The first proposed solution of this paper is based on the versioning extension of the uni-temporal solution. Index pointers are always routed to the newest version, thanks to that, each new analysis uses current version image at particular execution moment. Historical versions are stored in the nested tables of the same temporal structure. Fig. 8 shows the architecture of the solution using object granularity. In principle, any granularity can be used. Relevant data state is encapsulated by the validity time frame (*BD*, *ED*) and insertion date (*IND*). These data reflect the newest version of the state. Insertion date is recorded automatically using *sysdate* (date and time in the second granularity) or *systimestamp* (date, time, up to 1ns precision) function, or any analogous function for the used database system. If there is no previous version for the state, particular nested table is empty. If the new version for the particular state is inserted, original is transferred to such nested table and main structure continuously stores only top version. Therefore, it is necessary to distinguish between empty nested table (in that case, before the transfer, constructor function must be called) and existing nested table with previous state versions.

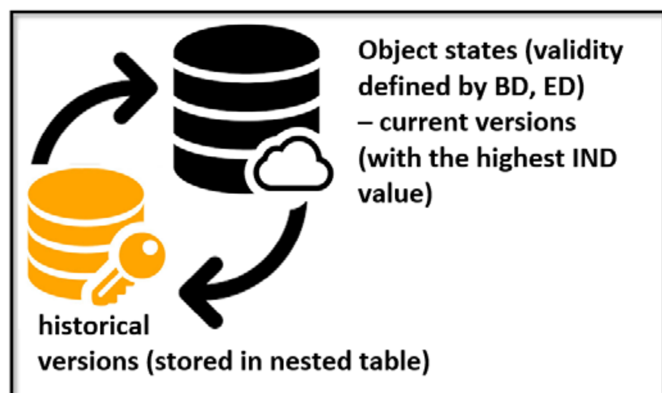


Figure 8. Nested table storing versions

Versioning storage in this defined solution can, however, form several state collisions, which is demonstrated in the fig. 9. Let have one existing state (*S1*) consisting of only one version. After the processing, state *S1* is modified. In that case, new version for the state *S1* is created. In principle, two situations can occur. In the positive change scenario, new version does not change the validity time frame (fig. 9, part A). More complicated situations occur, if the validity frame is changed. In that case, it is not sufficient to create only new state version, original state must be divided into two or three ones. Let assume, that the state *S1* is validity bordered by the attributes *BD1* and *ED1*. Afterwards, new version is created with the validity time frame delimited by the *BD2* and *ED2*. Three situations can be identified:

- *BD2* < *BD1* and *BD1* < *ED2* and *ED2* < *ED1* (fig. 9, part B). In this case, original state must be splitted into two parts and one new version is added:
    - State framed by the *BD2* and *BD1* is delimited by new version.
    - State framed by the *BD1* and *ED2* is formed by the original version, which is also replaced by the new version.
    - State framed by the *ED2* and *ED1* remains original (version is not changed, only validity interval is shortened from the left site)
- *BD1* < *BD2* and *ED2* < *ED1* (fig. 9, part C). In this case, original state must be splitted into three parts:
    - State framed by the *BD1* and *BD2* remains original (version is not changed, only validity is shortened from the rigth site).
    - State framed by the *BD2* and *ED2* is formed by the original version, which is also replaced by the new version.
    - State framed by the *ED2* and *ED1* remains original (version is not changed, only validity interval is shortened from the left site)
- *BD1* < *BD2* and *BD2* < *ED1* and *ED2* > *ED1* (fig. 9, part D). In this case, original state must be splitted into two parts and one new version is added:
    - State framed by the *BD1* and *BD2* remains original (version is not changed, only validity interval is shortened from the right site)
    - State framed by the *BD2* and *ED1* is formed by the original version, which is also replaced by the new version.
    - State framed by the *ED1* and *ED2* remains original (version is not changed, only validity interval is shortened from the left site)

