Temporal Query Languages

Fabio Grandi
fabio.grandi@unibo.it
DISI, Università di Bologna

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Temporal Query Languages

- Data model: *DM = (DS, QL)*
  - *DS* is a set of data structures
  - *QL* is a language for querying and updating the data structures
- Example: the relational data model is composed of relations and SQL (or relational algebra)
- Many extensions of the relational data model and SQL to support time have been proposed

Relational Algebra for the BCDM

- An algebra provides a procedural/operational language for a data structure that is suitable for implementation
- Algebra for the standard relational algebra operators in BCDM
  - Schema: $R = (A_1, \ldots, A_n, T)$
  - Domains: A_i has domain D_i and T has domain $\mathcal{P}(D_{TT} \times D_{VT})$
    - D_{TT} is the transaction-time domain and D_{VT} is the valid-time domain
  - r is an instance relations of schema R
  - The operators then have the following signature

$$\begin{aligned} \pi^B_D &: \quad r \to r \\ \sigma^B_P &: \quad r \to r \\ \cup^B &: \quad r \times r \to r \\ \bowtie^B &: \quad r \times r \to r \end{aligned}$$

$$\begin{aligned} -^B &: \quad r \times r \to r \\ \rho^B_t &: \quad r \to r_{vt} \\ \tau^B_t &: \quad r \to r_{tt} \end{aligned}$$

Projection in BCDM

- Temporal projection: Project a relation r with non-timestamp attributes A_1, …, A_n to a subset D of attributes

$$\begin{aligned}\pi^B_D(r) = \{z^{(|D|+1)} \mid & \exists x \in r(z[D] = x[D]) \wedge \\ & \forall y \in r(y[D] = z[D] \implies y[T] \subseteq z[T]) \wedge \\ & \forall t \in z[T] \exists y \in r(y[D] = z[D] \wedge t \in y[T])\}\end{aligned}$$

- Calculation of timestamps of result tuples
  - All chronons in any value-equivalent tuple of r must be included and no spurious chronons can be introduced
  - (automatic coalescence is performed)
- Ex. Projection on the Emp attribute: $\pi^B_{Emp}(dept)$

dept

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}

result

Emp	T
Jake	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15), (now,10),. . . ,(now,15) }
Kate	{(now,25),. . . ,(now,30)}

Selection in BCDM

- Temporal selection: Select from relation r with non-timestamp attributes $A_1, \ldots, A_n$ all tuples that satisfy a predicate P defined on the non-timestamp attributes

$$\sigma_P^B(r) = \{z \mid z \in r \land P(z[A])\}$$

- Ex. Select all tuples of employee Kate: $\sigma^B_{Emp='Kate'}(dept)$

dept

Emp	Dept	T
Jake	Ship	{(5,10),...,(5,15),...,(9,10),...,(9,15), (10,5),...,(10,20),...,(14,5),...,(14,20), (15,10),...,(15,15),...,(19,10),...,(19,15) }
Jake	Load	{(now,10),...,(now,15)}
Kate	Ship	{(now,25),...,(now,30)}

result

Emp	Dept	T
Kate	Ship	{(now,25),...,(now,30)}

Union in BCDM

- Temporal union: Compute the union of tuples from two relations r_1 and r_2 that are instances of the same schema (or union-compatible schemas)

$$
\begin{aligned}
r_1 \cup^B r_2 = \{z^{(n+1)} \mid & (\exists x \in r_1 \exists y \in r_2 (z[A] = x[A] = y[A] \wedge z[T] = x[T] \cup y[T])) \vee \\
& (\exists x \in r_1 (z[A] = x[A] \wedge (\neg \exists y \in r_2 (y[A] = x[A])) \wedge z[T] = x[T])) \vee \\
& (\exists y \in r_2 (z[A] = y[A] \wedge (\neg \exists x \in r_1 (x[A] = y[A])) \wedge z[T] = y[T]))\}
\end{aligned}
$$

  - The first clause handles value-equivalent tuples found in r_1 and r_2
  - The second (third) clause handles those tuples that are found only in r_1 (r_2)

Union in BCDM

- Ex. Compute the union of relations dept and emp:

$$dept \cup^B emp$$

dept

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}

emp

Name	Inst	T
Jake	Ship	{(5,20),. . . ,(5,25),. . . ,(9,20),. . . ,(9,25) }
Sue	Load	{(5,20),. . . ,(5,25),. . . ,(9,20),. . . ,(9,25) }

result

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15), (5,20),. . . ,(5,25),. . . ,(9,20),. . . ,(9,25) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}
Sue	Load	{(5,20),. . . ,(5,25),. . . ,(9,20),. . . ,(9,25) }

Difference in BCDM

- Temporal difference: Compute those tuples that are in r_1 and not in r_2 where the two relations are instances of the same schema (or union-compatible schemas)

$$
\begin{aligned}
r_1 -^B r_2 = \{z^{(n+1)} \mid \exists x \in r_1((z[A] = x[A]) \wedge \\
&((\exists y \in r_2(z[A] = y[A]) \wedge z[T] = x[T] - y[T]) \vee \\
&(\neg\exists y \in r_2(z[A] = y[A]) \wedge z[T] = x[T])))\}
\end{aligned}
$$

  - The last two lines compute the bitemporal element, depending on whether a value-equivalent tuple may be found in r_2 or not

Difference in BCDM

- Ex. Compute the difference of relations dept and emp:

$$dept -^B emp$$

dept

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}

emp

Name	Inst	T
Jake	Ship	{(10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20) }
Jake	Load	{(15,10),. . . ,(15,15),. . . ,(now,10),. . . ,(now,15) }

result

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Kate	Ship	{(now,25),. . . ,(now,30)}

Join in BCDM

- Temporal join: Two tuples join if they match on the join attributes $A_1, \ldots, A_n$ and have overlapping bitemporal-element timestamps
  - r and s are instances over the following schemas:

