UNIVERSITÄT ZU LÜBECK
INSTITUT FÜR INFORMATIONSSYSTEME

Özgür L. Özçep

Stream Processing

Lecture 13: Time, Stream Basics, CQL
9 July 2020

Informationssysteme
CS4130 (Summer 20)

This Lecture

- Infinite sequences from stream processing perspective
  - Additional aspects: temporality of data, recency, data-driveness, velocity
- Resume OBDA and consider how to lift them to temporal OBDA and streaming OBDA
  - Temporal OBDA: Add time aspect (somewhere)
  - Stream OBDA: Higher-level stream w.r.t. ontology (and mappings)

Stream Basics

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- "It's a streaming world!"

  Lit: E. Della Valle, et al. It's a streaming world! Reasoning upon rapidly changing information. Intelligent Systems, IEEE, 24(6):83–89, nov.-dec. 2009.

Stream Stack and Stream Research

- Low-level sensor perspective (semantic sensor networks)
  - Develop fast algorithms on high-frequency streams with minimal space consumption
  - Considers approximate algorithms for aggregation functions
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  - Provide whole DB systems for streams of structured (relational) data
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  - Processing stream of assertions (RDF triples) w.r.t. an ontology
  - Related: Complex Event Processing (CEP)
  - a little bit in this lectus

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- Foundational aspects
  - stringology, stream automata, infinite words, circuit complexity
  - this lecture

Local vs. Global Stream Processing

- Global aim: Learn about the whole by looking at the parts
  - Examples: inductive learning, ontology change, iterated belief revision (see slides before), robotics oriented stream processing with plan generation
  - May produce also an output stream
  - But in the end the whole stream counts

- Local aim: Monitor window contents with time-local
  - Examples: Real-time monitoring, simulation for reactive diagnostics

- Categories not exclusive
  - In learning one applies operation on (NOW)-window to learn about stream
  - In predictive analytics one monitors with window in order to predict upcoming events

Domain Objects for Streams

Definition (Temporal Stream)

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D_1 = a set of typed relational tuples adhering to a relational schema

- Streams at the backend sources
- $S_{rel} = \{(s_1, 90^\circ)\langle 1s\rangle, (s_2, 92^\circ)\langle 2s\rangle, (s_1, 94^\circ)\langle 3s\rangle, \dots\}$
- Schema: hasSensorRelation(Sensor:string, temperature:integer)

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D_2 = set of untyped tuples (of the same arity)

- Stream of tuples resulting as bindings for subqueries

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D_3 = set of assertions (RDF tuples).

- $S_{rdf} = \{\ val(s_0, 90^\circ)\langle 1s\rangle, val(s_2, 92^\circ)\langle 2s\rangle,\ val(s_1, 94^\circ)\langle 3s\rangle, \ldots\ \}$

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D_4 = set of RDF graphs

Taming the Infinite

Nearly all stream processing approaches provide a fundamental means to cope with potential infinity of streams, namely ...

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- Stream query continuous, not one-shot activity
- Window content continuously updated

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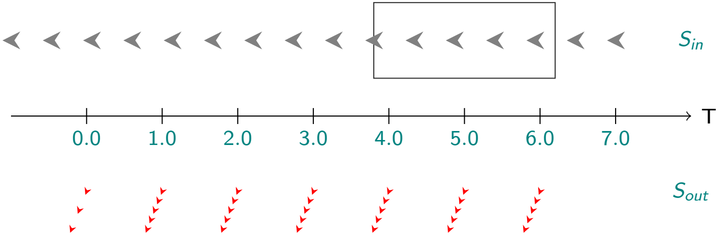

- Here a time-based window of width 3 seconds
- and slide 1 second is applied

Window Operators: Classification

- Direction of movement of the endpoints
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  - Partitioned window
  - Predicate window
- Window update
  - tumbling
  - sampling
  - overlapping

Streams in Stringology

Why is the Window Concept so Important?

- We give an answer using the word perspective/stringology on stream processing according to (Gurevich et al. 07)
- Streams = finite or infinite words over an alphabet (domain) D
  - D^* = finite words over D
  - D^ω = infinite (ω-) words over D
  - D^∞ = finite and infinite words over D
  - $\circ$ = word concatenation (usually not mentioned)
- Stream operators Q are functions/queries of the form

$$Q : D_1^\infty \longrightarrow D_2^\infty$$

- Assume w.l.o.g that $D_1 = D_2 = D$.

