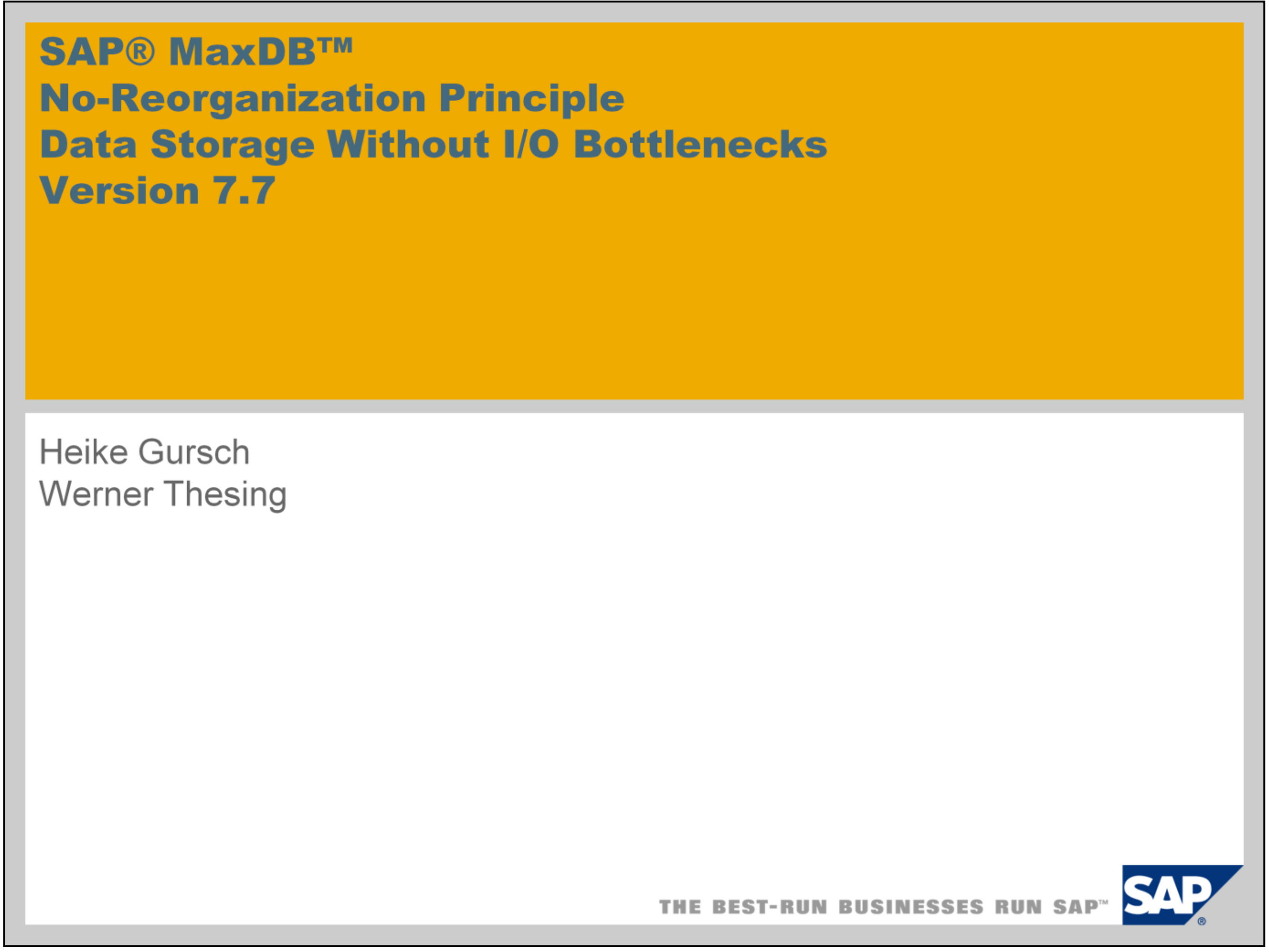

# SAP® MaxDB™ No-Reorganization Principle Data Storage Without I/O Bottlenecks Version 7.7

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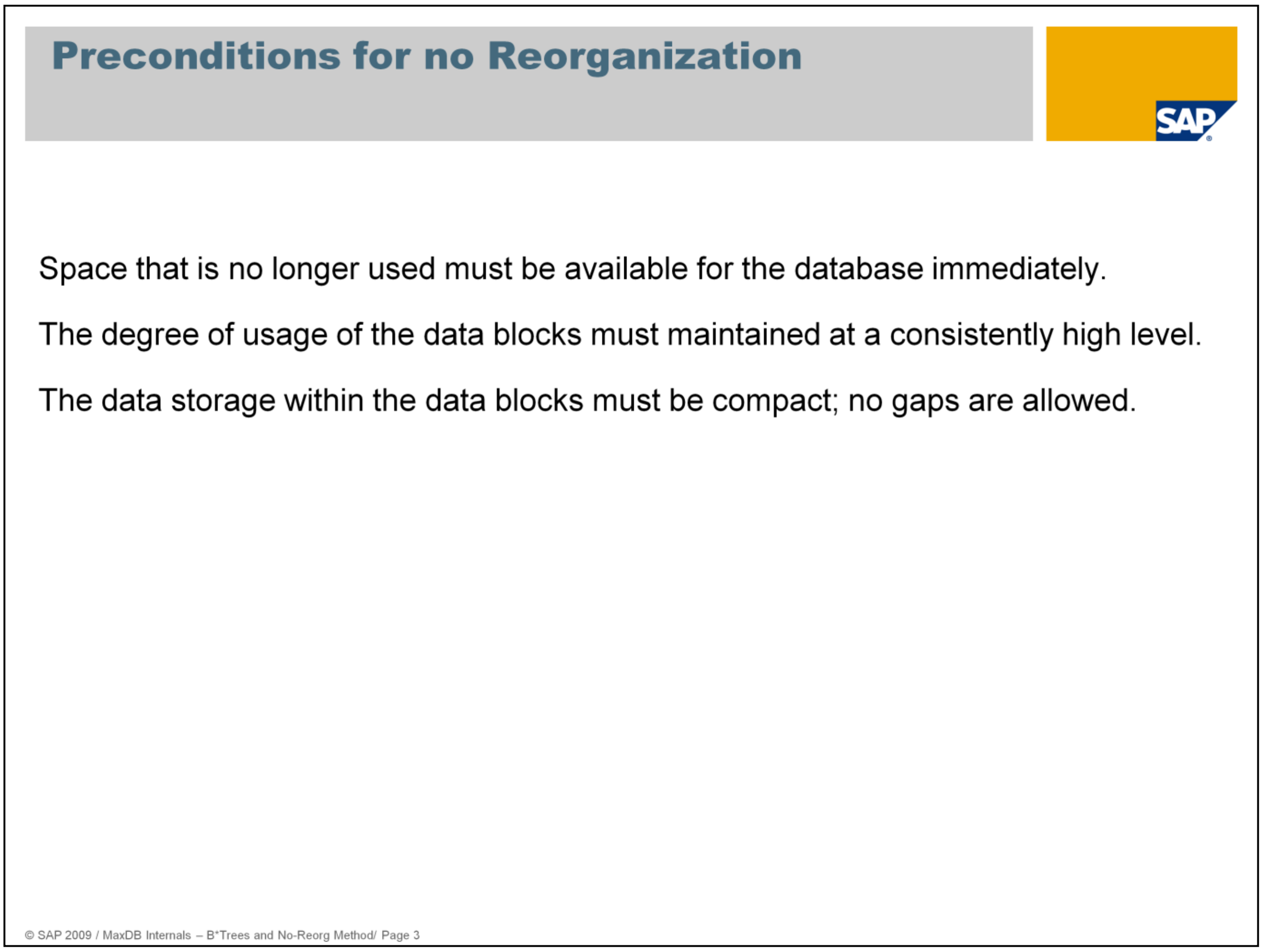
## Overview

No-reorganization principle

B* trees

Shadow page algorithm



## Preconditions for no Reorganization

Space that is no longer used must be available for the database immediately.