    $R(A_1, \ldots, A_n, B_1, \ldots, B_l, T) = R(A, B, T)$

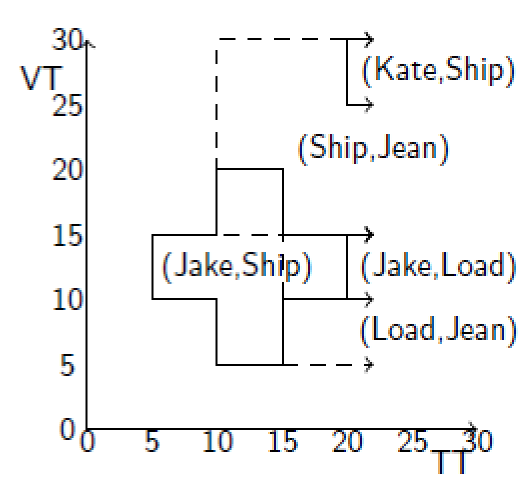
    $S(A_1, \ldots, A_n, C_1, \ldots, C_m, T) = S(A, C, T)$

$$
\begin{aligned}
r \bowtie^B s = \{z^{(n+l+m+1)} \mid (\exists x \in r \exists y \in s(x[A] = y[A] \land x[T] \cap y[T] \neq \emptyset \land \\
z[A] = x[A] \land z[B] = x[B] \land z[C] = y[C] \land \\
z[T] = x[T] \cap y[T]))\}
\end{aligned}
$$

  - The timestamp of a result tuple is the intersection of the timestamps of the corresponding argument tuples

Join in BCDM

- Ex. Temporal join to compute “Who managed whom”?: $dept \bowtie^B mgr$



dept

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}

mgr

Dept	Mgr	T
Ship	Jean	{(10,15),. . . ,(10,30),. . . ,(now,15),. . . ,(now,30),
Load	Jean	{(15,5),. . . ,(15,15),. . . ,(now,5),. . . ,(now,15)}

The timestamp is the overlap of timestamp regions of tuples with matching join attribute

result

Emp	Dept	Mgr	T
Jake	Ship	Jean	{(10,15),. . . ,(10,20),. . . ,(15,15),. . . ,(15,20),
Jake	Load	Jean	{(now,10),. . . ,(now,15)}
Kate	Ship	Jean	{(now,25),. . . ,(now,30)}

Timeslice Operators in BCDM

- Transaction-timeslice operator: selects the relation at transaction time t_1 (not exceeding the current time)
  - Takes a bitemporal relation r as input and returns a valid-time relation

$$\rho^B_{t_1}(r) = \{z^{(n+1)} \mid \exists x \in r(z[A] = x[A] \wedge z[T_v] = \{t_2 | (t_1, t_2) \in x[T]\} \wedge z[T_v] \neq \emptyset)\}$$

- Valid-timeslice operator: selects the relation at valid time t_2
  - Takes a bitemporal relation r as input and returns a transaction-time relation

$$\tau^B_{t_2}(r) = \{z^{(n+1)} \mid \exists x \in r(z[A] = x[A] \wedge z[T_t] = \{t_1 | (t_1, t_2) \in x[T]\} \wedge z[T_t] \neq \emptyset)\}$$

Timeslice Operators in BCDM

- Timeslice operators can be extended for transaction-time and valid-time relations
  - ρ^T gets as input a transaction-time relation and returns a snapshot relation
  - τ^V gets as input a valid-time relation and returns a snapshot relation
- Ex.

dept

Emp	Dept	T
Jake	Ship	{(5,10),. . . ,(5,15),. . . ,(9,10),. . . ,(9,15), (10,5),. . . ,(10,20),. . . ,(14,5),. . . ,(14,20), (15,10),. . . ,(15,15),. . . ,(19,10),. . . ,(19,15) }
Jake	Load	{(now,10),. . . ,(now,15)}
Kate	Ship	{(now,25),. . . ,(now,30)}

- τ^B_{12} (dept) = { (Jake,Ship, {5,…,19}), (Jake,Load, {now}) }
- ρ^V_7 (τ^B_{12} (dept)) = { (Jake,Ship) }

Sequenced Semantics

- There is a close relationship between a temporal and a non-temporal database:
  - the snapshot of a temporal relation at a time t is a non-temporal relation
  - a temporal relation is a collection of timestamped snapshots
- All non-temporal statements can be evaluated at each snapshot of a temporal database (“at each time point”)
- There should be a close relationship between a temporal and a non-temporal statement:
  - e.g. a temporal aggregation should resemble a non-temporal aggregation
- With SQL this is not the case (remember temporal join versus join)…

Sequenced Semantics

Notations (we assume R is a valid-time relation):

- Relation schema: $R(A_1, ..., A_n, T_S, T_E)$
- r is a relation with schema R (instance of R)
- $A_1, ..., A_n$ are the explicit (non-temporal) attributes
- T_S, T_E are temporal attributes
  - T_S is the valid time start
  - T_E is the valid time end
- $z^{(n+2)}$ denotes a tuple of arity n+2
- We assume periods are half open intervals $[T_S, T_E)$
- We write T to refer to the period $[T_S, T_E)$
  - $t \in T \equiv T_S \leq t < T_E$

Sequenced Semantics

Notations:

- The timeslice operator τ maps a temporal to a non-temporal relation
- Definition of the timeslice operator:

$$\tau_t(r) = \{ z^{(n)} \mid \exists x \in r \; (z.\mathbf{A} = x.\mathbf{A} \land x.T_S \leq t < x.T_E) \}$$

- Two temporal relations, r and s, are snapshot equivalent iff for all times t their snapshots are identical
- Definition of snapshot equivalence:

$$r \stackrel{s}{\equiv} s \quad \text{iff} \quad \forall t (\tau_t(r) = \tau_t(s))$$

Sequenced Semantics

- Snapshot reducibility reduces the semantics of temporal operators to the semantics of the corresponding non-temporal operators

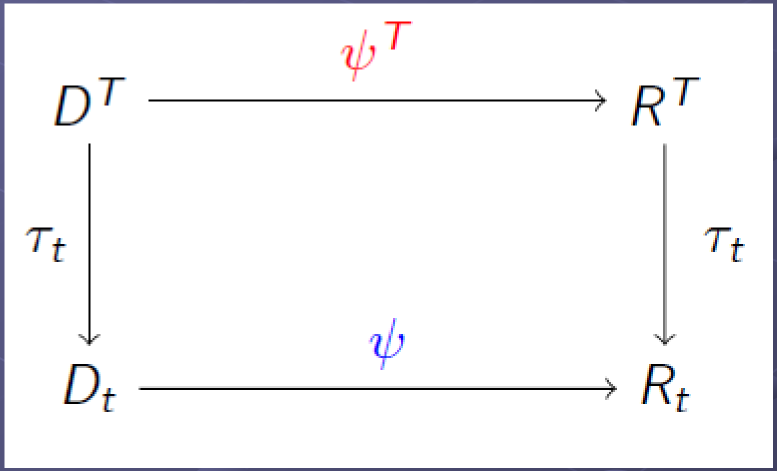
- temporal operator ψ^T is snapshot-reducible to the non-temporal operator ψ iff for all t:

$$\tau_t(\psi^T(R_1, \ldots, R_n)) \equiv \psi(\tau_t(R_1), \ldots, \tau_t(R_n))$$