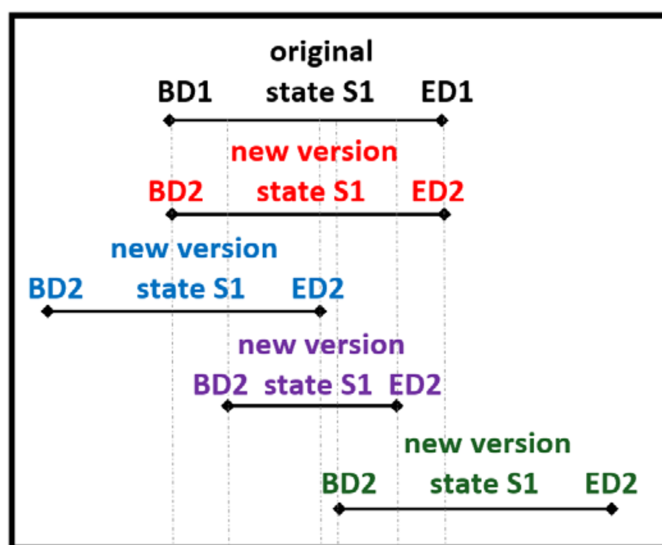


Figure 9. New version

Generally, new version can influence many states, however, only interval marginal parts (the top left and right) are splitted into two parts.

Second our proposed architecture divides current vesioning from the historical ones by forming separate database storage. In that case, main structure is uni-temporal, the rest versions are stored in the historical database, which consists of the validity time frame (*BD, ED*) and insertion date (*IND*), as well. Versioning itself is covered by the triggers, which shift original version to the historical database reposity. Consecutively, it is replaced in the main structure by the new version. Previously mentioned situations changing validity of the original state can occur in this architecture, as well. On the other hand, it is not necessary to deal with constructors and specific storage for nested tables. Triggers are associated with the destructive operations – *Update* (modification of the object by adding new state or version) and *Delete* (removing object from the system, either by the direct delete operation or by moving historical data to another repository, like data warehouse). *Insert* operation expressing adding new object in the system is not necessary to be triggered, whereas it always loads the first and only one version for each statement.

The third architectural solution is similar to the second one, but the trigger management module is replaced by the new background processes (*DBVern*, *n* expresses the number of such processes in the system) of the instance. They have direct database access, thus it removes the slight impact of the trigger firing. Moreover, performance benefits, because these processes are always accessible in the memory (information about their existence is written in the *spfile* and are created during the *mounting* process of the instance). In distributed environment, version processes are present on each node. Several *Database version processes* can be present in the instance, they can be either general (in that case, if new version is to be loaded, random free *Database version process* (*DBVern*) is selected to process the request. In practice, we select the process to ensure performance balance. Number (*n*) of version processes is dynamic, if there is no enough processes, versions are too much queued, system (using *SMON* background process) automatically creates new processes based on predicted future workload (evaluated based on the version statistics collected periodically). Another principle is based on the process association to the precisely defined object group.

The last forth model proposed in this paper is the generalization and simplification of the bi-temporal architecture and deals only with validity and database insertion date. It does not cover the whole interval. In principle, each new version delimits the validity of the previous one. In comparison with previous solution described in this chapter, there is no necessity to split existing states into parts, only during the image reflection to the user, individual positional time intervals must be evaluated. As you can see in the performance evaluation, it can be the bottleneck of the system. It is based on the assumption, that the state version correlates the insertion date (*IND*). For the evaluation and sorting, analytical function *RANK* is used:

```
RANK() over (PARTITION BY state_id
             ORDER BY insert_date DESC).
```

Function *RANK* is analytical and for these purposes, it gets the serial number for each version. Each current version of the state gets the value *1*, historical versions are then covered chronologically using insertion date to the database. There should be no gaps of the obtained values from the *RANK* function. If there is some gap present, it means, that data are not consistent – object state is covered during some defined interval by more than one valid version, which is not allowed.