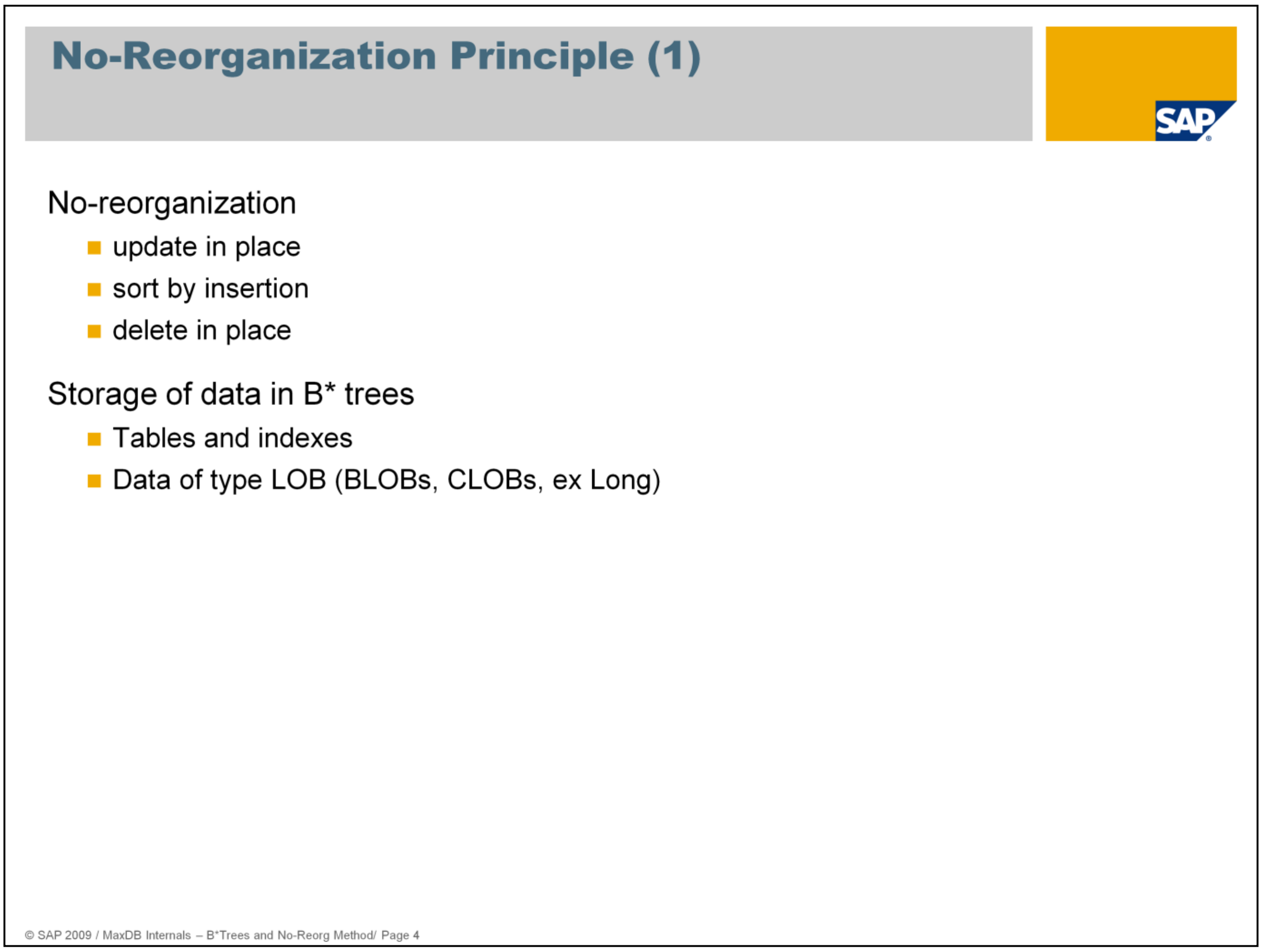
The degree of usage of the data blocks must maintained at a consistently high level.

The data storage within the data blocks must be compact; no gaps are allowed.

This slide describes the paradigms of a database system that is reorganization free.

As MaxDB does not need to be reorganized, the database can be operated with minimal administrative outlays.

The absence of the need to reorganize also means that the database always works with optimal access structures. That means consistently good performance.



## No-Reorganization Principle (1)

No-reorganization

- update in place
- sort by insertion
- delete in place

Storage of data in B* trees

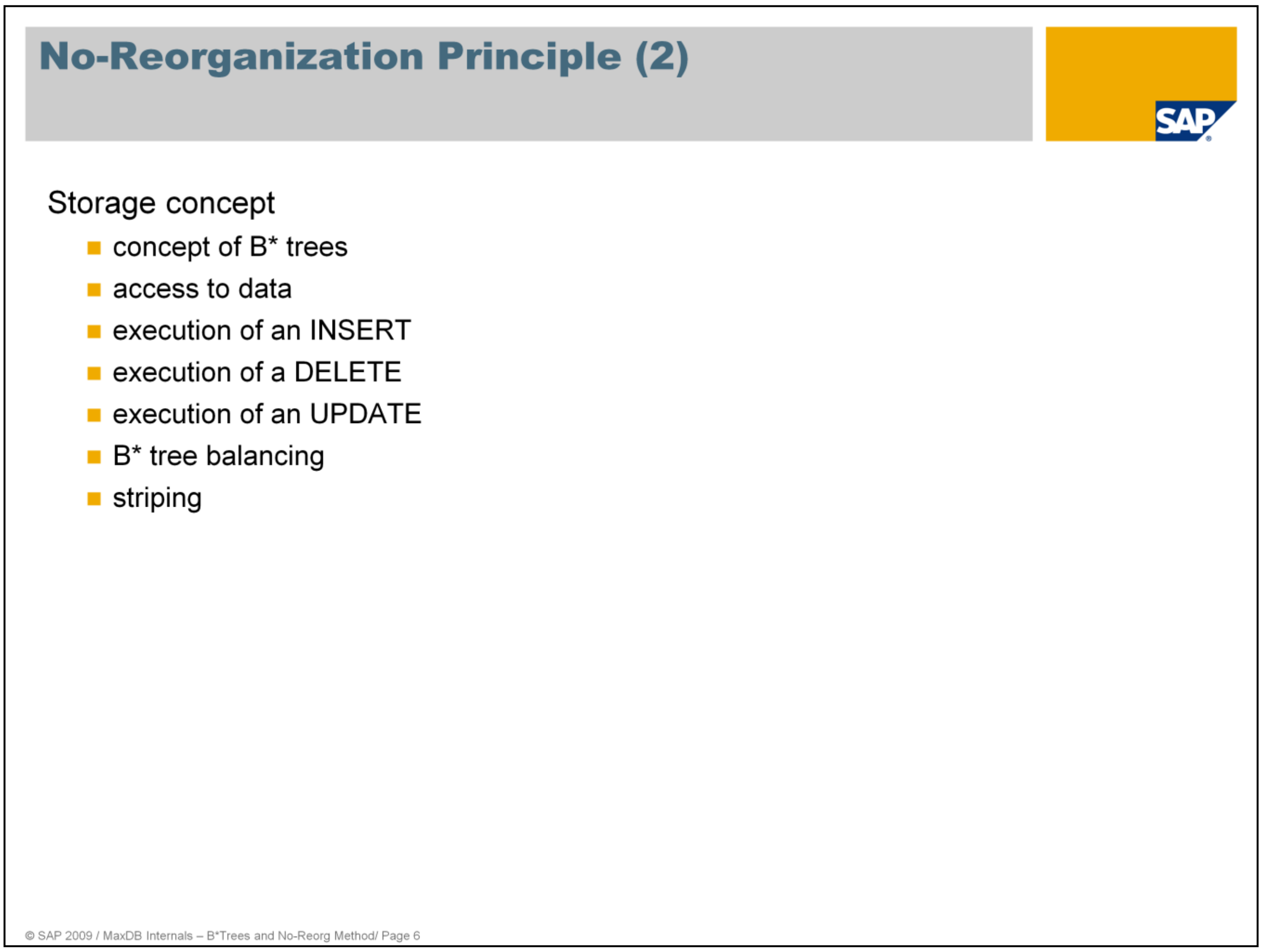
- Tables and indexes
- Data of type LOB (BLOBs, CLOBs, ex Long)