Sequenced Semantics

Illustration of snapshot Reducibility:

$$\forall t : \tau_t(\psi^T(D^T)) = \psi(\tau_t(D^T))$$



- D^T = temporal DB
- $\psi^T = \{\sigma^T, \pi^T, \theta^T, x^T, U^T, -^T\}$
- R^T = temporal result relation
- τ_t = snapshot at time point t
- D_t = snapshot of D^T at time t
- $\psi = \{\sigma, \pi, \theta, x, U, -\}$
- R_t = result relation at time t

Sequenced Semantics

- A temporal relation can be viewed as made up of a sequence of timestamped snapshot relations
- Mutual consistency of the two viewpoints along the time axis gives rise to the notion of snapshot reducibility
- If period/element timestamping is adopted, timestamps of the argument tuples are taken into account when forming the timestamp associated to the result tuples (e.g. intersection is used when executing a join)
- Enforcement of snapshot reducibility gives rise to a sequenced semantics (i.e. “at each time point”) in query execution [Böhlen, Jensen, Snodgrass]

Non-Sequenced Semantics

- Snapshot reducibility does not apply to queries involving predicates and functions over the timestamps of argument relations
- In such queries, snapshots valid at different times have to be mixed in in order to find the answer
- Hence, their evaluation requires a non-sequenced semantics
- Such queries give the full temporal expressivity to a temporal query language (and fully exploits the power of a temporal database)
  - Ex. Find the employees who were programmer before becoming DBA
  - The information about being programmer and about being DBA must be found by combining (with a join) different snapshots

Beyond Sequenced Semantics [Böhlen]

- Period-based semantics (even in a weak sense) requires the preservation of the individual timestamp periods through the application of operators
- *Extended snapshot reducibility* allows non-sequenced queries to be executed with a sequenced semantics
- It can be enforced via *timestamp propagation* (making copies of timestamp columns to be treated as explicit attributes)
- Enforcement of *change propagation* corresponds to a correct application of a sequenced semantics with true period-based timestamping (coalescence not automatic)
- It can be implemented via manipulation of lineage sets (sets of witness lists of argument tuples)

Upward Compatibility [Snodgrass et al.]

- Let $M_1=(DS_1,QL_1)$ and $M_2=(DS_2,QL_2)$ two data models, then M_1 is *syntactically upward compatible* with M_2 if
  - $\forall\ db_2 \in DS_2 \Rightarrow db_2 \in DS_1$
  - $\forall\ q_2 \in QL_2 \Rightarrow q_2 \in QL_1$

  (a database/query in M_2 is also a database/query in M_1)

- Let $M_1=(DS_1,QL_1)$ and $M_2=(DS_2,QL_2)$ two data models, then M_1 is upward compatible with M_2 if
  - M_1 is syntactically upward compatible with M_2
  - $\forall\ db_2 \in DS_2, \forall\ q_2 \in QL_2 \Rightarrow [[\ q_2(db_2)\ ]]_{M_2} = [[\ q_2(db_2)\ ]]_{M_1}$

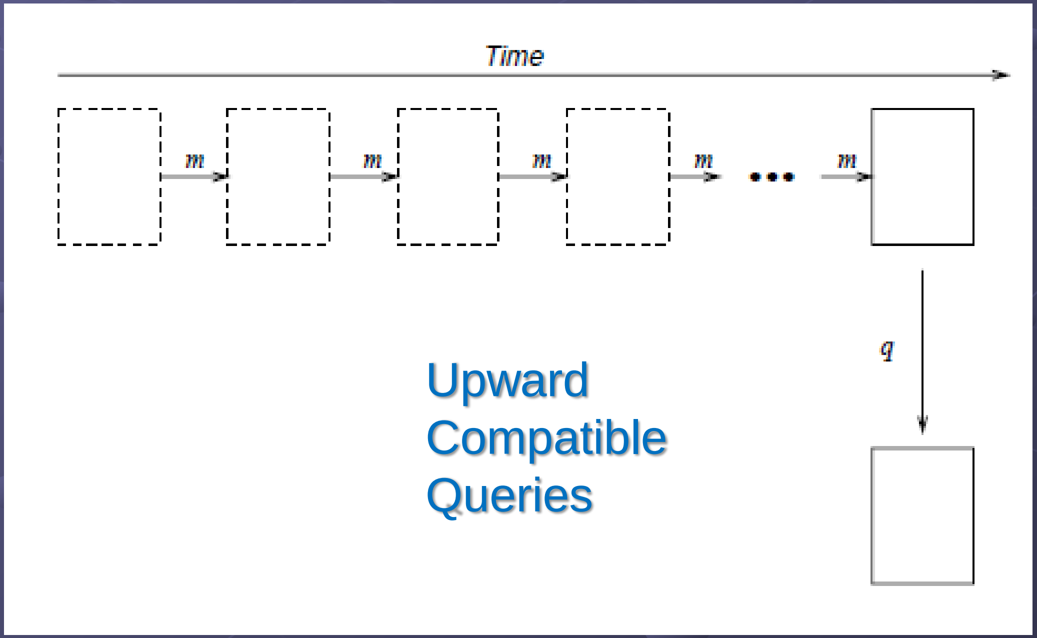
  (evaluating a query on a database instance in M_2 gives identical results if evaluated in M_1)

- We will use this notion with M_1 = TDB and M_2 = Rel. DB…

Upward Compatibility

- A Temporal Query Language (TQL) is upward compatible with SQL if
  - Traditional tables are also legal instances of tables in the underlying temporal data model
  - Traditional SQL queries are also queries in the TQL and give the same results when evaluated according to the TQL semantics

(TQL and SQL queries give the same results on a non-temporal table)

