Querying Temporal Databases and Data Streams

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Representing and querying temporal data

We want to extend the basic relational data model and develop methods and tools to be able:

- to represent when data are true (*validity & transaction time*),
- to query data taking into account this temporal information.

References:

- David Toman, Jan Chomicki, **Time in Database Systems**. In Handbook of Temporal Reasoning in Artificial Intelligence, Michael Fisher, Dov Gabbay, and Lluis Vila, eds., Elsevier 2005, 429-467.
- Brian Babcock, Shivnath Babu, Mayur Datar, Rajeev Motwani, Jennifer Widom: **Models and Issues in Data Stream Systems**. PODS 2002:

Relational model and time

A *relational database* is a first-order structure over a (finite) *data domain D* and a *schema* $\rho = (r_1, \ldots, r_k)$, consisting of a set of relations $(\mathbf{r}_1, \ldots, \mathbf{r}_k)$. A tuple $r_i(\vec{a})$ is true in an instance of (D, ρ) *iff* $\vec{a} \in \mathbf{r}_i^D$.

Emp	
name	department
john	d1
mark	d2

Definition (Temporal domain)

A *temporal domain* T_P is a tuple $(T, <)$, where T is a nonempty set of elements called *time instants* and $<$ is an irreflexive, linear ordering on T.

Temporal data model

Definition (Timestamp model)

A *timestamp TDB* is a first-order structure $D \cup T_P \cup (\mathbf{R}_1, \ldots, \mathbf{R}_k)$, where $\mathbf{R}_i$ are temporal relations-instances of the temporal extensions R_i of r_i, where:

$$R_i(t, \vec{a}), \text{ for some } t \in T_P, \textit{ iff } r_i(\vec{a}).$$

Emp		
time	name	department
1999	john	d1
2000	john	d1
2001	john	d3
2002	john	d3
2000	mark	d2
2001	mark	d2

Temporal data model

Definition (Snapshot model)

A *snapshot TDB* over D, T_P, and ρ, is a map $\mathcal{DB} : T_P \mapsto \mathcal{DB}(D, \rho)$, where $\mathcal{DB}(D, \rho)$ is the class of (finite) relational databases over D and ρ.

1999:

Emp	
name	department
john	d1

2001:

Emp	
name	department
john	d3
mark	d2

Temporal data model

There exists a direct correspondence between the timestamp and the snapshot models:

$$\forall t \in T.\forall a_1, \ldots, a_k \in D : (\mathbf{r}_i^{D(t)}(a_1, \ldots, a_k) \leftrightarrow \mathbf{R}_i^D(t, a_1, \ldots, a_k))$$

TDBs expressed in the timestamp and snapshot models are called *abstract*.

Abstract query languages

The most natural languages for querying abstract TDBs are variants of FOL over the vocabulary $(=, r_1, \ldots, r_k)$ of the extended structure:

- *two-sorted FOL* (the timestamp model)
- *FO temporal logic* (the snapshot model)

Two-sorted FOL

The syntax of the *two-sorted FO language* L^P:

$$M \ ::= \ R_i(t_i, \vec{x}) \ | \ t_i < t_j \ | \ x_i = x_j \ | \ \neg M \ | \ M \wedge M \ | \ \exists t_i.M \ | \ \exists x_i.M$$

where R_i is the temporal extension of r_i, for $r_i \in \rho$. Variables t_i range over T and x_i over D.

Example:

$$\exists x_2.(Emp(t_0, x_1, x_2) \wedge \exists t_1.(t_0 < t_1 \wedge \exists x_3.(Emp(t_1, x_1, x_3) \wedge \neg(x_2 = x_3))))$$

Answers: $t_0 \mapsto 1999$, $x_1 \mapsto john$ and $t_0 \mapsto 2000$, $x_1 \mapsto john$.