VI. USED DATA VERSION IDENTIFICATION

Functions, analytics and aggregations are based on current image of the database, which is evaluated. When result set is stored or provided to the user, it is not clear, which specific versions were available at the time, and which are were not present. Thus, although the data result set is provided, it is not transparent, whether the results are still usable, since it was possible, that some other versions were loaded later giving previously images non-reliable. Typical example can be prediction on the one site and real data processing on the second site replacing calculated (predicted) values by effective ones. Therefore, to determine input image of the processing, data signature hash is stored with each processed data result. From such value, it is easy to determine validity and usability of the results. Moreover, there can be automatized functionality executed either automatically or based on specific conditions to remove old function results. In our approach, each new data shifts the signature hash to another value.

Each change, regardless of whether it changes the state or affects the version of the existing state, is stored in the database. Evidence of a given event is in the temporal layer of a particular model with respect to granularity (object, column, or hybrid design). The change itself can, but does not need to change already processed data in analytical tools. It depends on the images entering the analytical module, whether they are also modified. Therefore, each object changes the signature of the entire system, it creates own and unique fingerprint of the change. It works like following. Let have the complete image of the database covered by the actual signature *SIGNact*. New state is added (*Snew*). Fingerprint hash is added to the actual signature *SIGNact* and the whole unit is signature hashed. Such value is then accessible in the system, therefore each function dealing with data gets the actual hash as the parameter, which is directly copied to the result set.

Whereas signature hashes are based on *SIGNact* value, used image is trivial to determine – individual executed operations are consecutively subtracted from the hash. Principles are shown in the following figure. Current data are covered by the *SIGNact* value, each new states replaces it. It is sufficient to store only actual value, the rest ones can be dynamically calculated based on provided data (which are stored in the temporal architecture, so there is always possibility to get historical data image).

The data management is sophistical, on the other hand, if new data are loaded, but they do not influence already processed results (as the output of analytics, functions, etc.), new function result set are not created, whereas it would provide the same values.

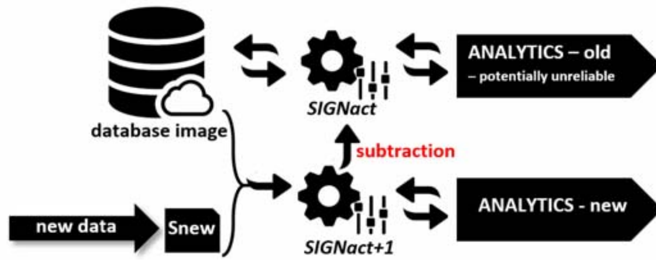


Figure 10. Signature hash calculation

VII. Performance

Experiment results were provided using Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - 64bit Production; PL/SQL Release 11.2.0.1.0 – Production. Parameters of used computer are:

- Processor: Intel Xeon E5620; 2,4GHz (8 cores),
- Operation memory: 16GB,
- HDD: 500GB.

Environment characteristics are based on real environment consisting of *1000* sensors producing data *ten times for one minute*. 10 percent of the provided data are consecutively replaced by newer ones using versions.

Five models have been used for the evaluation. The first one (*M1*) is based on original uni-temporal solution, individual versions are not processed, at all. Thus, approximately 10 percent of the processed data are unreliable. The second model (*M2*) deals with versions stored in the nested table for the particular state. Model 3 (*M3*) uses separate data structure (physical table) for dealing with historical versions. Model 4 (*M4*) is characterized by the background processes managing and accessing data versions. The last, fifth model (*M5*) uses bi-temporal architecture. Each state is delimited by the validity and reliability expressed by the time frame.