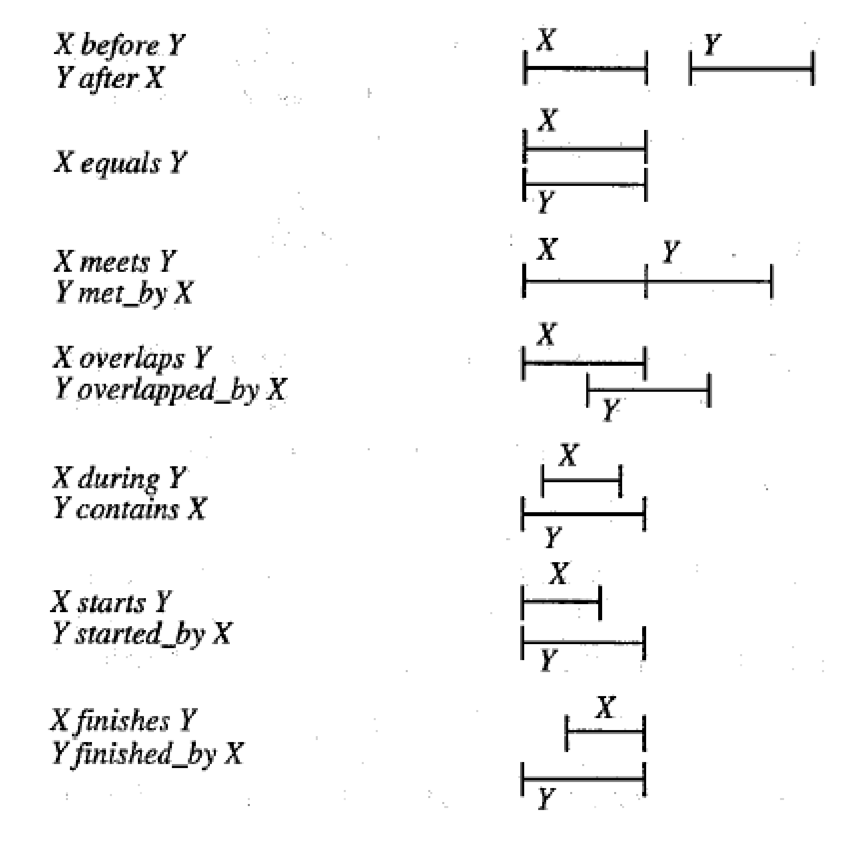


Language Design Criteria

- Expressive power
  - Suitable for intended applications
  - Economy of encoding is relevant
- Clarity
  - Syntax should reflect the semantics
  - Consistent naming style
- Consistency
  - Upward compatibility with standards, e.g. SQL standard
  - Systematic (not a new construct per query, no exceptions)
- Orthogonality
  - Possibility to freely combine query language constructs
  - Zero-One-Infinity principle (the only reasonable numbers in a programming language design are zero, one, and infinity)
- Closed-form evaluation
  - The result of a query is a proper object of the data model

Comparison of Timestamps

- Comparison of Timestamps is part of every temporal query language
- Many query languages adopt (a variant of) Allen's 13 period relations:



SQL + Abstract Data Types

- Extend existing language (e.g. SQL) with time data types and associated predicates and functions
  - e.g. predicates for timestamp comparison
- Earliest and (from a language design perspective) simplest approach
- Has limited impact on existing language and is well understood technically

- An abstract data type does not offer a systematic way to generalize snapshot queries to temporal queries
- New and very complex solutions must be invented (i.e. programmed) to implement common temporal operations:
  - Temporal join, temporal aggregates, coalescence…
  - Enforcement of key constraints, sequenced semantics…

The IXSQL Approach [Lorentzos et al.]

- IXSQL extends SQL-92 with (time) period data type
- Periods are convenient for representing temporal aspects, but create difficulties when formulating temporal queries
- IXSQL addresses this problem by normalizing timestamps so that they are aligned (identical or disjoint):
  - Function *UNFOLD*: decompose a period-timestamped tuple into a set of point-timestamped tuples (one for each point in the original period)
  - Function *FOLD*: collapse a set of point timestamped tuples into value-equivalent tuples timestamped with maximum periods
- General pattern for query processing using fold/unfold:
  1. Construct the point-based representation by unfolding the argument relation(s)
  2. Compute the query on point-based representation
  3. Fold the result to end up with an period-based representation

The IXSQL Approach

- Example of a temporal join (sequenced semantics):

```
SELECT DeptName, Location, DeptManager, Salary,
        intervsect(Department.T, Employee.T) as T
FROM Employee, Department
WHERE EmpName = DeptManager
    AND Department.T overlaps Employee.T
    AND Location = 'Miami'
REFORMAT AS FOLD T
```

- (the REFORMAT AS FOLD instruction, i.e. UNFOLD to time instants followed by FOLD to time periods, is necessary for coalescence of tuples in the result)

The IXSQL Approach

- Only two functions, fold and unfold, are added to SQL
- Unfold can be used when needed to formulate queries about each time point (it is optional and not an invasive change at query language level)
- Efficient evaluation of queries formulated using fold/unfold has yet to be resolved
- Neither a purely point-based nor period-based view:
  - Sensitive to specific period representation of data (e.g. queries that do not use fold/unfold)
  - Fold/unfold only preserve information of a point-based view
    - Normalization step using unfold/fold loses period information
    - Fold is not the inverse of unfold (information about the original periods is lost)
  - The combination of “at each time point” and periods is not supported (sequenced semantics with periods cannot be supported)

The TSQL2 Language
(Temporal SQL-92 Extension)

The TSQL2 Language

Desired features of the underlying data model that inspired the TSQL2 design:

- TSQL2 should not distinguish between value-equivalent instances (to provide conceptual simplicity)
- TSQL2 should support only one valid-time dimension
- TSQL2 should support transaction time
- For simplicity, tuple timestamping should be employed
- Event and state tables should be supported
- Valid-time support should include support for both the past and the future
- Timestamp values should not be limited in range or precision

The TSQL2 Language

Proper desired features of the query language that inspired the TSQL2 design:

- TSQL2 should be a consistent, fully upward compatible extension of SQL-92
- TSQL2 should allow the restructuring of tables on any set of attributes
- TSQL2 should allow for flexible temporal projection
- Operations in TSQL2 should not accord any explicit attributes special semantics (e.g. op. relying on keys)
- Temporal support should be optional, on a per-table basis

The TSQL2 Language

Proper desired features of the query language that inspired the TSQL2 design:

- User-defined time support should include instants, periods and intervals
- Existing aggregates should have temporal analogues in TSQL2
- Multiple calendars and multiple language support should be present in timestamp I/O and operations
- It should be possible to derive temporal and non-temporal tables from underlying temporal and non-temporal tables

The TSQL2 Language

Ease of implementation was made a priority in the design:

- TSQL2 tables should be implemented in terms of tables in some 1NF representational model
- TSQL2 should have an efficiently implementable algebra that allows for optimization and that is an extension of the snapshot algebra
- The TSQL2 data model should allow multiple representational data models