Lit: Y. Gurevich, D. Leinders, and J. Van Den Bussche. A theory of stream queries. In Proceedings of the 11th International Conference on Database Programming Languages, DBPL'07, pages 153–168, 2007.

Genuine Streams are Finite Prefix Determined

- Open ball around u:
  $B(u) := uD^\infty = \{s \in D^\infty \mid \text{There is } s' \in D^\infty \text{ s.t. } s = u \circ s'\}$

Definition (Axiom of finite prefix determinedness (FP))

For all $s \in D^\infty$ and all $u \in D^*$:
If $Q(s) \in uD^\infty$, there is $w \in D^*$ s.t. $s \in wD^\infty \subseteq Q^{-1}(uD^\infty)$

- (FP) expresses a continuity condition w.r.t. a topology

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- (FP) expresses a continuity condition w.r.t. a topology
- Reminder: A topology is a structure $(X, \mathcal{O})$ where
  - $\mathcal{O} \subseteq Pow(X)$
  - $\emptyset, X \in \mathcal{O}$
  - $\mathcal{O}$ closed under finite intersections
  - $\mathcal{O}$ closed under arbitrary unions
- A basis for $\mathcal{O}$ is a set $\mathcal{B} \subseteq Pow(X)$ s.t.: Every $S \in \mathcal{O}$ is a union of elements of $\mathcal{B}$.

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- (FP) expresses a continuity condition w.r.t. a topology
- Gurevich topology
  $\mathcal{T}_G = (D^{\infty}, \{AD^{\infty} \mid A \subseteq D^{*}\})$
- Set of all $B(u)$ for $u \in D^{*}$ constitute basis for $\mathcal{T}_G$.
- A function $Q : D^{\infty} \longrightarrow D^{\infty}$ is continuous iff for every open ball B: $Q^{-1}(B)$ is open.

  i.e., iff Q fulfils (FP)

Abstract Computability

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Definition (Gurevich et al. 2007)

K is a kernel for Q iff $Q = Repeat(K)$.

Q is abstract computable (AC) iff it has a kernel.

A Representation Theorem

Theorem

The set of AC functions are exactly those stream functions fulfilling FP (i.e. that are continuous) and mapping finite streams to finite streams

- Further interesting representation results by considering restrictions on window

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- Further interesting representation results by considering restrictions on window
- Gurevich et al. also describe computation model (abstract state machines)

Example for non-continuous stream functions

Example

Query $CHECK$

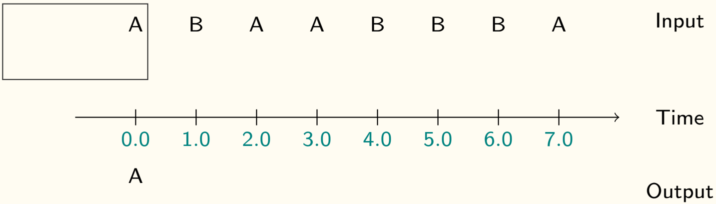
- $a, b \in D$
- $CHECK(s) = (a)$ if b does not occur in s
- Otherwise $CHECK(s) = ()$ = empty stream

- $CHECK$ is not continuous (and hence not an AC function):
  - Consider open ball $B(a)$.
  - $() \in CHECK^{-1}(B(a))$
  - But the only open ball containing $()$ is $B(()) = D^{\infty}$
  - But $B(()) \nsubseteq CHECK^{-1}(B(a))$ because
  - $CHECK(b) = () \notin B(a)$

Simple Case: Constant-Width Kernels

n-width kernel K $=$ n-window
$=$ K determined by n-suffix

Example (K = output As in last 3 units)



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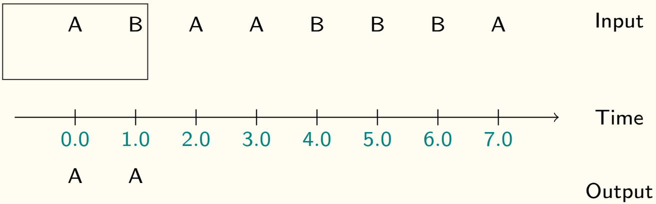

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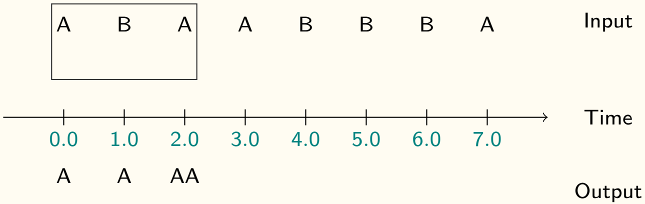

