathcal{O}(\frac{1}{\epsilon^2} ln \frac{1}{\delta})$ examples

Online Rule Learning

initiatedAt($meet(X, Y), T$)

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$).
score: 0.644

initiatedAt($meet(X, Y), T$) $\leftarrow$
holdsAt($close(X, Y, 25), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
happensAt($active(X), T$).
score: 0.618

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
holdsAt($close(X, Y, 25), T$).
score: 0.588

Input stream

Online Rule Learning

initiatedAt($meet(X, Y), T$)

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$).
score: 0.689

initiatedAt($meet(X, Y), T$) $\leftarrow$
holdsAt($close(X, Y, 25), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
happensAt($active(X), T$).
score: 0.656

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
holdsAt($close(X, Y, 25), T$).
score: 0.522

Input stream

Online Rule Learning

initiatedAt($meet(X, Y), T$)

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(X), T$).
score: 0.672

initiatedAt($meet(X, Y), T$) $\leftarrow$
holdsAt($close(X, Y, 25), T$).

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
happensAt($active(X), T$).
score: 0.693

initiatedAt($meet(X, Y), T$) $\leftarrow$
happensAt($active(Y), T$),
holdsAt($close(X, Y, 25), T$).
score: 0.503

Input stream

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Online Rule Learning

initiatedAt($meet(X, Y)$, T)

initiatedAt($meet(X, Y)$, T) $\leftarrow$
happensAt($active(Y)$, T).

initiatedAt($meet(X, Y)$, T) $\leftarrow$
happensAt($active(X)$, T).

initiatedAt($meet(X, Y)$, T) $\leftarrow$
holdsAt($close(X, Y, 25)$, T).

initiatedAt($meet(X, Y)$, T) $\leftarrow$
happensAt($active(Y)$, T),
happensAt($active(X)$, T).

initiatedAt($meet(X, Y)$, T) $\leftarrow$
happensAt($active(Y)$, T),
holdsAt($close(X, Y, 25)$, T).

Best rule so far

Used $\mathcal{O}(\frac{1}{\epsilon^2} ln \frac{1}{\delta})$ examples

Online Rule Learning

$\text{initiatedAt}(\mathit{meet}(X, Y), T)$

$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{happensAt}(\mathit{active}(Y), T).$

$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{happensAt}(\mathit{active}(X), T).$

$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{holdsAt}(\mathit{close}(X, Y, 25), T).$

$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{happensAt}(\mathit{active}(Y), T),$
$\quad \text{happensAt}(\mathit{active}(X), T).$

score: 0.693

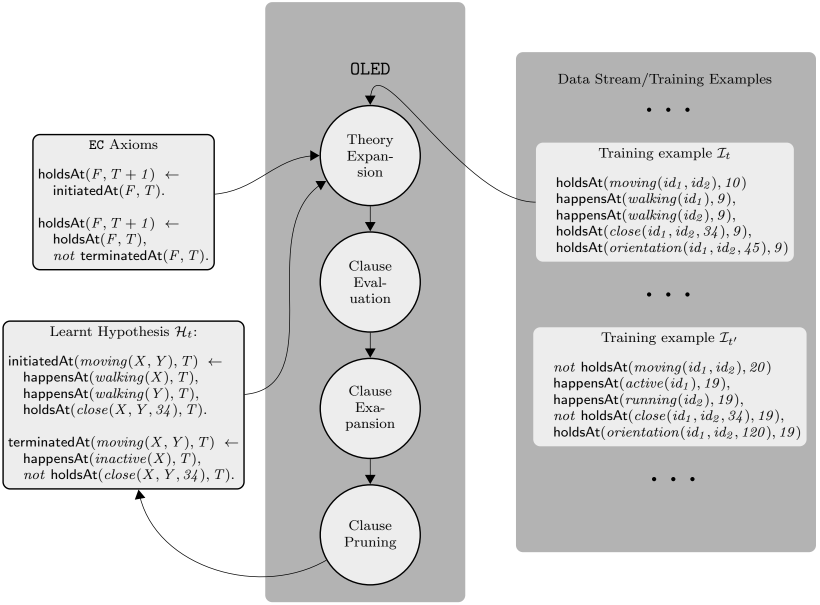
$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{happensAt}(\mathit{active}(Y), T),$
$\quad \text{holdsAt}(\mathit{close}(X, Y, 25), T).$

$\text{initiatedAt}(\mathit{meet}(X, Y), T) \leftarrow$
$\quad \text{happensAt}(\mathit{active}(Y), T),$
$\quad \text{happensAt}(\mathit{active}(X), T),$
$\quad \text{holdsAt}(\mathit{close}(X, Y, 25), T).$

score: 0.618

And so on...