The TSQL2 Language

- Timestamping columns are “hidden columns” with an implied special semantics and syntactic defaults have been embedded in order to make the formulation of common temporal queries easier
- For example, intersection of the valid time of all the relations involved in a query to be assigned as timestamps to the results is automatically done, yielding:
  - Snapshot reducibility is ensured
  - Sequenced semantics is enforced by default
- The implied sequenced semantics can be overridden via a custom temporal projection or explicit manipulation of timestamps for temporal selection

Time Representation in TSQL2

- Time representation conforms to the BDCM
- Time is discrete with chronons as base unit
- Available base temporal datatypes:
  - Datetime (instant)
  - Period
  - Interval
- Such datatypes are inherited from the SQL-92 specification but with several flaws fixed

The Datetime Datatype

- Conforms to predefined SQL-92 types: DATE, TIME, TIMESTAMP (compliant to ISO 8601 standard formats)

- Examples:

DATE '2016-02-29'

DATE 'February 29, 2016'

TIME '21:30:10'

TIME '9:30:10 PM'

TIMESTAMP '2015-12-31 12:00:00.00'

TIMESTAMP 'Noon December 31, 2015'

The Period Datatype

- Represents open/closed time periods

- Examples:

PERIOD '[March 2014]'

PERIOD '(2010]'

PERIOD '[1994-01-01 - 1994-01-31)'

PERIOD '(12:15:00.0 - 12:16:00.0)'

PERIOD '[Midnight July 1, 2013
- September 10, 2014 10:20 AM]'

The Interval Datatype

- Represents unanchored pure durations
- Examples:

INTERVAL '10' YEAR

INTERVAL 'November' DAY

INTERVAL '3' WEEK

INTERVAL '02:30' HOUR TO MINUTE

INTERVAL '-20' SECOND (cf. negative duration)

Mixed Expressions

- A set of any datetime (period) data is an instant set (temporal element): in any case it is a set of chronons

- Examples:

PERIOD '[2014-01-01 - 2014-06-01]'

+ INTERVAL '10' MONTH

= PERIOD '[2014-11-01 - 2015-04-01]‘

TIMESTAMP ‘2000-01-01 12:30'

+ INTERVAL 'February 2016' DAY

= TIMESTAMP ‘2000-01-30 12:30'

Mixed Expressions

- Further examples:

  PERIOD 'March 2014' + INTERVAL '10' DAY
  = PERIOD '[2014-03-11 - 2014-04-10]'

  TIMESTAMP '13:30 April 1, 2000'
  + INTERVAL '1' YEAR - INTERVAL '15' MINUTE
  = TIMESTAMP '2001-04-01 13:15'

- Special predefined constants:
  BEGINNING, FOREVER, INITIATION, UNTIL_CHANGED, CURRENT_TIMESTAMP, NOW (possibly with *nobind option*)

Schema Declaration and Modification

- Temporal definition clause AS… (6 temporal table types)
- Examples:

```
CREATE TABLE Employee ( … )
   AS VALID STATE

CREATE TABLE Department ( … )
   AS VALID AND TRANSACTION

CREATE TABLE Transfer ( … )
   AS VALID EVENT DAY

ALTER TABLE Employee
   ADD TRANSACTION
```

-

Temporal Selection

- Selection based on temporal conditions in the WHERE clause
- Temporal comparison operators
  (for datetime, period, instant set and element):
  PRECEDES, =, OVERLAPS, MEETS, CONTAINS
- Comparison (<, =, >) and arithmetic (+, -, *) operators for intervals
- Various functions:
  BEGIN(.), END(.), FIRST(.), LAST(.),
  INTERSECT(.,.), + , -
- Constructors: PERIOD(.,.)
- Timestamp extractors: VALID(.), TRANSACTION(.)

Temporal Comparison Operators

- The semantics of TSQL2 temporal comparison operators corresponds to their meaning in natural language (whereas Allen's operators have artificial and innatural names), following the SQL (SEQUEL) philosophy

- X PRECEDES Y iff END(X) < BEGIN(Y)
- X = Y iff X and Y are identical
- X OVERLAPS Y iff $X \cap Y \neq \emptyset$
- X MEETS Y iff X PRECEDES Y without any instants in between
- X CONTAINS Y iff $X \supseteq Y$

Temporal Comparison Operators

- The TSQL2 temporal comparison operators can be used with instants, periods and elements, and also for mixed comparisons (e.g. elements with instants)
- As to periods, TSQL2 is anyway Allen-complete
- X = Y has been preferred to X EQUALS Y not to introduce a new keyword
- For the same reason, inverse operators have not been considered necessary
  - X MET_BY Y can be expressed as Y MEETS X
  - X FOLLOWS Y can be expressed as Y PRECEDES X
  - X DURING Y can be expressed as Y CONTAINS X

Temporal Selection - Examples

- SELECT * FROM Employee
  WHERE EmpName = 'Ted'

- SELECT Salary FROM Employee
  WHERE VALID(Employee) CONTAINS DATE 'NOW'

- SELECT * FROM Employee
  WHERE EmpName = 'Ted'
  AND VALID(Employee) OVERLAPS
  PERIOD '[2013]' + PERIOD '[2015]'

Temporal Selection - Examples

- SELECT EmpName, Salary
  FROM Employee
  WHERE FIRST(VALID(Employee)) CONTAINS
  PERIOD '[1990-06-15 - 1990-07-15]'

- SELECT EmpName, Salary
  FROM Employee
  WHERE Job = 'Programmer'
  AND LAST(VALID(Employee))
  PRECEDES DATE '2014-03-01'

Temporal Projection

- Assignment of a timestamp to the results of a query done with the VALID (VALID INTERSECT) clause

- Examples:

- SELECT SNAPSHOT EmpName, DateOfBirth
  FROM Employee
  WHERE Job='Engineer'

- SELECT DISTINCT EmpName
  FROM Employee
  VALID PERIOD(DateOfBirth, DATE 'FOREVER')
  WHERE Job = 'Manager'

Temporal Projection - Examples

- SELECT Department.*, Employee.Salary
  FROM Employee, Department
  VALID INTERSECT (Employee, Department)
  WHERE EmpName = DeptManager
  AND VALID(Employee)
  OVERLAPS VALID(Department)
  AND Location = 'Miami'

- SELECT Department.*, Employee.Salary
  FROM Employee, Department
  WHERE EmpName = DeptManager
  AND Location = 'Miami'

(the same VALID clause as above is understood and, thus, the overlap is implied; cf. temporal join)