FO temporal logic

Temporal operators syntax:

$$O \ ::= \ t_i < t_j \ | \ \neg O \ | \ O \wedge O \ | \ \exists t_i . O \ | \ X_i$$

where X_i are propositional variables. An n-ary *temporal operator* is an O-formula with exactly one free variable t_0 and n free propositional variables $X_1, \ldots X_n$. A set of temporal connectives is denoted by Ω.

Examples:

$$\begin{aligned}
\textbf{always-in-future}(X) &\triangleq \forall t_1 . (t_0 < t_1 \rightarrow X(t_1)) \\
\textbf{sometime-in-future}(X) &\triangleq \exists t_1 . (t_0 < t_1 \wedge X(t_1)) \\
\vdots &\triangleq \vdots
\end{aligned}$$

FO temporal logic

The syntax of the *FO temporal language* L^{Ω}:

$$F \;::=\; r_i(\vec{x}) \mid x_i = x_j \mid \neg F \mid F \wedge F \mid \omega(F_1, \ldots, F_n) \mid \exists x_i.F$$

where $r \in \rho$ and ω is an n-ary temporal operator.

Example:

$$\exists x_2.(Emp(x_1, x_2) \wedge \textbf{sometime-in-future}(\exists x_3.(Emp(x_1, x_3) \wedge \neg(x_2 = x_3))))$$

Answer: $x_1 \mapsto \textit{john}$ in 1999, 2000.

Expressive power

There exists a translation from L^{Ω} to L^{P}, hence $L^{\Omega} \sqsubseteq L^{P}$.

Theorem (Abiteboul et al., 1996)

$L^{\textbf{since},\textbf{until}} \sqsubset L^{P}$ *over the class of finite timestamp TDBs.*

Theorem (Toman, Niwinski, Bidoit et al.)

$L^{\Omega} \sqsubset L^{P}$ *over the class of timestamp TDBs for an arbitrary finite set of first-order temporal connectives* Ω.

Observation: L^{Ω} cannot express query "*are there two distinct time instants at which a unary relation R contains exactly the same values?*". In L^{P}:

$$\exists t_1, t_2.(t_1 < t_2 \wedge \forall x.(R(t_1, x) \leftrightarrow R(t_2, x)))$$

Concrete databases

Abstract TDBs can be in principle infinite but should be representable in a finite form. *Concrete* TDBs are these finite representations.

Definition (Interval-based temporal domain)

Let $T_P = (T, <)$ be a discrete linearly ordered point-based temporal domain. We define the set:

$$I(T) = \{(a, b) : a \leq b, a \in T \cup \{-\infty\}, b \in T \cup \{\infty\}\}.$$

Interval-based temporal domain is the structure $T_I = (I(T), <_{--}, <_{+-}, <_{-+}, <_{++})$, where $<_{--}, <_{+-}, <_{-+}, <_{++}$ express ordering relationships over $I(T)$.

Concrete databases

Definition (Concrete TDB)

A concrete TDB is a finite first-order structure $D \cup T_I \cup \{\mathbf{R}_1, \ldots \mathbf{R}_k\}$, where $\mathbf{R}_i$ are the concrete temporal relations which are finite instances of R_i over D and T_I.

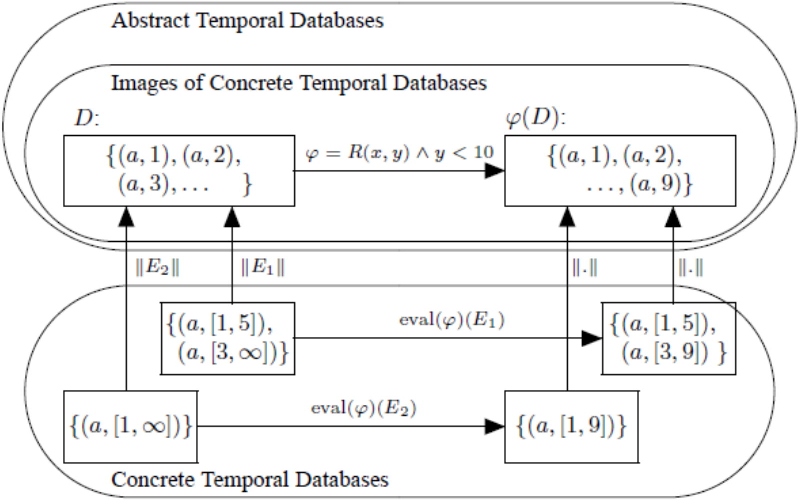
Emp		
time	name	department
[1999, 2000]	john	d1
[2001, 2002]	john	d3
[2000, 2001]	mark	d2