Theory (Event Pattern Set) Learning



Empirical Evaluation

- Activity recognition using a benchmark dataset (CAVIAR).
  - 28 surveillance videos.
- Input: short-term activities per video frame+contextual information:
  - walking, active, inactive, running.
  - coordinates, orientation, occlusion.
- Learn concepts for *Move* and *Meet*.
- 10-fold cross-validation.

Empirical Evaluation

	Method	Precision	Recall	F_1-score	Time (sec)
Move	EC_{crisp}	**0.909**	0.634	0.751	–
	EC_{MM}	0.844	0.941	**0.890**	1692
	XHAIL	0.779	0.914	0.841	7836
	OLED	0.709	**0.948**	0.812	**12**
	OSL	–	–	–	N/A ($>$ 25h)
	OSLα	0.7823	0.8882	0.8319	1342
Meet	EC_{crisp}	0.687	0.855	0.762	–
	EC_{MM}	0.919	0.813	0.863	1133
	XHAIL	0.804	**0.927**	0.861	7248
	OLED	**0.943**	0.750	0.836	**23**
	OSL	–	–	–	N/A ($>$ 25h)
	OSLα	0.9055	0.8966	**0.9010**	174

Current work

- Statistical Relational Learning
  - Logic + Probability
  - Online structure + parameter learning.
- Distributed/parallel learning.

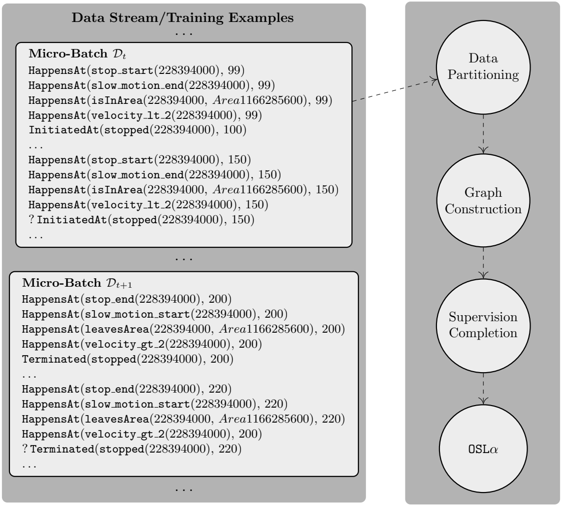
Resources

- N. Katzouris, A. Artikis and G. Paliouras. Online Learning of Event Definitions, TPLP 16(5-6), pp. 817-833, 2016
- N. Katzouris, A. Artikis and G. Paliouras. Parallel Online Learning of Event Definitions, ILP, 2017
- `http://github.com/nkatzz/OLED`

Semi-Supervised Online Structure Learning

- Common problem in Big data applications:
  - Incomplete annotation of activities of 'special significance'.
  - Providing complete annotation is time-consuming.
  - The process of complex event pattern construction is hindered.
- Solution: Online supervision completion
  - Use given labels to complete the missing ones as data arrive.
  - Perform supervised structure learning.

Semi-Supervised Online Structure Learning



Data Partitioning

Training Sequence

Micro-Batch $\mathcal{D}_t$

`HappensAt`(`stop_start`(228394000), 5)
`HappensAt`(`slow_motion_end`(228394000), 5)
`HappensAt`(`isInArea`(228394000, $Area$1166285600), 5)
`HappensAt`(`velocity_lt_2`(228394000), 5)
`InitiatedAt`(`stopped`(**228394000**), **5**)
...
`HappensAt`(`stop_end`(228394000), 20)
`HappensAt`(`slow_motion_start`(228394000), 20)
`HappensAt`(`leavesArea`(228394000, $Area$1166285600), 20)
`HappensAt`(`velocity_gt_2`(228394000), 20)
$\neg$`InitiatedAt`(`stopped`(228394000), 20)
...
`HappensAt`(`stop_start`(228394000), 50)
`HappensAt`(`slow_motion_end`(228394000), 50)
`HappensAt`(`isInArea`(228394000, $Area$1166285600), 50)
`HappensAt`(`velocity_lt_2`(228394000), 50)
? `InitiatedAt`(`stopped`(228394000), 50)
...