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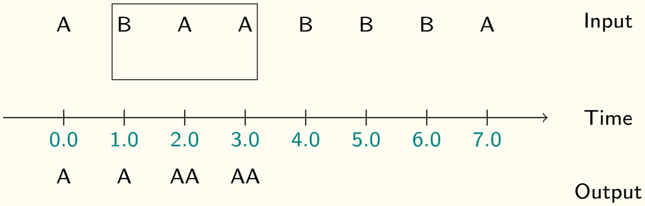

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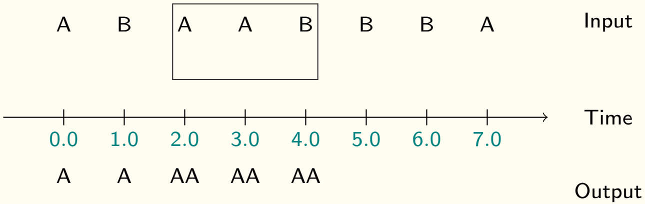

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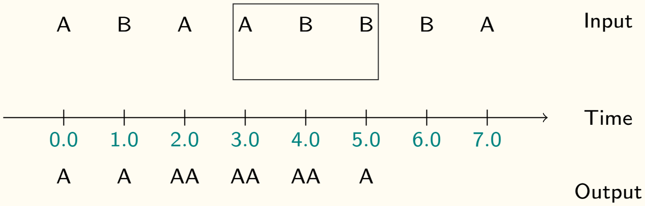

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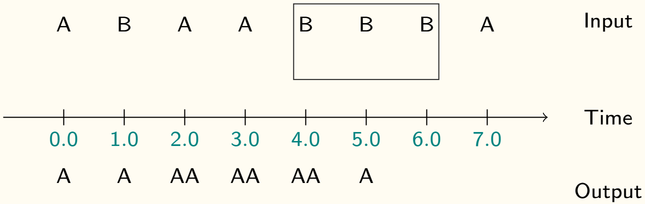

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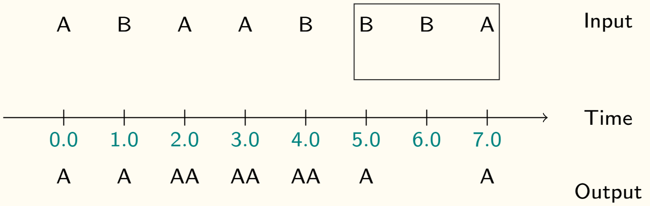

Example (Parity)

- Stream query

$$PARITY = Repeat(K_{par}) : \{0,1\}^{\infty} \longrightarrow \{0,1\}^{\infty}$$

- Based on kernel $K_{par} : \{0,1\}^{*} \longrightarrow \{0,1\}$

$$K_{par}(s) = \begin{cases} 1 & \text{if the number of } 1\text{s in } s \text{ is odd} \\ 0 & \text{else} \end{cases}$$

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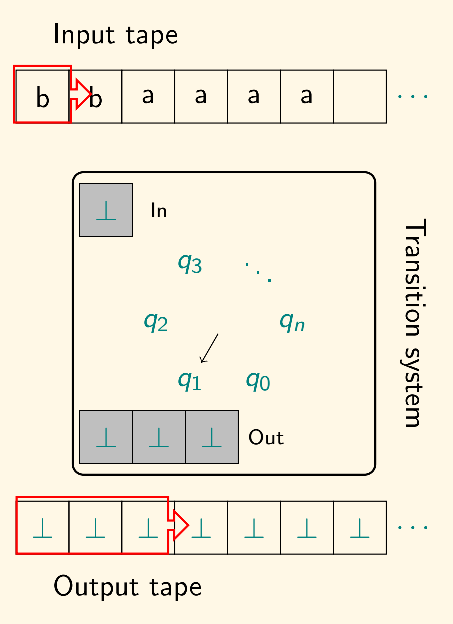
- Formalization:
  bounded-memory stream abstract machine (sASM)