To achieve an efficient I/O strategy while maintaining the no-reorganization principle of the database system, a framework of structural and functional prerequisites was developed for MaxDB. These include, on the one hand, the no-reorganization principle itself, which is the result of separate memory management for the secondary storage media and the logical data pages and is primarily based on the following functions:

- Sorting of data records when they are inserted,
- Changing of data records in place,
- Changing of data records in place,

On the other hand, there are the logical storage structures and terms. We will take a closer look at:

- B* Trees,
- Tables and indexes,
- Primary and secondary keys
- and the storage of LOBs (BLOBs – binary large objects, CLOBS – character large objects)



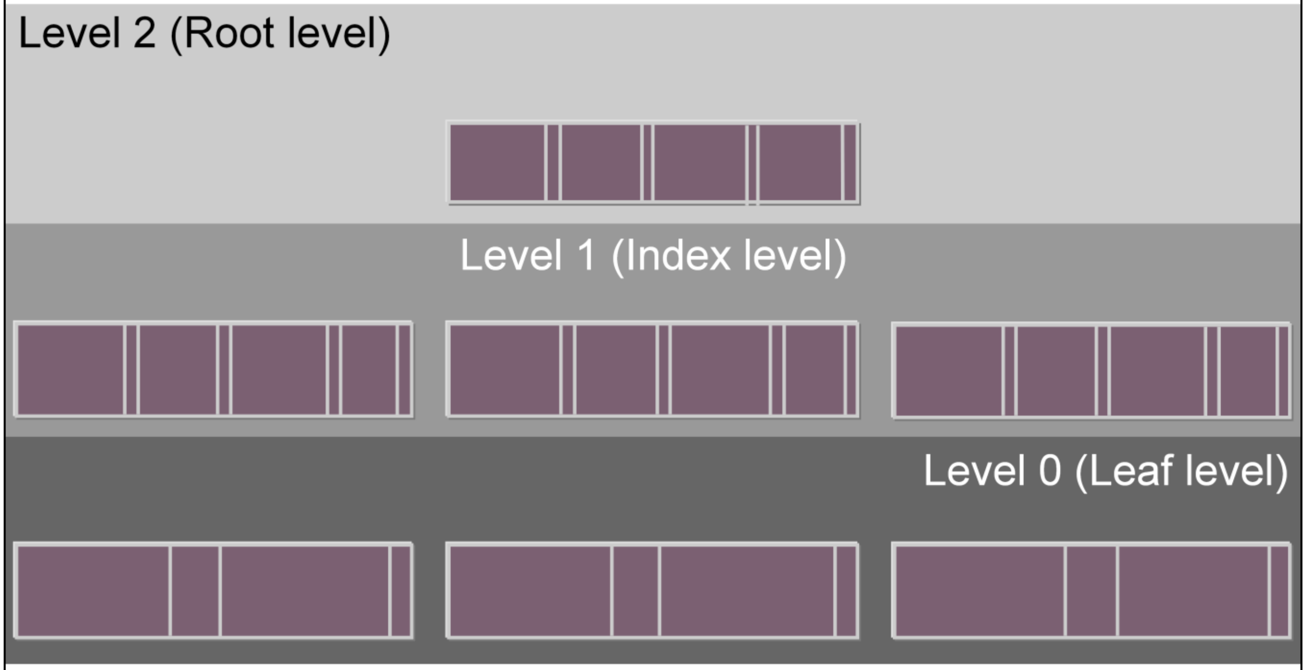
## No-Reorganization Principle (2)

Storage concept

- concept of B* trees
- access to data
- execution of an INSERT
- execution of a DELETE
- execution of an UPDATE
- B* tree balancing
- striping

The MaxDB storage concept ensures that data is quickly stored and found on the available disks. It is the key to automatic load balancing by MaxDB and thus guarantees the no-reorganization principle of the database system.

## B* Tree Concept



In MaxDB, data is stored in B* tree structures.

The smallest storage unit is the page. In MaxDB, the size of a page is 7.5/8 KB.

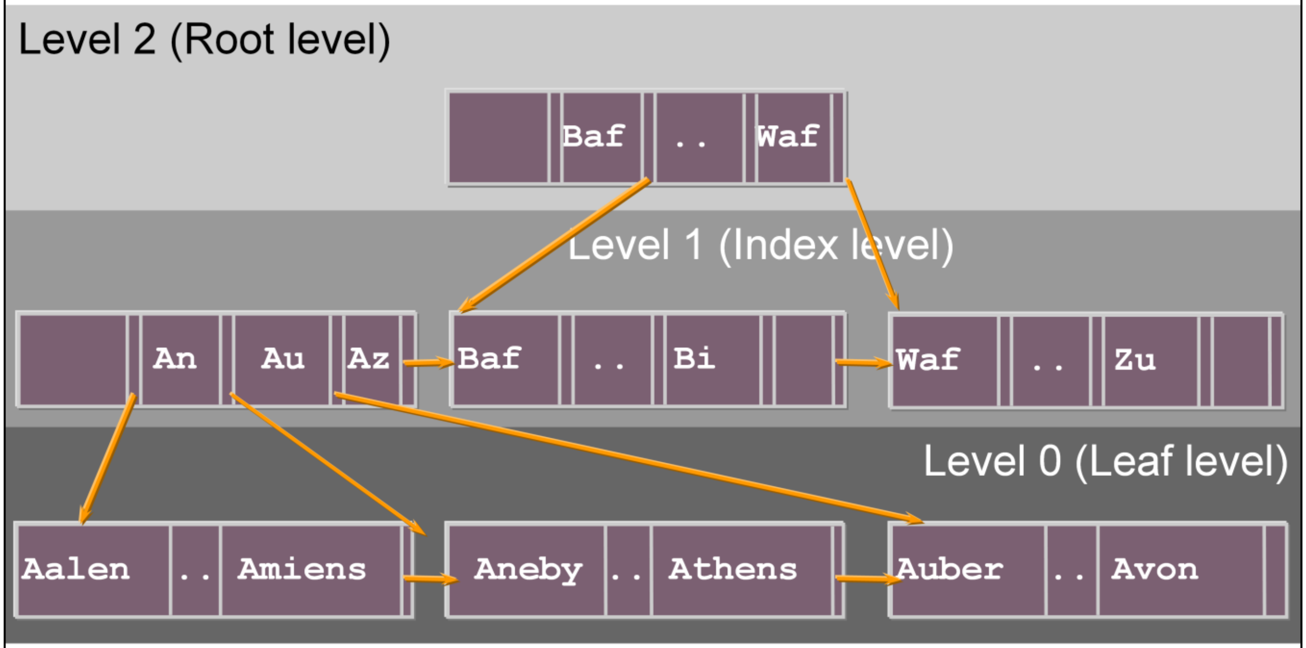
A B* tree is created for each table and secondary index.