Definition (Semantic Mapping $\|\cdot\|$)

Let D_1 be an abstract TDB and D_2 a concrete TDB over the same schema ρ. D_2 encodes D_1 (written $\|D_2\| = D_1$) if:

$$\mathbf{R}_i^{D_1}(t, x) \Leftrightarrow \exists I \in T_I.\mathbf{R}_i^{D_2}(I, x) \wedge t \in I$$

Abstract vs. concrete TDBs



Concrete temporal query language

The syntax of the *interval-based language* L^I:

$$M \;::=\; R_i(I, \vec{x}) \;\mid\; I_i^* < I_j^* \;\mid\; x_i = x_j \;\mid\; \neg M \;\mid\; M \wedge M \;\mid\; \exists I_i.M \;\mid\; \exists x_i.M$$

where R_i is the temporal extension of r_i, for $r_i \in \rho$, and $I_i^* \in \{I^+, I^-\}$

Example:
For databases D_1, D_2 and the relation $r \in \rho$, such that $\mathbf{R}^{D_1} = \{([1,2], a), ([1,3], a)\}$ and $\mathbf{R}^{D_2} = \{([1,3], a)\}$:

$$\exists I, J.\exists x.(R(I, x) \wedge R(J, x) \wedge I \neq J)$$

Answer:
$x \mapsto a$ in D_1, and $\emptyset$ in D_2.

$\|\cdot\|$-generic querying

Definition ($\|\cdot\|$-generic queries)

Let $\|\cdot\|$ be the semantic mapping and $\varphi \in L^I$. We say that φ is $\|\cdot\|$-generic if $\|D_1\| = \|D_2\|$ implies $\|\varphi(D_1)\| = \|\varphi(D_2)\|$ for all concrete TDBs D_1, D_2.

The challenge is then to devise methods ensuring that querying remains $\|\cdot\|$-generic.

$\|\cdot\|$-generic querying

One solution is to use *compilation* techniques, i.e., transform T^P queries into L^I while preserving meaning under $\|\cdot\|$.

Theorem (Toman 1996)

There is a (recursive) mapping $F : L^P \mapsto L^I$ *such that* $\varphi(\|D\|) = \|F(\varphi)(D)\|$.

Theorem (Toman 1996)

For every $\|\cdot\|$*-generic* $\varphi \in L^I$ *there is* $\psi \in L^P$ *such that* $\|\varphi(D)\| = \psi(\|D\|)$ *for all concrete temporal databases* D.

Temporal extensions of SQL

Challenges for practical temporal extensions

- Multi-set (bag) semantics of SQL,
- Extensions must support the chosen model of time,
- Efficient query evaluation over concrete databases.

- The majority of extensions assume point based semantics but use syntax based on intervals (Allen's interval algebra),
- Extensions based on: abstract and concrete query languages.

Based on abstract language L^p: SQL/TP

- Simple extension of SQL with data type based on the point-based temporal domain,
- Bag semantics,
- Can be efficiently evaluated via translation of L^p to L^I,

```
select r1.name
from Emp r1, Emp r2
where r1.name = r2.name
   and r1.time < r2.time
   and not exists ( select *
                    from Emp r3
                    where r3.name = r1.name
                       and r1.time < r3.time
                       and r3.time < r2.time )
```

Based on abstract language L^Ω

- Added similarly to set operators.