Data Partitioning

Training Sequence

Micro-Batch $\mathcal{D}_t$

HappensAt(stop_start(**228394000**), **5**)
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HappensAt(isInArea(**228394000**, $Area$1166285600), **5**)
HappensAt(velocity_lt_2(**228394000**), **5**)
InitiatedAt(stopped(**228394000**), **5**)
...
HappensAt(stop_end(**228394000**), **20**)
HappensAt(slow_motion_start(**228394000**), **20**)
HappensAt(leavesArea(**228394000**, $Area$1166285600), **20**)
HappensAt(velocity_gt_2(**228394000**), **20**)
¬InitiatedAt(stopped(228394000), **20**)
...
HappensAt(stop_start(**228394000**), **50**)
HappensAt(slow_motion_end(**228394000**), **50**)
HappensAt(isInArea(**228394000**, $Area$1166285600), **50**)
HappensAt(velocity_lt_2(**228394000**), **50**)
? InitiatedAt(stopped(**228394000**), **50**)
...

Data Partitioning

Vertex: InitiatedAt(stopped(**228394000**), **5**)

HappensAt(stop_start(**228394000**), **5**)
HappensAt(slow_motion_end(**228394000**), **5**)
HappensAt(isInArea(**228394000**, *Area*1166285600), **5**)
HappensAt(velocity_lt_2(**228394000**), **5**)
...

Training Sequence

Micro-Batch $\mathcal{D}_t$

HappensAt(stop_start(**228394000**), **5**)
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HappensAt(isInArea(**228394000**, *Area*1166285600), **5**)
HappensAt(velocity_lt_2(**228394000**), **5**)
InitiatedAt(stopped(**228394000**), **5**)
...
HappensAt(stop_end(**228394000**), **20**)
HappensAt(slow_motion_start(**228394000**), **20**)
HappensAt(leavesArea(**228394000**, *Area*1166285600), **20**)
HappensAt(velocity_gt_2(**228394000**), **20**)
¬InitiatedAt(stopped(**228394000**), **20**)
...
HappensAt(stop_start(**228394000**), **50**)
HappensAt(slow_motion_end(**228394000**), **50**)
HappensAt(isInArea(**228394000**, *Area*1166285600), **50**)
HappensAt(velocity_lt_2(**228394000**), **50**)
? InitiatedAt(stopped(**228394000**), **50**)
...

Data Partitioning

Training Sequence

Micro-Batch $\mathcal{D}_t$

```
HappensAt(stop_start(228394000), 5)
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...
```

Vertex: InitiatedAt(stopped(228394000), 5)

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HappensAt(stop_start(228394000), 5)
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...
```

Vertex: ¬InitiatedAt(stopped(228394000), 20)

```
HappensAt(stop_end(228394000), 20)
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...
```

Data Partitioning

Training Sequence

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HappensAt(stop_start(**228394000**), **5**)
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InitiatedAt(stopped(**228394000**), **5**)
...
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HappensAt(slow_motion_start(**228394000**), **20**)
HappensAt(leavesArea(**228394000**, $Area$1166285600), **20**)
HappensAt(velocity_gt_2(**228394000**), **20**)
¬InitiatedAt(stopped(**228394000**), **20**)
...
HappensAt(stop_start(**228394000**), **50**)
HappensAt(slow_motion_end(**228394000**), **50**)
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? InitiatedAt(stopped(**228394000**), **50**)
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...

Vertex: ¬InitiatedAt(stopped(228394000), 20)

HappensAt(stop_end(228394000), 20)
HappensAt(slow_motion_start(228394000), 20)
HappensAt(leavesArea(228394000, $Area$1166285600), 20)
HappensAt(velocity_gt_2(228394000), 20)
...

Vertex: ? InitiatedAt(stopped(**228394000**), **50**)

HappensAt(stop_start(**228394000**), **50**)
HappensAt(slow_motion_end(**228394000**), **50**)
HappensAt(isInArea(**228394000**, $Area$1166285600), **50**)
HappensAt(velocity_lt_2(**228394000**), **50**)
...

Graph Construction

Vertex: `InitiatedAt(stopped(228394000), 5)`

```
HappensAt(stop_start(228394000), 5)
HappensAt(slow_motion_end(228394000), 5)
HappensAt(isInArea(228394000, Area1166285600), 5)
HappensAt(velocity_lt_2(228394000), 5)
...
```

Vertex: `¬InitiatedAt(stopped(228394000), 20)`

```
HappensAt(stop_end(228394000), 20)
HappensAt(slow_motion_start(228394000), 20)
HappensAt(leavesArea(228394000, Area1166285600), 20)
HappensAt(velocity_gt_2(228394000), 20)
...
```

Vertex: `? InitiatedAt(stopped(228394000), 50)`

```
HappensAt(stop_start(228394000), 50)
HappensAt(slow_motion_end(228394000), 50)
HappensAt(isInArea(228394000, Area1166285600), 50)
HappensAt(velocity_lt_2(228394000), 50)
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Graph Construction

Vertex: `InitiatedAt`(`stopped`(228394000), 5)

`HappensAt`(`stop_start`(228394000), 5)
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Vertex: ¬`InitiatedAt`(`stopped`(228394000), 20)

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`HappensAt`(`velocity_gt_2`(228394000), 20)
...