A B* tree reaches from the highest level, the root level, to the lowest, the leaf level. The data is always on the leaf level.

The primary index of the tables serves as a sorting criterion for the setup of the tree structure.

It can be demonstrated that a B* tree procedure generally requires fewer accesses to find single records than other access methods.

## Structure of a B* Tree



The entries in the data pages are comprised of two parts:

- The fist part is comprised by the contents of the **key fields of a table row**. We shall refer to this as the **separator**.
- The second part is comprised by the remaining data.

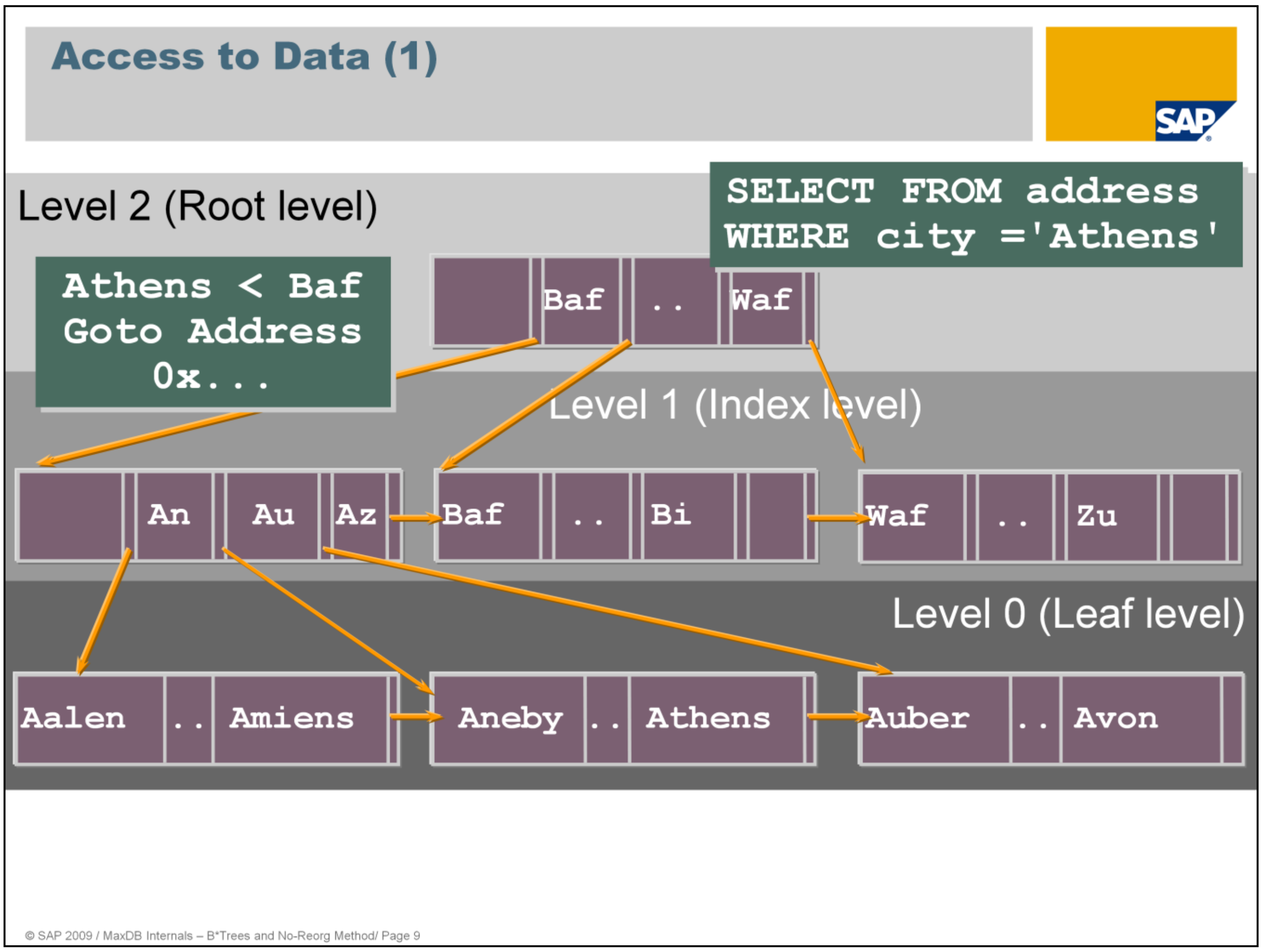
On index pages, every separator is followed by a **logical address** that refers to a page on a lower index level or on the leaf level. The number of entries that fits on an index page depends on the length of the separators.

A node of the B* tree always comprises one page. Thus the number of entries per B* tree level depends on the length of the separators.

In addition to the separator, leaf pages contain the contents of the other columns of the respective table row. The number of entries that fits on an index page depends on the length of the separators.

The amount of memory required for a table depends on the length of the key fields and the total length of a table row.

The procedure described here is supplemented by special treatment of tables that contain LOB columns (**L**arge **Ob**jects). Additional auxiliary trees are created for the purpose of accepting the contents of LOB columns, which can be many times longer than a data page.