Bounded-Memory sASM



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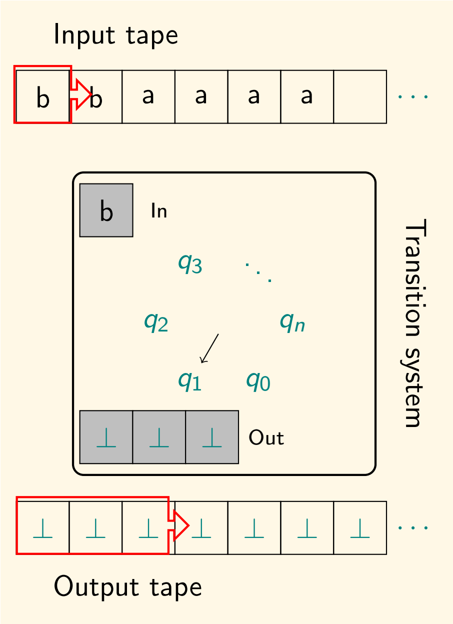

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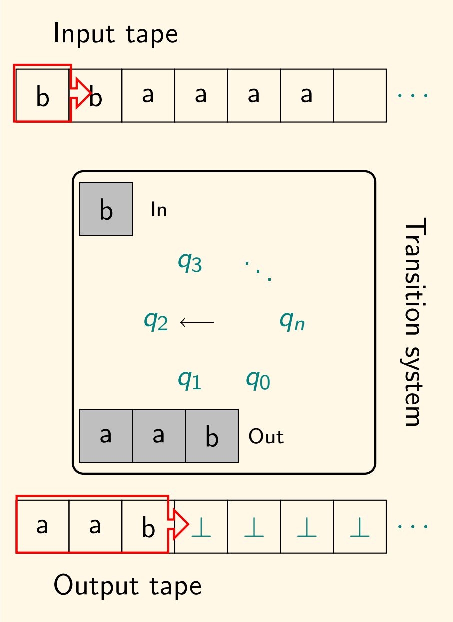

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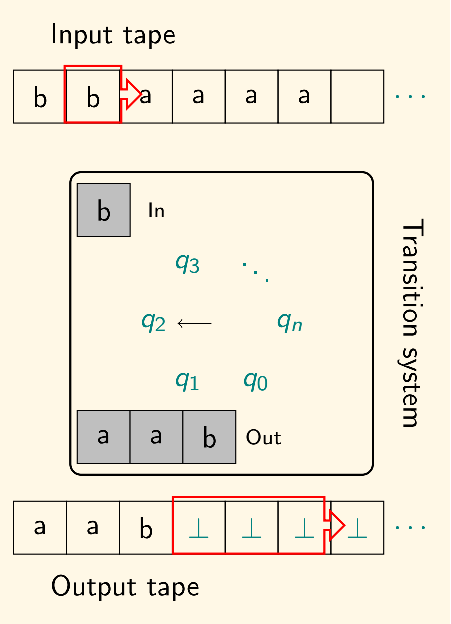

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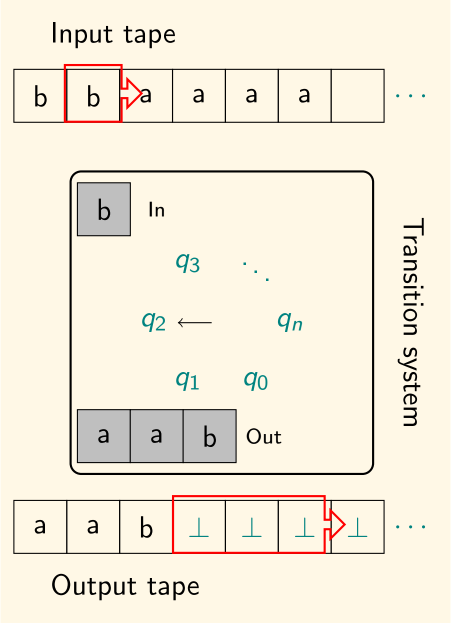

q_i = FOL structures

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  - user defined registers

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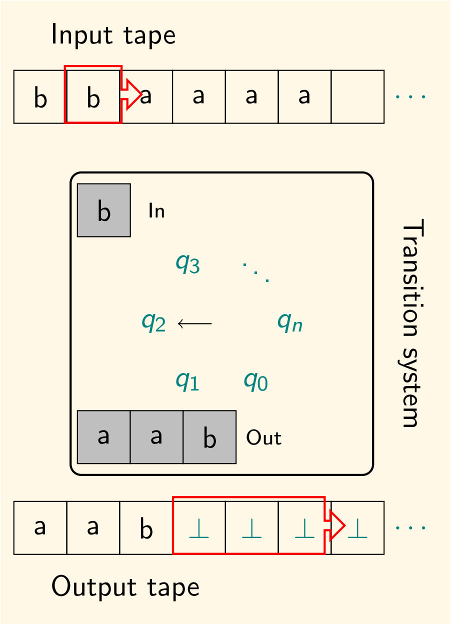

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Program = sequence of rules

- $c_0 := c_1$
- $out_i := t$ (term t without out_js)
- If ϕ then r_i else r_j (ϕ quantifier-free FOL)
- Par $r_1, \ldots r_n$ end

Stringology

- There's lot more to say . . .