TSQL2 Range Variables

- The TSQL2 range variables generalize the concept of history variables [Grandi] and allow for temporal restructuring [Gadia] of a relation. Automatic coalescing of timestamps is implied
- In the FROM clause:
  FROM Employee(EmpName) AS Emp
  the variable Emp ranges over groups of tuples of the relations with the same EmpName attribute value. Grouping can also be based on periods
- Notice that the clause FROM Employee
  is equivalent to FROM Employee AS Employee
  that is to FROM Employee(*) AS Employee

TSQL2 Range Variables

- Declaration of range variables (and, thus, grouping) can be nested:

```
FROM Employee(EmpName) AS Emp,
     Emp(Job) AS E1, E2
```

  is equivalent to:

```
FROM Employee(EmpName) AS Emp,
     Employee(EmpName,Job) AS E1, E2
WHERE E1.EmpName=Emp.EmpName
  AND E2.EmpName=Emp.EmpName
```

(groups are *synchronized* on the common attributes; nested declarations are "syntactic sugar")

TSQL2 Range Variables

- Examples:

```
SELECT *
FROM Employee(EmpName,Salary) AS Emp
WHERE Salary = 2500
    AND CAST(Emp AS INTERVAL YEAR)
            >= INTERVAL '2' YEAR


SELECT SNAPSHOT E1.EmpName, BEGIN(VALID(E2))
FROM Employee(EmpName) AS Emp,
        Emp(Job,Salary) AS E1, E2
WHERE E1 MEETS E2
    AND E1.Job <> E2.Job
    AND E1.Salary = E2.Salary
```

TSQL2 Range Variables

- Examples:

```
SELECT E1.EmpName, E1.Job
FROM Employee(EmpName) AS Emp,
        Emp(Job)(PERIOD) AS E1, E2, E3
WHERE E1 MEETS E2 AND E2 MEETS E3
    AND E1.Job <> E2.Job AND E1.Job = E3.Job
    AND E2.Job = 'Manager'


SELECT Emp.*
FROM Employee(EmpName) AS Emp,
        Emp(Job) AS E1, Emp(Salary) AS E2
WHERE E1.Salary = 2300 AND E2.Job = 'DeptHead'
    AND BEGIN(VALID(E2)) - END(VALID(E1))
            > INTERVAL '18' MONTH
```

TSQL2 Modification Operations

- The VALID clause allows for the specification of the *applicability period* of the modification
- Examples:

```
INSERT INTO Employee
VALUES ('Kim', '1982-05-15', 'Engineer', 2500)
VALID PERIOD( DATE '2016-01-01',
                        NOBIND(DATE 'NOW') )
```

Employee

EmpName	DateOfBirth	Job	Salary	VALID
Kim	15/5/1982	Engineer	2500	[1/1/2016, Now)

TSQL2 Modification Operations

- Examples:

```
UPDATE Employee
SET Salary = Salary + 200
WHERE EmpName = 'Kim'
    AND VALID(Employee)
            CONTAINS DATE 'CURRENT_TIMESTAMP'
VALID PERIOD 'February 2016'
```

Employee

EmpName	DateOfBirth	Job	Salary	VALID
Kim	15/5/1982	Engineer	2500	[1/1/2016, 1/2/2016)
Kim	15/5/1982	Engineer	2700	[1/2/2016, 1/3/2016)
Kim	15/5/1982	Engineer	2500	[1/3/2016, Now)

TSQL2 Modification Operations

- Examples:

```
DELETE FROM Employee
WHERE EmpName = 'Kim'
VALID PERIOD '[2016-06-01 - FOREVER]'
```

Employee

EmpName	DateOfBirth	Job	Salary	VALID
Kim	15/5/1982	Engineer	2500	[1/1/2016, 1/2/2016)
Kim	15/5/1982	Engineer	2700	[1/2/2016, 1/3/2016)
Kim	15/5/1982	Engineer	2500	[1/3/2016, 1/6/2016)

TSQL2 Modifications and Surrogates

- Surrogates are transparent time-invariant identifiers
- Example:

```
CREATE TABLE
Supplier(ID SURROGATE, Name CHAR PRIMARY KEY,
         Address CHAR)
AS VALID;

INSERT INTO Supplier
VALUES (NEW, 'Acme Inc.', 'New York')
VALID PERIOD '[2014-01-01 - FOREVER]'
```

Supplier

ID	Name	Address	VALID
[S1]	Acme Inc.	New York	[1/1/2014, Forever)

TSQL2 Modifications and Surrogates

```
INSERT INTO Supplier
SELECT ID, 'New Acme Ltd.', Address
FROM Supplier
WHERE Name = 'Acme Inc.'
VALID PERIOD '[2016-01-01 - FOREVER]'
```

or:

```
UPDATE Supplier
SET Name = 'New Acme Ltd.'
WHERE ID = ( SELECT ID FROM Supplier
             WHERE Name = 'Acme Inc.' )
VALID PERIOD '[2016-01-01 - FOREVER]'
```

Supplier

ID	Name	Address	VALID
[S1]	Acme Inc.	New York	[1/1/2014, 1/2/2016)
[S1]	New Acme Ltd.	New York	[1/1/2016, Forever)

TSQL2 Aggregate Functions

- Temporal grouping criteria:
  - Partition domain (valid or user-defined, instant or period)
  - Partition granularity
  - Associated time window (LEADING and TRAILING options)
  - Group belonging
- Example:

```
SELECT Salary
FROM Employee AS Emp1
WHERE Emp1.EmpName = 'Tony'
  AND VALID(Emp1) OVERLAPS
    ( SELECT MIN(VALID(Emp2))
      FROM Emp AS Emp2
      WHERE Emp2.EmpName = 'Eve' )
```

TSQL2 Aggregate Functions

- Examples:

```
SELECT EmpName, SUM(WEIGHTED Salary)
FROM Employee(EmpName) AS Emp
GROUP BY VALID(Emp) USING '1' YEAR
HAVING MIN(Salary) > 2500
```

```
SELECT AVG(WEIGHTED Salary)
FROM Employee
WHERE EmpName = 'Tony'
GROUP BY VALID(Employee)
    USING '1' MONTH LEADING '11' MONTH
```

Calendars and Calendric Systems

- Calendars and calendric systems composed of multiple calendars are supported in TSQL2
- Ex. of calendars: Gregorian, Julian, Astronomic, Traditional_Chinese, US_Fiscal, UniBO_Academic
- Ex. of a calendric system: Russian (Roman till100 B.C. then Julian till1917, then Gregorian till1929, then Communist till1931 and then Gregorian again)

- Selection of a calendric system (Gregorian) in TSQL2:

```
DECLARE CALENDRIC SYSTEM
    AS SQL92_CALENDRIC_SYSTEM
```

Calendars and Calendric Systems

- Calendars are necessary for correct I/O and formatting of time data, that can be specified via the DATETIME_FORMAT property, ex.