## Access to Data (1)

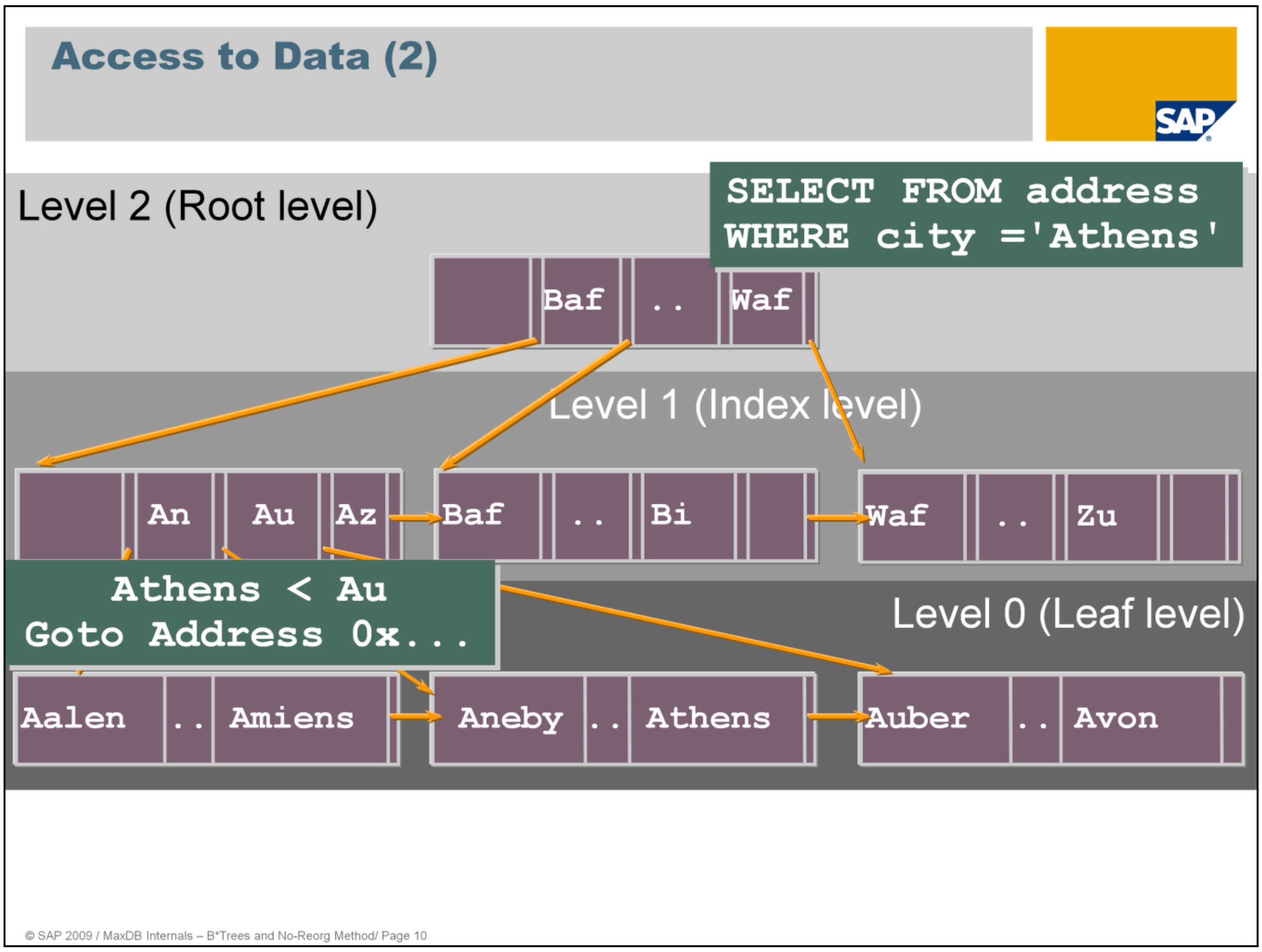
The B* tree procedure makes it possible to find data quickly.

Here's an example of how a data record is found: looking in an address table with the primary index '`city`', you want to find an entry for ‘`Athens`’.

The search begins on the root level. The comparisons described in the following take place on a character by character basis.

The database system checks if the value '`Athens`' is smaller than the second entry on the root page, '`Baf`'.

As the value is smaller, the corresponding logical address information from the first branch is evaluated. It points to a page on the next level (index level).



## Access to Data (2)

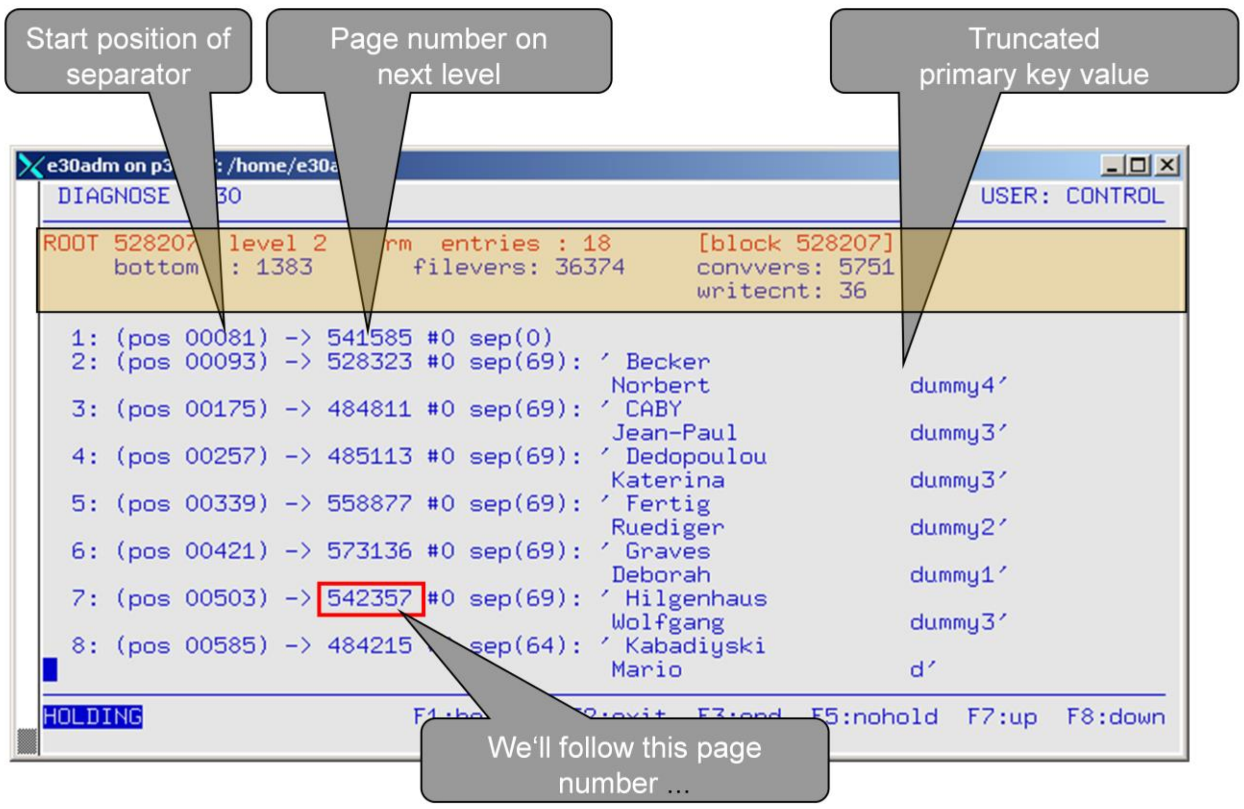
© SAP 2009 / MaxDB Internals – B*Trees and No-Reorg Method/ Page 10

The comparison then continues on the index level. Now the desired value, '`Athens`', is smaller than the entry '`Au`' on the data page.

So the ‘`An`’ branch is evaluated.

The pointer points to the second page on the leaf level. Now we are on the leaf level (level 0).

## Example Root Level


Start position of separator
Page number on next level
Truncated primary key value
We'll follow this page number ...