  `Q1 until Q2`   `Q1 since Q2`

- A natural extension of ATSQL's sequenced semantics [Snodgrass et al., 1995],
- Two ways of evaluating:
  - Over coalesced concrete databases using the translation from L^Ω to L^I;
  - By composing the translation of L^Ω to L^p with translation to L^p to L^I.

Based on concrete language L^I

A lot of proposals

- SQL/Temporal,
- AT-SQL,
- Temporal extension of Informix.

- Syntax is extended with Allen's interval algebra expressions,
- Multi-set semantics.

Example for SQL/Temporal

```
select r1.name
from Emp r1, Emp r2
where r1.name = r2.name
   and r1.time before r2.time
```

Incorrect! Reason: non-generic.
Two approaches to overcome this:

- Coalescing. → incompatible with bag semantics
- Folding and Unfolding. → space blow-up

Further extensions

- Beyond first order logic.
  - Extended with monadic quantifiers over temporal domain,
  - Fixpoints.
- Beyond Closed World Assumption.
  - Quickly leads to undecidability even in append-only databases.
  - Decidable fragments: monadic temporal extensions, temporal logic programs.

Updating temporal databases

- Insertion is easy for both abstract and concrete databases.
- Deletion and update is not straightforward for concrete databases.

Example

Assume DB contains a tuple ([1999, 2005] , john, d1). We want to specify that john was sacked in 2001 but was hired back to the same department in 2003.

- Delete ([1999, 2005] , john, d1),
- Add tuples ([1999, 2001] , john, d1) and ([2003, 2005], john, d1).

Updates in append-only database, expiration and stream

- An update adds a new state to the existing finite history,
- Expiration techniques are needed for forgetting old data: administrative and query-driven approaches
- This is very similar to the problem of efficient data storing in data streams
- Continuous queries in data streams are similar to queries over database histories.

Data Streams

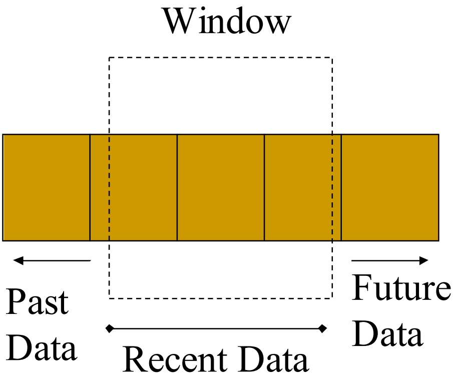
- Different Applications
  - Sensor Networks (smart homes, smart cities)
  - Social Data
  - Network Traffic Anaysis
  - Financial Tickers
  - ...
- Common Requirements
  - Input stream(s) unbounded in space and time (only a small portion of data available at a time)
  - Timely reaction is needed, i.e. *continuous queries*
  - Order and rate of data arrival is not under control of the system

Data & Query Model

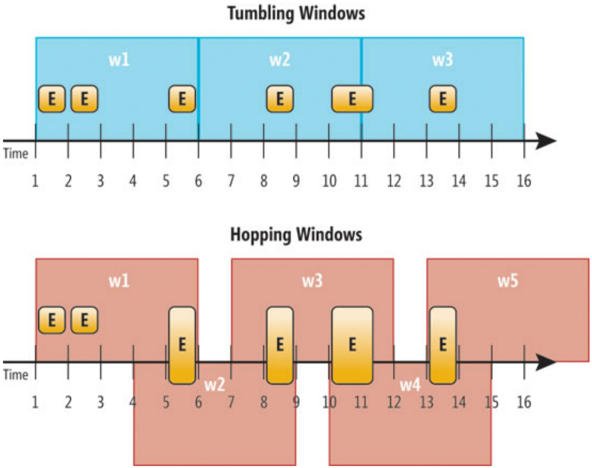
"Kind of" the Temporal DBs *timestamp model*, but...