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- but not today (and not in this course)

- Have a look at the vast literature in theoretical computer sciences (also under the term infinite words)
- Some interesting books on the topic
  - **Lit:** J.-P. Allouche and M. M. France. Automata and automatic sequences, pages 293?367. Springer Berlin Heidelberg, Berlin, Heidelberg, 1995.
  - **Lit:** D. Perrin and J. Pin. Infinite Words: Automata, Semigroups, Logic and Games. Pure and Applied Mathematics. Elsevier Science, 2004.

Adding a Time Dimension

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What is a flow of time?

Flow of Time

- Flow of time $(T, \leq_T)$ is a structure with a time domain T and a binary relation $\leq_T$ over it.
- Flow metaphor hints on directionality and dynamic aspect of time
- But still different forms of flow are possible

- One can consider concrete structures of flow of (time), as done here
- Or investigate them additionally axiomatically
- An early model-theoretic and axiomatic treatise:
  Lit: J. van Benthem. The Logic of Time: A Model-Theoretic Investigation into the Varieties of Temporal Ontology and Temporal Discourse. Reidel, 2. edition, 1991.

The Family of Flows of Time

- Domain T
  - points (atomic time instances)
  - pairs of points (application time, transaction time)
  - intervals etc.
- Properties of the time relation $\leq_T$
  - Non-branching (linear) vs. branching
    Linearity:
    - reflexive: $\forall t \in T$: $t \leq_T t$
    - antisymmetric: $\forall t_1, t_2 \in T$: $(t_1 \leq t_2 \wedge t_2 \leq_T t_1) \Rightarrow t_1 = t_2$
    - transitive: $\forall t_1, t_2, t_3 \in T : (t_1 \leq_T t_2 \wedge t_2 \leq t_3) \Rightarrow t_1 \leq t_3$.
    - total: $\forall t_1, t_2 \in T$: $t_1 \leq t_2 \vee t_2 \leq t_1 \vee t_1 = t_2$.

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    - total: $\forall t_1, t_2 \in T$: $t_1 \leq t_2 \vee t_2 \leq t_1 \vee t_1 = t_2$.
- Existence of first or last element
- discreteness (Example: $T = \mathbb{N}$); also used for modeling state sequences;
- density (Example: $T = \mathbb{Q}$);
- continuity (Example: $T = \mathbb{R}$)

Sequence Determines Arrival Ordering

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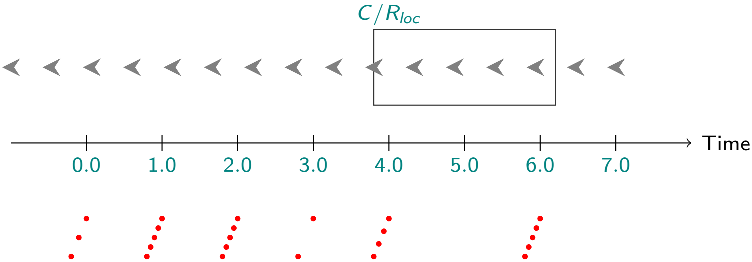
- $<_{ar}$ is a strict total ordering on the elements of S
- Synchronuous streams: $\leq_T$ compatible with $<_{ar}$
- Compatibility: For all $d_1\langle t_1\rangle, d_2\langle t_2\rangle \in S$: If $d_1\langle t_1\rangle <_{ar} d_2\langle t_2\rangle$, then $t_1 \leq_T t_2$.
- Asynchronous streams: $\leq_T$ not necessarily compatible with $<_{ar}$

High-Level Declarative stream processing: CQL

High-Level Declarative Stream Processing

Local Reasoning Service



- Need to apply calculation/reasoning CR_{loc} locally, e.g.
  - arithmetics, timeseries analysis operations
  - SELECT querying, CONSTRUCT querying, abduction, revision, planning