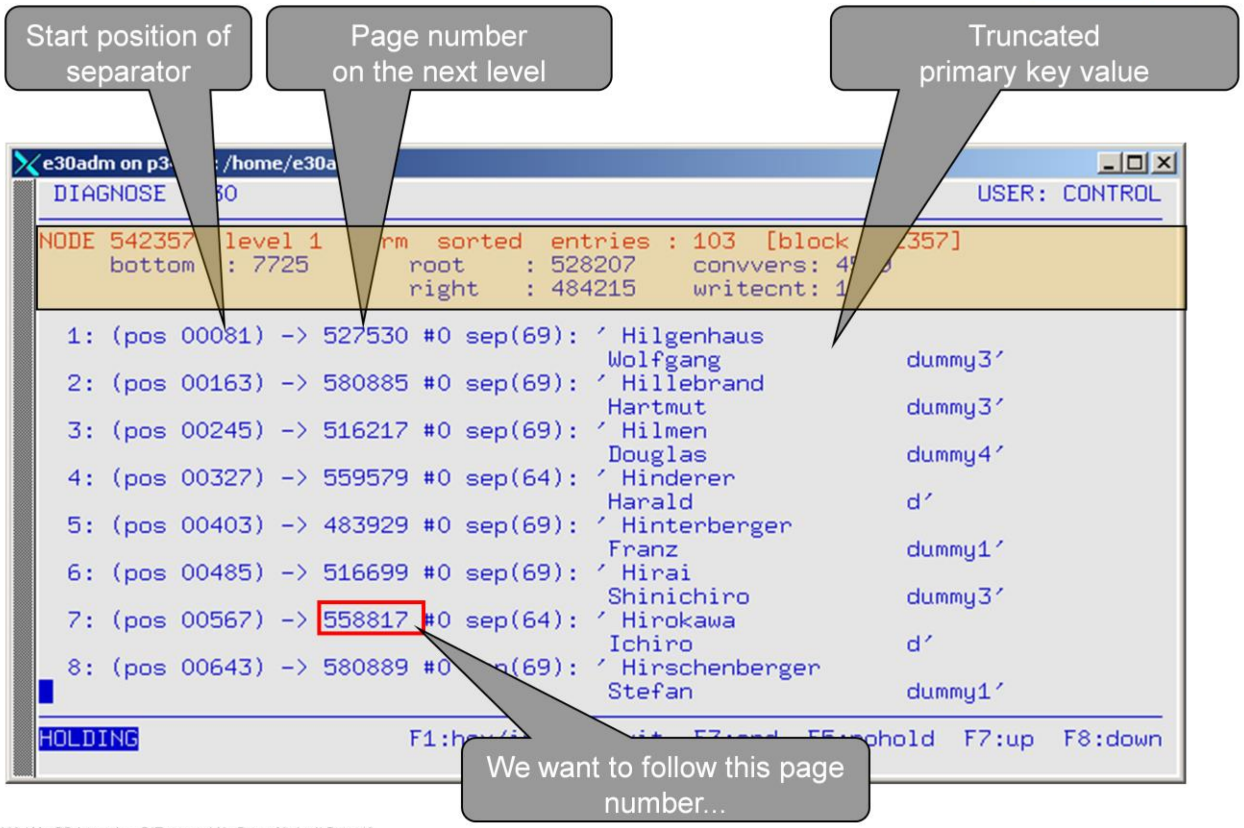
```
e30adm on p3    : /home/e30a
DIAGNOSE     30                                           USER: CONTROL

ROOT 528207   level 2      rm  entries : 18       [block 528207]
     bottom   : 1383          filevers: 36374     convvers: 5751
                                                  writecnt: 36

 1: (pos 00081) -> 541585 #0 sep(0)
 2: (pos 00093) -> 528323 #0 sep(69): ' Becker
                                       Norbert                   dummy4'
 3: (pos 00175) -> 484811 #0 sep(69): ' CABY
                                       Jean-Paul                 dummy3'
 4: (pos 00257) -> 485113 #0 sep(69): ' Dedopoulou
                                       Katerina                  dummy3'
 5: (pos 00339) -> 558877 #0 sep(69): ' Fertig
                                       Ruediger                  dummy2'
 6: (pos 00421) -> 573136 #0 sep(69): ' Graves
                                       Deborah                   dummy1'
 7: (pos 00503) -> 542357 #0 sep(69): ' Hilgenhaus
                                       Wolfgang                  dummy3'
 8: (pos 00585) -> 484215    sep(64): ' Kabadiyski
                                       Mario                     d'

HOLDING                    F1:he    F2:exit  F3:end  F5:nohold  F7:up  F8:down
```

This page shows a root page as displayed by the MaxDB Tool x_diagnose.

At the top you see the page header. As the page number and root number on this page are the same, this is a root page. The B* tree has three levels (levels 0 – 2). This page has 18 entries. It was changed 36 times.

The separators are shown in their alphanumeric order. You see the respective start position, the page number on the next page to the separator, the length and the value of the separator.

## Example Index Level


Start position of separator
Page number on the next level
Truncated primary key value
We want to follow this page number...

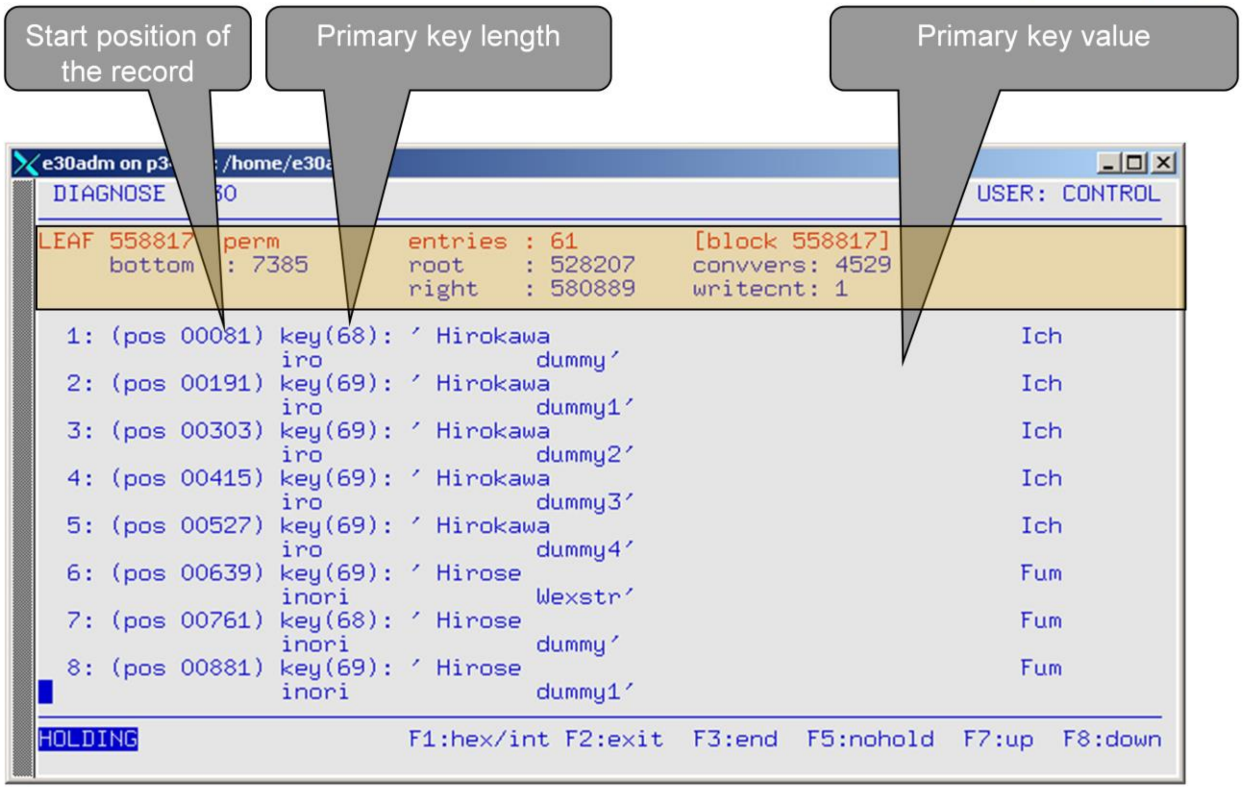
```
e30adm on p3      :/home/e30a
 DIAGNOSE      30                                            USER: CONTROL
NODE 542357   level 1      rm   sorted   entries : 103   [block     357]
     bottom    : 7725          root     : 528207     convvers: 4
                               right    : 484215     writecnt: 1
  1: (pos 00081) -> 527530 #0 sep(69): ' Hilgenhaus
                                        Wolfgang                dummy3'
  2: (pos 00163) -> 580885 #0 sep(69): ' Hillebrand
                                        Hartmut                 dummy3'
  3: (pos 00245) -> 516217 #0 sep(69): ' Hilmen
                                        Douglas                 dummy4'
  4: (pos 00327) -> 559579 #0 sep(64): ' Hinderer
                                        Harald                  d'
  5: (pos 00403) -> 483929 #0 sep(69): ' Hinterberger
                                        Franz                   dummy1'
  6: (pos 00485) -> 516699 #0 sep(69): ' Hirai
                                        Shinichiro              dummy3'
  7: (pos 00567) -> 558817 #0 sep(64): ' Hirokawa
                                        Ichiro                  d'
  8: (pos 00643) -> 580889 #0     (69): ' Hirschenberger
                                        Stefan                  dummy1'
HOLDING                        F1:h                   F5:    hold  F7:up   F8:down
```