Vertex: ? `InitiatedAt`(`stopped`(228394000), 50)

`HappensAt`(`stop_start`(228394000), 50)
`HappensAt`(`slow_motion_end`(228394000), 50)
`HappensAt`(`isInArea`(228394000, $Area$1166285600), 50)
`HappensAt`(`velocity_lt_2`(228394000), 50)
...

Graph Construction

Vertex: `InitiatedAt`(`stopped`(228394000), 5)

`HappensAt`(`stop_start`(228394000), 5)
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`HappensAt`(`isInArea`(228394000, *Area*1166285600), 5)
`HappensAt`(`velocity_lt_2`(228394000), 5)
...

0.1

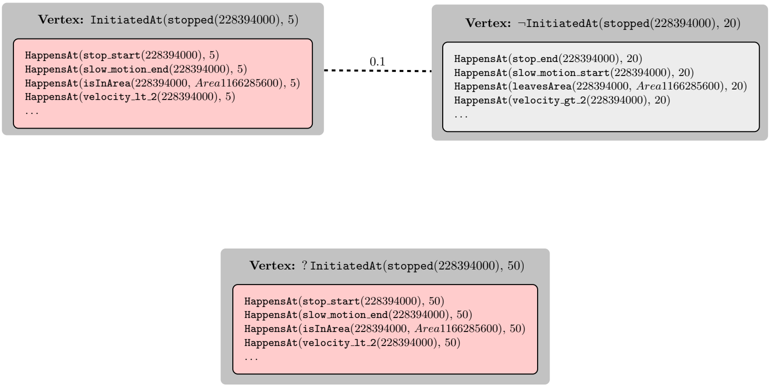
Vertex: ¬`InitiatedAt`(`stopped`(228394000), 20)

`HappensAt`(`stop_end`(228394000), 20)
`HappensAt`(`slow_motion_start`(228394000), 20)
`HappensAt`(`leavesArea`(228394000, *Area*1166285600), 20)
`HappensAt`(`velocity_gt_2`(228394000), 20)
...

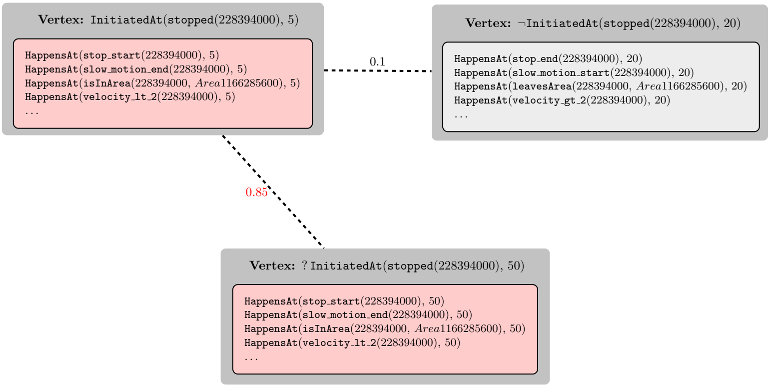
Vertex: ? `InitiatedAt`(`stopped`(228394000), 50)

`HappensAt`(`stop_start`(228394000), 50)
`HappensAt`(`slow_motion_end`(228394000), 50)
`HappensAt`(`isInArea`(228394000, *Area*1166285600), 50)
`HappensAt`(`velocity_lt_2`(228394000), 50)
...