High-Level and Declarative

- Declarative:
  Stream elements have “assertional status” and allow for symbolic processing

Example (Relational data streams)

Stream element $(sensor, val)\langle 3sec\rangle$ “asserts” that sensor shows some value at second 3

High-Level and Declarative

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Example (Relational data streams)

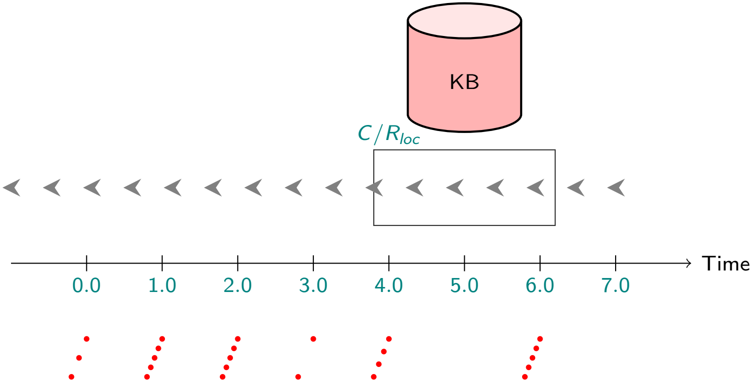
Stream element $(sensor, val)\langle 3sec \rangle$ "asserts" that sensor shows some value at second 3

- High-Level:
  Streams are processed with respect to some background knowledge base such as a set of rules or an ontology.

Example (Streams of time-tagged ABox assertions)

Streams elements of form $val(sensor, val)\langle 3sec \rangle$ evaluated w.r.t. to an ontology containing, e.g., axiom $tempVal \sqsubseteq val$

Local Reasoning Service



- Need to apply calculation/reasoning CR_{loc} locally, e.g.
  - arithmetics, timeseries analysis operations
  - SELECT querying, CONSTRUCT querying, abduction, revision, planning ($\Longrightarrow$ high-level & declarative)

Declarativ Stream Processing in DSMS

- Different groups working on DSMS around 2004
  - Academic prototypes: STREAM and CQL (Stanford); TelgraphCQ (Berkeley) (extends PostGreSQL); Aurora/Borealis (Brandeis, Brown and MIT); PIPES from Marburg University
  - Commercial systems: StreamBase, Truviso (Standalone), extensions of commercial DBMS (MySQL, PostgreSQL, DB2 etc.)

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- Though well investigated and many similarities there is no streaming SQL standard
- First try for standardization:

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- But if development speed similar to that for introducing temporal dimension into SQL, then we have to wait...

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- UPDATE January 2020): There seems to be an ISO-standard in the making: ISO/IEC NP TR 29075-1

CQL (Continuous Query Language)

- Early relational stream query language extending SQL
- Developed in Stanford as part of a DSMS called STREAM

Lit: A. Arasu, S. Babu, and J. Widom. The CQL continuous query language: semantic foundations and query execution. The VLDB Journal, 15:121–142, 2006.

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- Had immense impact also on development of early RDF streaming engines in RSP community https://www.w3.org/community/rsp/)

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CQL Details

see lecture Non-standard databases

Streamified OBDA

- Nearly ontology layer stream processing
  - CEP (Complex event processing)
  - EP-SPARQL/ETALIS, T-REX/ TESLA, Commonsens/ESPER
- RDF-ontology layer stream processing
  - C-SPARQL (della Valle et al. 09), CQELS, . . . , RSP (most recent suggestion unifying the RDF stream approaches
- Classical OBDA stream processing
  - $\text{SPARQL}_{\textit{Stream}}$ (Calbimonte et al. 12) and MorphStream
- All approaches rely on CQL window semantics
- extend SPARQL or use some derivative of it
- Treat timestamped RDF triples but use reification

Example of Reified Handling

Example

```
SELECT ?windspeed ?tidespeed
FROM NAMED STREAM <http://swiss-experiment.ch/
                   data#WannengratSensors.srdf>
[NOW-10 MINUTES TO NOW-0 MINUTES]
WHERE
  ?WaveObs a ssn:Observation;
           ssn:observationResult ?windspeed;
           ssn:observedProperty sweetSpeed:WindSpeed.
  ?TideObs a ssn:Observation;
           ssn:observationResult ?tidespeed;
           ssn:observedProperty sweetSpeed:TideSpeed.
  FILTER (?tidespeed<?windspeed)
```

SRBench (Zhang et al. 2012)

- Benchmark for RDF/SPARQL Stream Engines
- Contains data from LinkedSensorData, GeoNames, DBPedia
- Mainly queries for functionality tests, with eye on SPARQL 1.1. functionalities

Example (Example Query (to test basic pattern matching))

Q1. Get the rainfall observed once in an hour.