Tab. 1 shows the performance results with emphasis on the size for the whole structure and processing time - getting current image of the database with the latest versions of the individual states. As you can see, bi-temporal architecture reaches the worst results, for the size, as well as processing time. The reason is based on storing all data versions in the same table, thus the data amount is significantly rising. Although there are indexes to optimize data access, individual versions, as well as number of processed data, complicates the situation and huge data amount causing it widespread. Looking to the results, it can be concluded, that although size is increased using 9 percent, costs, CPU and processing time are increased by approximately 30 percent.

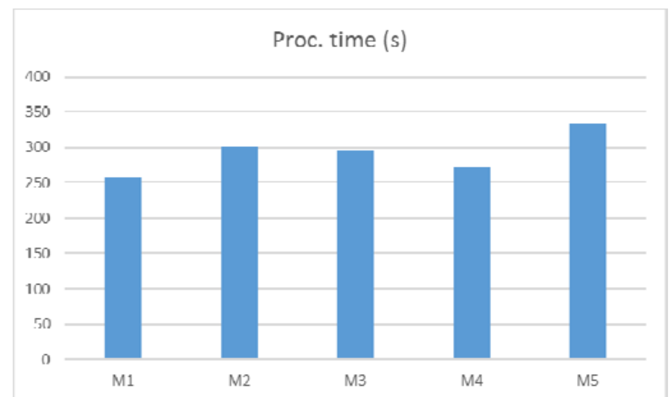
On the first sight, the best solution provides original uni-temporal solution (*M1*), however, it does not manage versions at all. As we can see from the experiment results, module for dealing with versions (*M4*) requires less than 7% increase of the processing time, however, it provides robust architecture and can cover all data changes during the object lifecycle.

Comparing the results of the model *M4* ensuring version management by background processes with other solutions, slowdown of the model *M3* is 5,82% for the costs, 9,26% for the CPU and 8,56% for processing time (reference model is *M4* – 100%). Model *M2* reached the following slowdown (reference model is *M4* – 100%): 9,50% for the costs, 11,11% for the CPU and 10,17% for the processing time.

TABLE I. Results

	M1	M2	M3	M4	M5
Costs	17 011	19 990	19 232	18 174	22 110
CPU (%)	52	60	59	53	67
Proc. time (s)	257,5	301,1	296,7	273,3	334,8
Size (%)	100	106	106	106	109

Query processing time is the main performance limitation of the whole system. Results are expressed in the fig. 11.



VIII. Conclusions

Conventional database systems are based on storing only current valid data. Historical images are not the goal of the management and are not reflected. Individual data corrections are versions are targeted to deal with only the most recent ones, as well. Temporal evolution has brought the possibility to cover all the states of the object in the time spectrum. Thanks to that, image of the object or the whole ecosystem at defined time point or interval can be reached. Principle of the uni-temporality is based on the term validity, thus each data tuple is time bordered. In this paper, we extend the paradigm of the temporal database approaches by adding sophisticated module for dealing with data versions. Thanks to that, data can be evaluated anytime with the reflection to the database image used as the input. Each data version is secured by the unique signature hash delimiting data image. Theoretical part of the paper deals with the temporal architectures with emphasis on processed granularity and antidating problem. Own proposed solution architecture is based on version management using

several models, which are experimentally compared. Most important parameters are just used resources and processing time. The best solution is based on the background process extension, by which data versions are covered.

Based on the used environment, proposed solution requires less than 7 percent addition for the processing time and CPU. On the other hand, proposed solution significantly improves performance of the bi-temporal architecture, which deals with the validity and transaction time for versioning. Proposed solution lowers the costs up to 18 percent. Processing time saving is more than 18 percent, as well.

During the future research, we will extend the solution to cover distributed environment complexly. We will deal with automation of the version and error detection in ad-hoc networks to ensure processed data to be always reliable. Solution could be used in any field. One of the strongest sphere is intelligent transport and GPS navigation systems, where particular node can obtain either raw data, if the communication channel is fast, or pre-processed package with emphasis on the security aspect.

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PROJEKT JE SPOLUFINANCOVANÝ ZO ZDROJOV EÚ

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