This page is an index page of level 1. The separators refer to pages of the leaf level.

The header contains the known root page. It is checked with each access.

The page has 103 entries, sorted.

## Example Leaf Level I

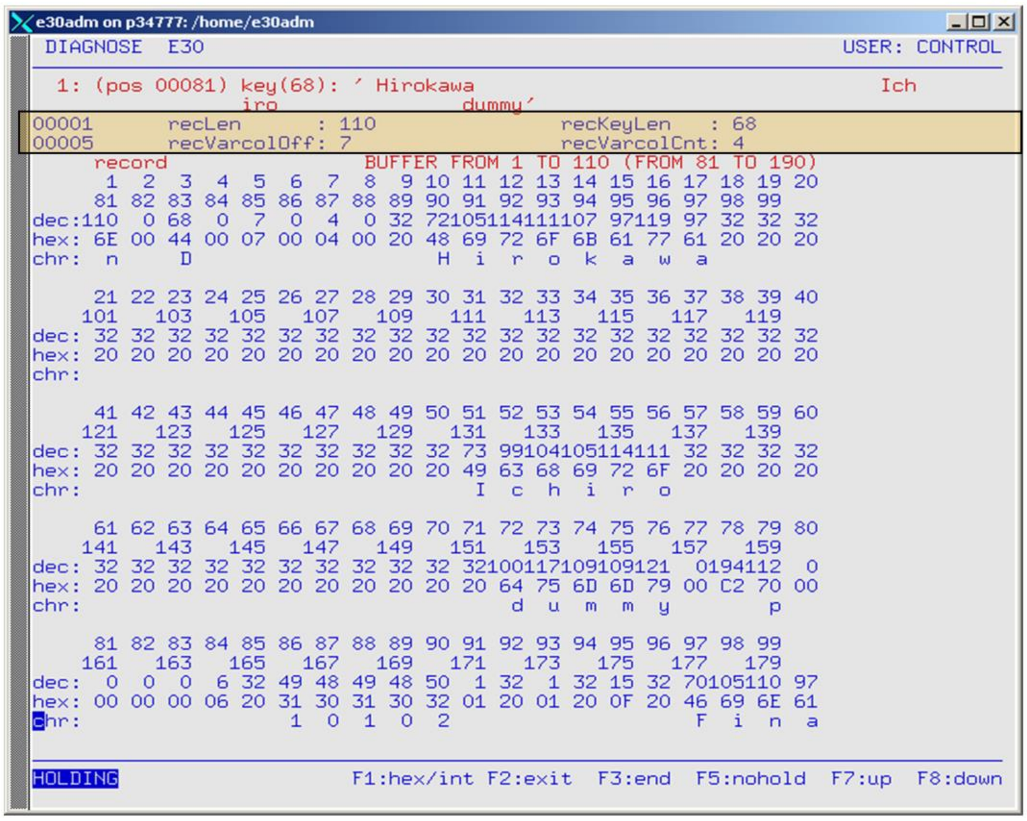


```
 DIAGNOSE     30                                                USER: CONTROL
LEAF 558817  perm          entries : 61        [block 558817]
     bottom   : 7385       root    : 528207    convvers: 4529
                           right   : 580889    writecnt: 1
  1: (pos 00081) key(68): ' Hirokawa                                   Ich
                 iro                dummy'
  2: (pos 00191) key(69): ' Hirokawa                                   Ich
                 iro                dummy1'
  3: (pos 00303) key(69): ' Hirokawa                                   Ich
                 iro                dummy2'
  4: (pos 00415) key(69): ' Hirokawa                                   Ich
                 iro                dummy3'
  5: (pos 00527) key(69): ' Hirokawa                                   Ich
                 iro                dummy4'
  6: (pos 00639) key(69): ' Hirose                                     Fum
                 inori              Wexstr'
  7: (pos 00761) key(68): ' Hirose                                     Fum
                 inori              dummy'
  8: (pos 00881) key(69): ' Hirose                                     Fum
                 inori              dummy1'
HOLDING                   F1:hex/int F2:exit  F3:end  F5:nohold  F7:up  F8:down
```

In this example the diagnosis tool displays only the primary key values.

This page has 61 entries. The last record ends at position 7385.