- Tested on CQELS, $\text{SPARQL}_{\textit{Stream}}$ and C-SPARQL

- Test results (for engine versions as of 2012)
  - Basic SPARQL features supported
  - SPARQL 1.1 features (property paths) rather not supported
  - Only C-SPARQL supports reasoning (on RDFS level) (tested subsumption and sameAs)
  - Combined treatment of static data plus streaming data only for CQELS and C-SPARQL

Language Comparison of SOTA Stream Engines

- Update in 2016
- We also mention Lübecks contribution STARQL

Name	Data Model	Union, Join, Optional, Filter	IF Expression	Aggregate	Property Paths	Time Windows	Triple Windows
Streaming SPARQL	RDF streams	Yes	No	No	No	Yes	Yes
C-SPARQL	RDF streams	Yes	Yes	Yes	Yes	Yes	Yes
CQELS	RDF streams	Yes	No	Yes	No	Yes	No
SPARQLStream	(virtual) RDF streams	Yes	Yes	Yes	Yes	Yes	No
EP-SPARQL	RDF streams	Yes	No	Yes	No	No	No
TEF-SPARQL	RDF streams	Yes	No	Yes	No	Yes	Yes
RSP-QL	RDF streams	Yes	Yes	Yes	Yes(*)	Yes	No (*)
STARQL	(virtual) RDF streams	Yes	Yes	Yes	No	Yes	No

Name	W-to-S Operator	Named Streams	Intra window time	Sequencing	Pulse
Streaming SPARQL	RStream	No	No	No	No
C-SPARQL	RStream	Yes	Yes	No	Yes
CQELS	IStream	No	No	No	No
SPARQLStream	RStream, IStream, DStream	No	Yes	No	No
EP-SPARQL	RStream	Yes	Yes	Yes	No
TEF-SPARQL	RStream	No	No	Yes	No
RSP-QL	RStream, IStream, DStream	Yes	Yes	No	No(*)
STARQL	RStream	Yes	Yes	Yes	Yes

Architecture Comparison of SOTA Stream Engines

Used Language	Input	Execution	Query Optimization	Stored Data	Reasoning
Streaming SPARQL	RDF streams	physical stream algebra	Static plan optimization	Yes	No
C-SPARQL	RDF streams	DSMS based evaluation with triple store	Static plan optimization	Internal triple store	RDF entailment
CQELS	RDF streams	RDF stream processor	Adaptive query processing operators	Stored linked data	No
SPARQLStream	Relational streams	external query processing	Static algebra optimizations host evaluator specific	Data source dependent	No
EP-SPARQL	RDF streams	logic programming backward chaining rules	No	No	RDFS, Prolog equivalent
TEF-SPARQL	RDF streams	Yes	No	Yes	Yes
STARQL	Relational streams	external query processing	Static algebra optimizations	Datasource dependent	Yes (DL-Lite$_{\mathcal{A}}$)

Links SOTA Stream Engines

Lit: A. Bolles, M. Grawunder, and J. Jacobi. Streaming sparql - extending sparql to process data streams. In S. Bechhofer et al., editors, The Semantic Web: Research and Applications, vol. 5021 of LNCS, p. 448–462, 2008.

Lit: D. F. Barbieri, D. Braga, S. Ceri, E. D. Valle, and M. Grossniklaus. C-sparql: a continuous query language for rdf data streams. Int. J. Semantic Computing, 4(1):3–25, 2010.

Lit: D. L. Phuoc, M. Dao-Tran, J. X. Parreira, and M. Hauswirth. A native and adaptive approach for unified processing of linked streams and linked data. In L. Aroyo et al., editors, The Semantic Web - ISWC 2011, vol. 7031 LNCS, p. 370–388, 2011.

Lit: J.-P. Calbimonte, H. Jeung, O. Corcho, and K. Aberer. Enabling query technologies for the semantic sensor web. Int. J. Semant. Web Inf. Syst., 8(1):43–63, Jan. 2012.

Lit: D. Anicic, S. Rudolph, P. Fodor, and N. Stojanovic. Stream reasoning and complex event processing in Etalis. Semantic Web, 3(4):397–407, 2012.