- Time has a linear discrete model
- Temporal Relations have a finite encoding, while Data Streams may be *infinite*
- Temporal Queries are usually one-time, while Data Stream Queries are typically *continuous*
- Temporal Queries may be unbounded in time, while Data Stream Queries are typically on *windows*

Sliding Windows



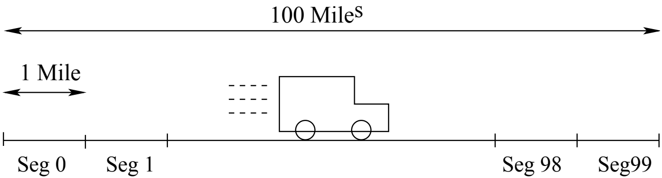
Tumbling Windows



Continuous Query Processing Model

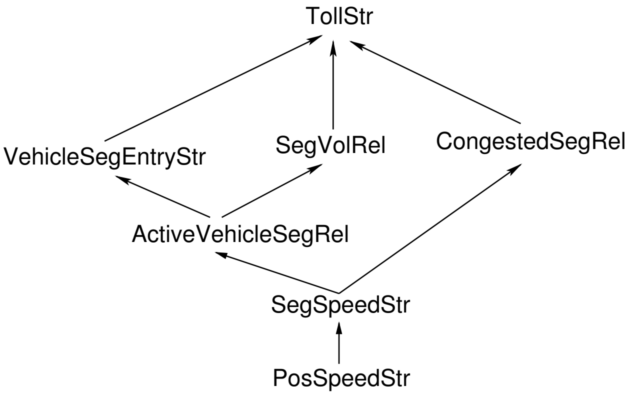
- Input/Outputs are Streams or (Temporal) Relations
- Network (DAG) of operators:
  - *Stream-to-relation* operators:
    - *Now* operator
    - *Time-based Sliding/Tumbling Window* operator
  - *Relation-to-relation* operators:
    - *Relational Algebra* operators
  - *Relational-to-stream* operators:
    - *Insert Stream*
    - *Delete Stream*
    - *Relation Stream*

An Example: Linear Road



Input: stream of positions and speeds of vehicles.
Output: the tolls for vehicles.

Linear Road: Network of Queries Used



Linear Road: Congested Segments Identification

```
CREATE VIEW CongestedSegRel(segNo) AS

    SELECT segNo
    FROM SegSpeedStr [RANGE 5 MINUTES]
    GROUP BY segNo
    HAVING AVG(speed) < 40
```

Linear Road: Computing Toll

```
CREATE VIEW TollStr(vehicleId, toll) AS

    SELECT RSTREAM(E.vehicleId,
                   2 * (V.numVehicles-50)
                     * (V.numVehicles-50)
                   AS toll)
    FROM VehicleSegEntryStr [NOW] AS E,
         CongestedSegRel AS C,
         SegVolRel AS V
    WHERE E.segNo = C.segNo AND
          C.segNo = V.segNo
```

Processing Strategies

- Asynchronous processing: `update/computeAnswer`
- Bounded Space (dealing with)
  - Avoid Unneeded Materialization
  - Synopsis Data Structures
  - Sketches (approximation of synopsis)
- Bounded Time (dealing with)
  - Incremental Evaluation
  - Batch Processing (slow `computeAnswer`)
  - Sampling (slow `update`)

Challenging Domains

- Streaming of Social Data
- Streaming and the Semantic Web
- Stream Monitoring
- XML Streams
- Uncertain Streams
- Streaming Frameworks and Systems
- Distributed Streams

Additional References

- Lukasz Golab, M. Tamer Ozsu: **Issues in Data Stream Management**. SIGMOD Record, Vol. 32, No. 2, June 2003
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- Michael Benedikt, Dan Olteanu: **Report on the first Workshop on Innovative Querying of Streams**. SIGMOD Record, June 2013 (Vol. 42, No. 2)