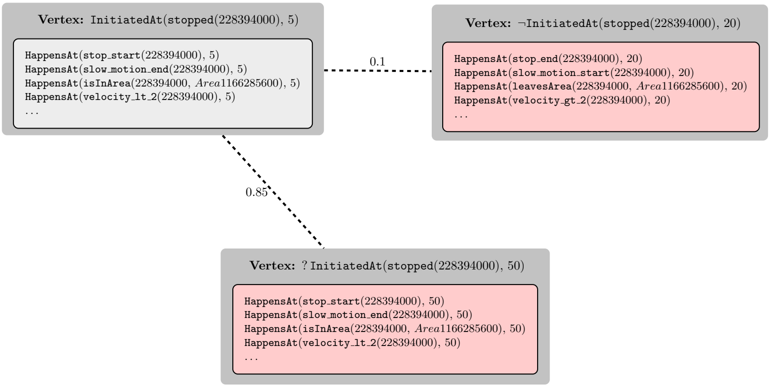
Graph Construction



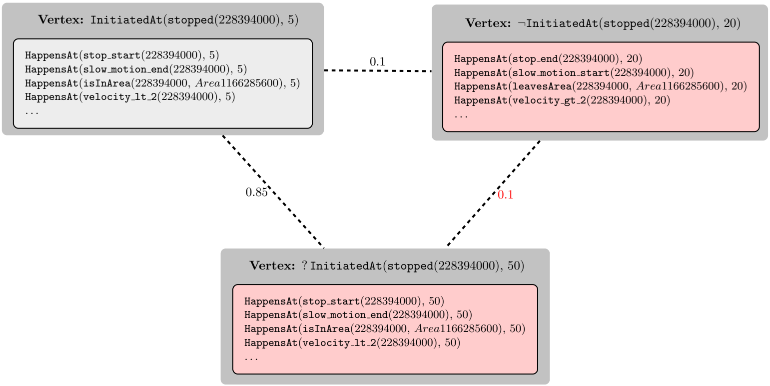
Graph Construction



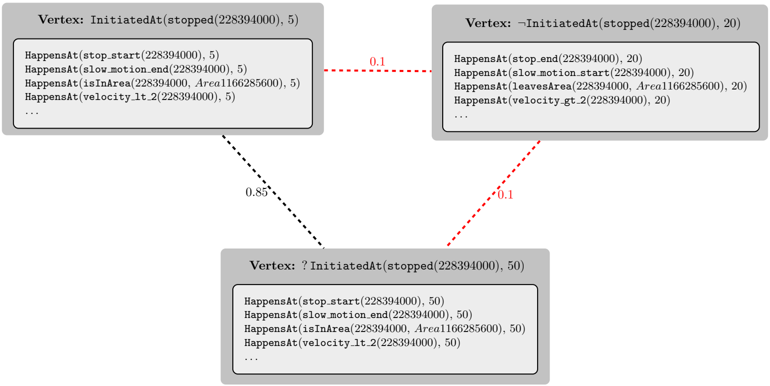
Graph Construction



Graph Construction



Supervision Completion



Supervision Completion

Vertex: `InitiatedAt`(`stopped`(228394000), 5)

`HappensAt`(`stop_start`(228394000), 5)
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...

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`HappensAt`(`velocity_gt_2`(228394000), 20)
...

0.85

Vertex: ? `InitiatedAt`(`stopped`(228394000), 50)

`HappensAt`(`stop_start`(228394000), 50)
`HappensAt`(`slow_motion_end`(228394000), 50)
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...

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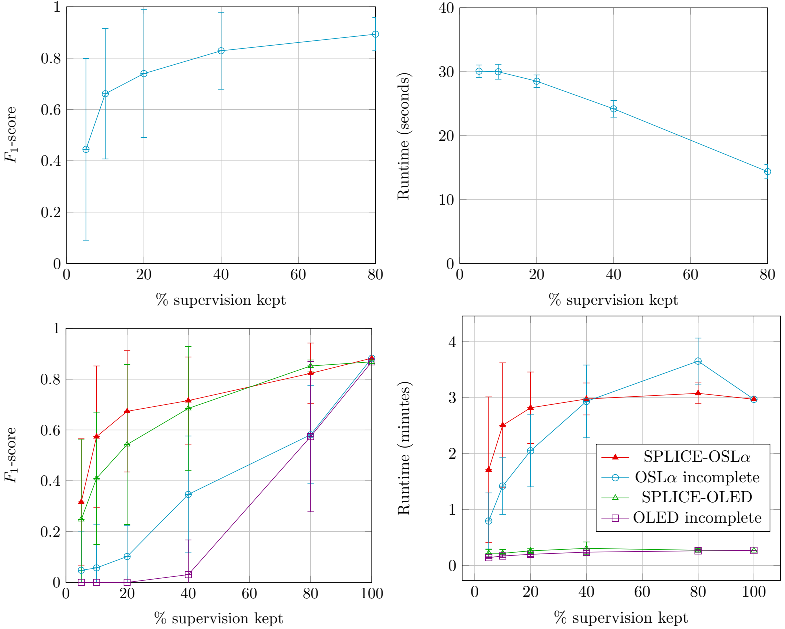
HappensAt(velocity_lt_2(228394000), 50)
...

Experimental Evaluation (1/2)



Experimental Evaluation (2/2)