  SET PROPERTY FOR Italian_Calendar WITH VALUES
  (' DATETIME_FORMAT ',
  ' <DAY>/<MONTH>/<YEAR> <HOUR>:<MINUTE>:<SECOND> ')

  then '19/02/2016 ' is a correct date literal for the Italian_Calendar

- Time zones and daylight saving are also supported, e.g. the following expressions are equivalent:

  TIME '10:30:25' AT TIME ZONE INTERVAL '1' HOUR

  TIME '10:30:25' AT TIME ZONE 'CET'

  TIME '10:30:25+01:00'

Calendars and Calendric Systems

- Like in SQL-92, an EXTRACT() operator is also available to extract components from a temporal expression.
- Examples:

EXTRACT (HOUR FROM TIME '01:27.30 PM')

returns 13

EXTRACT (MONTH FROM DATE 'June 7, 2010')

returns 6

EXTRACT (TIMEZONE_HOUR FROM
TIMESTAMP '2015-05-13 13:27.30-4:00')

returns -4

Temporal Indeterminacy

- Based on a probabilistic approach [Dyreson & Snodgrass]
- An indeterminate instant $t = (t^- \sim t^+, P)$ is represented through:
  - Its lower (t^-) and upper (t^+) support
  - Its probability distribution P (null outside the support)
- Evaluation of selection predicates involving indeterminate instants (at a given plausibility level p) is based on the *Before()* primitive:

$$Before(p, t_1, t_2) := \neg(t_1 \equiv t_2) \wedge \Pr[t_1 < t_2] \geq p/100$$

where the precedence probability is evaluated as:

$$\Pr[t_1 < t_2] = \sum_{i<j} P_1(i) P_2(j)$$

Temporal Indeterminacy

- The probability distribution can be STANDARD (i.e. UNIFORM or MISSING) or NONSTANDARD
- Non standard distributions are user-defined point by point such that:

  $P(i) = 0$ if $i<t^-$ or $i>t^+$

  $\sum_{t^- \leq i \leq t^+} P(i)=1$

- Non standard distributions samples with predefined shapes could be provided by the system or made available by a DBA (e.g. PROBABLY_EARLY, PROBABLY_VERY_LATE, AROUND etc.)

Temporal Indeterminacy

Example:

```
CREATE TABLE
Shipment( ParcelNo CHAR PRIMARY KEY, Destination CHAR,
          Arrival NONSTANDARD INDETERMINATE DATE )

INSERT INTO Shipment
VALUES ('P102', 'Rome', '2016-02-20 ~ 2016-02-24'
          WITH DISTRIBUTION PROBABLY_EARLY)

SELECT * FROM Shipment
WHERE Destination='Paris'
AND VALID(Shipment) OVERLAPS
          DATE '2016-03-01' WITH PLAUSIBILITY '95'
```

Granularities in TSQL2

- Granularities are based on the lattice associated to a calendar
- TSQL2 extends the mechanism available in SQL-92 for the INTERVAL datatype, e.g.

  INTERVAL DAY TO SECOND

  (duration at a granularity between day and second)
- The upper granularity may be expressed as a range, e.g.

  INTERVAL '1000' DAY TO SECOND
- TSQL2 allows granularity definitions also for instant and period datatypes
- A precision specification can also be used, e.g.

  TIME MINUTE(2) TO SECOND(3)

  The first is a range spec. (10^2 minutes) the second spec. is the maximum number of decimal digits (10^{-3} seconds)

Granularities in TSQL2

- Comparison on operands with different granularities are effected at the granularity of the left operand
- Explicit granularity conversions are possible by means of the SCALE and CAST operators, e.g.
  - SCALE(DATE '2010-01-01' AS MONTH)
    CAST(DATE '2010-01-01' AS MONTH)
    both return 'January 2010'
  - SCALE(DATE '2010-01-01' AS MINUTE)
    returns '2010-01-01 00:00 ~ 2010-01-01 23:59' (indeterm.)
  - CAST(DATE '2010-01-01' AS MINUTE)
    returns '2010-01-01 00:00' (the first value at the finer gran.)
  - SCALE(DATE 'March 2014 ~ April 2014' AS DAY)
    returns '2014-03-01 ~ 2014-04-30' (maximizes indet.)
  - CAST(DATE 'March 2014 ~ April 2014' AS DAY)
    returns '2014-03-01 ~ 2014-04-01' (converts the supports)

The ATSQL Approach

- ATSQL [Böhlen, Jensen & Snodgrass] uses temporal statement modifiers to add temporal support to SQL
- Statement modifiers are semantic defaults that indicate “at each time point” without specifying how to compute it
- Provides a systematic way to construct temporal queries from non-temporal queries:
  - 1. Formulate the corresponding non-temporal query
  - 2. Apply a statement modifier
- Example: Temporal join
  - Formulate the non-temporal join
  - Modifier ensures that the argument timestamps overlap and that the result timestamp is the intersection of the argument periods
- ATSQL assumes period-timestamped tuples:
  - Periods have a meaning beyond a set of points

The ATSQL Approach

- Example (temporal join):

```
SEQ VT
SELECT Department.*, Employee.Salary
FROM Employee, Department
WHERE EmpName = DeptManager
    AND Location = 'Miami'
```

- The NSEQ VT (“nonsequenced valid time”) modifier indicates that what follows should be treated as regular SQL, for example (tuple count):

```
NSEQ VT
SELECT COUNT(*) FROM Employee
```

The ATSQL Approach

- A query without a modifier considers only the present state of the argument relations (i.e. valid at NOW)
- Ensures that legacy queries on non-temporal relations are unaffected if the non-temporal relations are made temporal, e.g.