Lit: J.-U. Kietz, T. Scharrenbach, L. Fischer, M. K. Nguyen, and A. Bernstein. Tef-sparql: The ddis query- language for time annotated event and fact triple-streams. Technical Report IFI-2013.07, 2013.

Lit: D. Dell'Aglio, E. Della Valle, J. Calbimonte, and O. Corcho. Rsp-ql semantics: A unifying query model to explain heterogeneity of rdf stream processing systems. International Journal on Semantic Web and Information Systems (IJSWIS), 10(4), 2015.

Lit: Ö. Özçep, R. Möller, and C. Neuenstadt. A stream-temporal query language for ontology based data

A stream reasoning community is forming

Everyone is interested in (high-level) stream processing now

- Various new stream reasoners (based on Datalog extensions)
- Stream reasoning + Machine Learning
- Stream reasoning + Verification
- Further benchmark ambitions and testing frameworks
- For recent progress see, e.g., 4th stream reasoning workshop `https://sr2019.on.liu.se/`

- And for sure to come: Stream processing + Online Learning

Temporalized OBDA

Adding a Temporal Dimension to OBDA

- Most conservative strategy: handle time as "ordinary" attribute *time*

$$\left\{ \begin{array}{c} meas(x) \wedge \\ val(x, y) \wedge \\ time(x, z) \end{array} \right\} \longleftarrow$$

```
SELECT f(MID) AS m, Mval AS y, MtimeStamp AS z
FROM MEASUREMENT
```

- Classical Mapping
- Pro: Minimal (no) adaptation
- Contra:
  - No control on "logic of time"
  - Need reification
    - sometimes necessary (because DLs provided only predicates up to arity 2)
    - but not that "natural"

Temporalized OBDA: General Approach

- Semantics rests on family of interpretations $(\mathcal{I}_t)_{t \in T}$
- Temporal ABox $\tilde{A}$: Finite set of T-tagged ABox axioms

Example

$val(s_0, 90°)\langle 3s \rangle$ holds in $(\mathcal{I}_t)_{t \in T}$ iff $\mathcal{I}_{3s} \models val(s_0, 90°)$
"sensor s_0 has value $90°$ at time point 3s"

- Alternative sequence representation of temporal ABox $\tilde{A}$
  - $(\mathcal{A}_t)_{t \in T'}$ (where T' are set of timestamps in T)
  - $\mathcal{A}_t = \{ax \mid ax\langle t \rangle \in \tilde{A}\}$

Definition (Adapted notion of OBDA rewriting)

$$cert(Q, (Sig, \mathcal{T}, (\mathcal{A}_t)_{t \in T'}) = ans(Q_{rew}, (DB(\mathcal{A}_t))_{t \in T'})$$

Temporalized OBDA:TCQs

- Different approaches based on modal (temporal) operators
- LTL operators only in QL (Borgwardt et al. 13)

Example

$$\begin{aligned} \mathit{Critical}(x) &= \exists y. \mathit{Turbine}(x) \wedge \mathit{showsMessage}(x, y) \wedge \\ & \quad \mathit{FailureMessage}(y) \\ Q(x) &= \bigcirc^{-1} \bigcirc^{-1} \bigcirc^{-1} (\Diamond(\mathit{Critical}(x) \wedge \bigcirc \Diamond \mathit{Critical}(x))) \end{aligned}$$

"turbine has been at least two times in a critical situation in the last three time units"

- CQ embedded into LTL template
- Special operators taking care of endpoints of state sequencing
- Not well-suited for OBDA as non-safe
- Rewriting simple due to atemporal TBox

Lit: S. Borgwardt, M. Lippmann, and V. Thost. Temporal query answering in the description logic dl-lite. In FroCs, volume 8152 of LNCS, pages 165–180, 2013.

Temporalized OBDA: TQL

- LTL operators in TBox and T argument in QL

Example

TBox axiom : $\mathit{showsAnomaly} \sqsubseteq \Diamond \mathit{UnplanedShutDown}$
"if turbine shows anomaly (now)
then sometime in the future it will shut down"

Query : $\exists t.3s \leq t \leq 6s \wedge \mathit{showsAnomaly}(x, t)$

- Can formulate rigidity assumptions
- Rewriting not trivial

Lit: A. Artale, R. Kontchakov, F. Wolter, and M. Zakharyaschev. Temporal description logic for ontology- based data access. In IJCAI'13, pages 711–717. AAAI Press, 2013.