  SELECT * FROM Employee

- The modifiers mechanism is independent of the syntactic complexity of the queries
- The temporal parts are to a large degree separated from the non-temporal parts of the query
- The semantics of SQL extended with statement modifiers has been defined

TDB Support in SQL:2011

- The SQL/Temporal chapter was cancelled from the SQL3 definition in 2001 due to controversy within the ISO SQL committee (cf. ATSQL vs IXSQL approach)

- New temporal language extensions were recently submitted to and accepted by the ISO SQL committee as part of the SQL/Foundation Chapter of the new SQL:2011 standard

- The ability to create and manipulate temporal tables is the most important new feature in SQL:2011

TDB Support in SQL:2011

- Valid-time tables, dubbed as “Application-time period tables”, are supported
- Transaction-time tables, dubbed as “System-versioned tables”, are supported
- Bitemporal tables, dubbed as “System-versioned application-time period tables” (!), are supported
- Period timestamping is supported via 2 columns
- Temporal primary key and referential integrity constraints are supported
- Predicates are defined for querying along valid and transaction time

Application-time Period Tables

- Application-time period tables are tables that contain a PERIOD clause (newly-introduced) with a user-defined period name
- Application-time period tables must contain two (user-defined) additional columns to store the start and end time of a period associated with the row
- Values of both start and end columns are set by the users
- Additional syntax is provided for users to specify primary key/unique constraints that ensure no two rows with the same key value have overlapping periods

Creating an Application-time Period Table

```
CREATE TABLE Employee
(emp_name VARCHAR(50) NOT NULL PRIMARY KEY,
dept_id VARCHAR(10),
start_date DATE NOT NULL, end_date DATE NOT NULL,
PERIOD FOR emp_period (start_date, end_date),
PRIMARY KEY (emp_name, emp_period WITHOUT OVERLAPS),
FOREIGN KEY (dept_id, PERIOD emp_period) REFERENCES
Department (dept_id, PERIOD dept_period))
```

- PERIOD clause automatically enforces the constraint end_date > start_date
- The name of the period can be any user-defined name
- The timestamping period is considered open to the right, i.e. [start_date, end_date)

Querying an Application-time Period Table

- Application-time period tables can be queried using the regular SQL syntax (temporal selection predicates can be expressed using comparison conditions over the timestamping columns)
- More user-friendly and Allen-complete period comparators (reminiscent of the TSQL2 ones) are also available:

  CONTAINS, OVERLAPS, EQUALS, PRECEDES, SUCCEEDS, IMMEDIATELY PRECEDES, IMMDIATELY SUCCEEDS

- Ex.

```
SELECT * FROM Employee
WHERE emp_period CONTAINS PERIOD '2015'

SELECT DISTINCT E1.emp_name, E2.emp_name
FROM Employee E1, E2
WHERE E1.emp_name < E2.emp_name
    AND E1.dept_id = E2.dept_id
    AND E1.emp_period OVERLAPS E2.emp_period
```

Modifying an Application-time Period Table

- Regular INSERT, UPDATE, DELETE statements can be used by explicitly managing values of conventional columns but also of the timestamping columns
- A more user-friendly new FOR PORTION clause can be used to specify the applicability period of modifications

- Ex.

```
UPDATE Employee
FOR PORTION OF emp_period
        FROM DATE '2015-05-01' TO DATE '2015-06-01'
SET dept_id = 'D5' WHERE emp_name = 'Tom'

DELETE Employee
FOR PORTION OF emp_period
        FROM DATE '2016-03-01' TO DATE '9999-12-31'
WHERE emp_name = 'Annabel'
```

System-versioned Tables

- System-versioned tables are tables that contain a PERIOD clause with a pre-defined period name (SYSTEM_TIME) and specify WITH SYSTEM VERSIONING
- System-versioned tables must contain two additional (user-defined) columns to store the start and end time of the SYSTEM_TIME period
- Values of both start and end columns are set by the system (users are not allowed to supply values)

System-versioned Tables

- Unlike regular tables, system-versioned tables preserve the old versions of rows as the table is updated
- Rows whose periods intersect the current time are called current system rows. All others are called historical system rows
- Only current system rows can be updated or deleted. System time applicability of modifications cannot be managed by the user
- All constraints are enforced on current system rows only

Creating a System-versioned Table

```
CREATE TABLE Employee
(emp_name VARCHAR(50) NOT NULL, dept_id VARCHAR(10),
system_start TIMESTAMP(6) GENERATED ALWAYS AS ROW START,
system_end TIMESTAMP(6) GENERATED ALWAYS AS ROW END,
PERIOD FOR SYSTEM_TIME (system_start, system_end),
PRIMARY KEY (emp_name),
FOREIGN KEY (dept_id) REFERENCES Department (dept_id);
) WITH SYSTEM VERSIONING
```

- Unlike regular tables, system-versioned tables preserve the old versions of rows as the table is updated
- PERIOD clause automatically enforces the constraint system_end > system_start
- The name of the period must be SYSTEM_TIME
- The timestamping period is considered open to the right

Querying a System-versioned Table

- The clause FOR SYSTEM_TIME can be used after the FROM clause to access past states of a table along transaction time (rollback queries)

- It comes with three variants:
  - FOR SYSTEM_TIME AS OF T (current at T)
  - FOR SYSTEM_TIME FROM T1 TO T2 (current in [T1,T2))
  - FOR SYSTEM_TIME BETWEEN T1 AND T2 (current in [T1,T2])

- Ex.

```
SELECT * FROM Employee
FOR SYSTEM_TIME
        FROM TIME '2011-01-01'  TO TIME '2011-12-31‘

SELECT * FROM Employee
FOR SYSTEM_TIME
        AS OF TIMESTAMP '2014-04-01 12:30:00'
```

Creating a System-versioned Application-time Table

```
CREATE TABLE Employee
(emp_name VARCHAR(50) NOT NULL PRIMARY KEY,
dept_id VARCHAR(10),
start_date DATE NOT NULL, end_date DATE NOT NULL,
system_start TIMESTAMP(6) GENERATED ALWAYS AS ROW START,
system_end TIMESTAMP(6) GENERATED ALWAYS AS ROW END,
PERIOD FOR emp_period (start_date, end_date),
PERIOD FOR SYSTEM_TIME (system_start, system_end),
PRIMARY KEY (emp_name, emp_period WITHOUT OVERLAPS),
FOREIGN KEY (dept_id, PERIOD emp_period) REFERENCES
Department (dept_id, PERIOD dept_period)
) WITH SYSTEM VERSIONING
```

Cf. Creating the same Table in TSQL2…

```
CREATE TABLE Employee
(emp_name VARCHAR(50) NOT NULL PRIMARY KEY,
dept_id VARCHAR(10),
FOREIGN KEY dept_id REFERENCES Department
) AS VALID AND TRANSACTION
```

In practice, it is the same declaration done with regular SQL of a snapshot table Employee, simply augmented with the "AS VALID AND TRANSACTION" bitemporal specification (that implies the so deprecated syntactic and semantic defaults)