## Example Leaf Level II



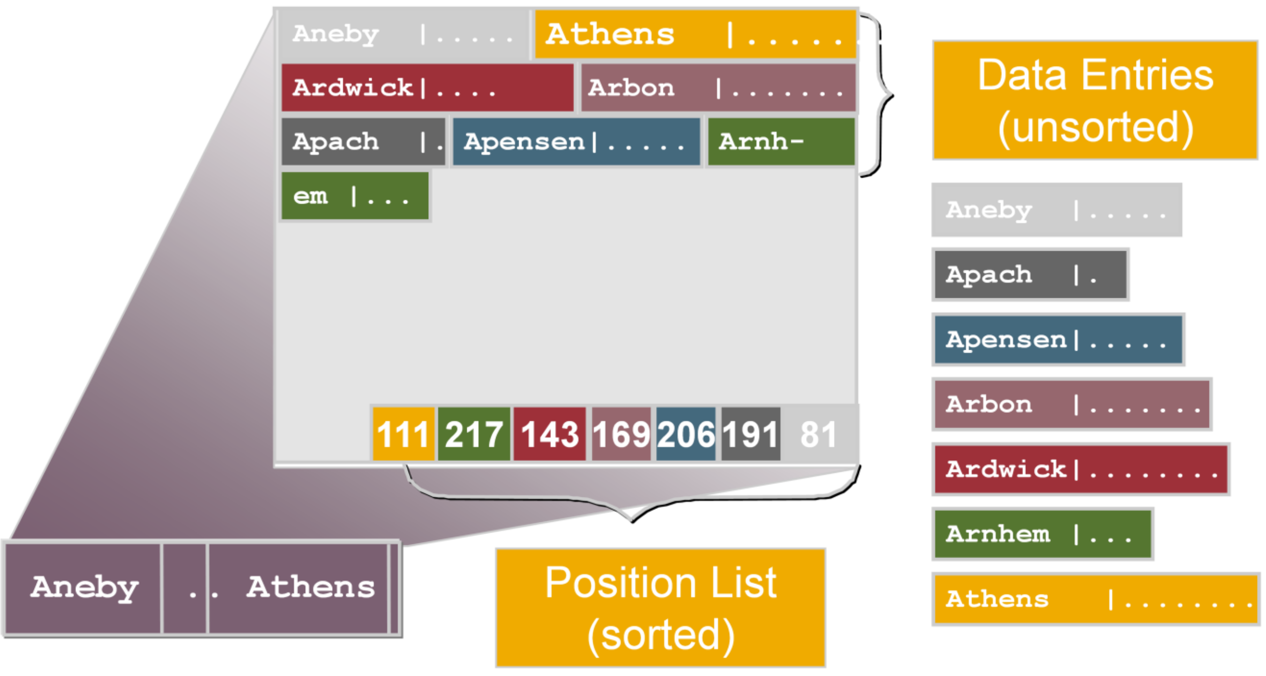
```
e30adm on p34777: /home/e30adm
 DIAGNOSE   E30                                              USER: CONTROL

  1: (pos 00081) key(68): ' Hirokawa                                 Ich
                  iro                dummy'
00001        recLen       : 110                 recKeyLen    : 68
00005        recVarcolOff: 7                    recVarcolCnt: 4
     record                   BUFFER FROM 1 TO 110 (FROM 81 TO 190)
      1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20
     81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
dec:110  0 68  0  7  0  4  0 32 72105114111107 97119 97 32 32 32
hex: 6E 00 44 00 07 00 04 00 20 48 69 72 6F 6B 61 77 61 20 20 20
chr:  n     D                    H  i  r  o  k  a  w  a

     21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
    101   103   105   107   109   111   113   115   117   119
dec: 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32 32
hex: 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20 20
chr:

     41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
    121   123   125   127   129   131   133   135   137   139
dec: 32 32 32 32 32 32 32 32 32 32 73 99104105114111 32 32 32 32
hex: 20 20 20 20 20 20 20 20 20 20 49 63 68 69 72 6F 20 20 20 20
chr:                                I  c  h  i  r  o

     61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
    141   143   145   147   149   151   153   155   157   159
dec: 32 32 32 32 32 32 32 32 32 32 32100117109109121  0194112  0
hex: 20 20 20 20 20 20 20 20 20 20 20 64 75 6D 6D 79 00 C2 70 00
chr:                                   d  u  m  m  y        p

     81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99
    161   163   165   167   169   171   173   175   177   179
dec:  0  0  0  6 32 49 48 49 48 50  1 32  1 32 15 32 70105110 97
hex: 00 00 00 06 20 31 30 31 30 32 01 20 01 20 0F 20 46 69 6E 61
chr:                 1  0  1  0  2                    F  i  n  a

HOLDING                  F1:hex/int F2:exit  F3:end  F5:nohold  F7:up  F8:down
```

This graphic shows the first 100 bytes of the first record of page 558817.

Each record begins with a header. This contains the length of the record, the length of the primary key value, the relative start position of the first variable-length value (e.g. VARCHAR) and the number of variable-length fields.

On this page the record begins on page 81. The primary key begins within the record at position 10.

## Contents of a Data Page

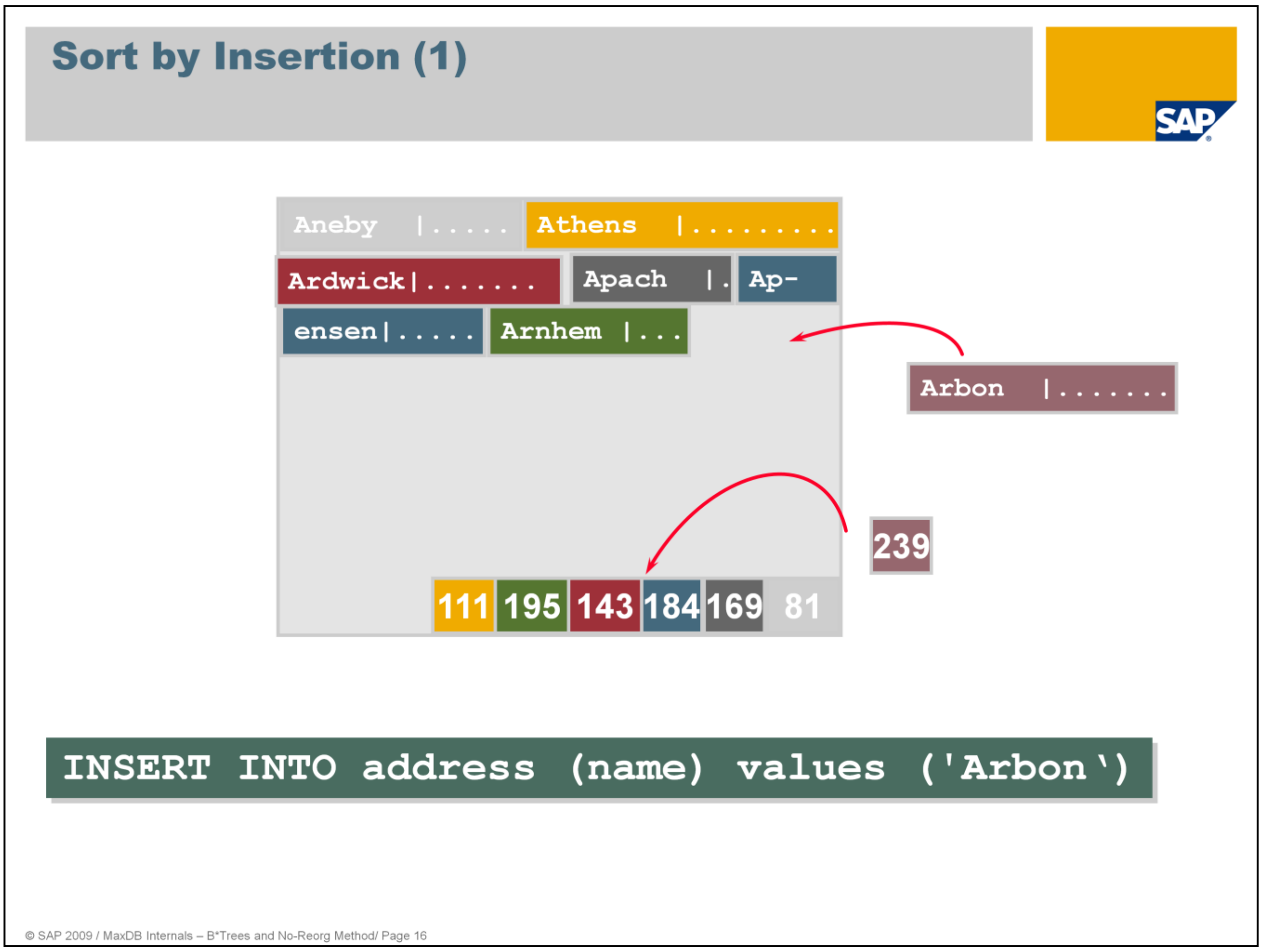


The data records are located unsorted in the start area of the target page.

In the end area of the data page, there is a position list that refers to the individual records of the data page. This address list is arranged so that in the case of sequential access via the position list, the data entries can be read sorted.

The database system searches the remaining entries and ultimately returns the requested table row.

The position list and the data record entries start at opposite corners of the page and grow towards each other.



## Sort by Insertion (1)

```
INSERT INTO address (name) values ('Arbon')
```

If a record is to be inserted into the database or edited, MaxDB first searches for the data page that is changed by the action. This is true for all the actions described in the following. Then, if necessary, the required space is made available by way of clearing operations.

**sort by insertion**

The records are:

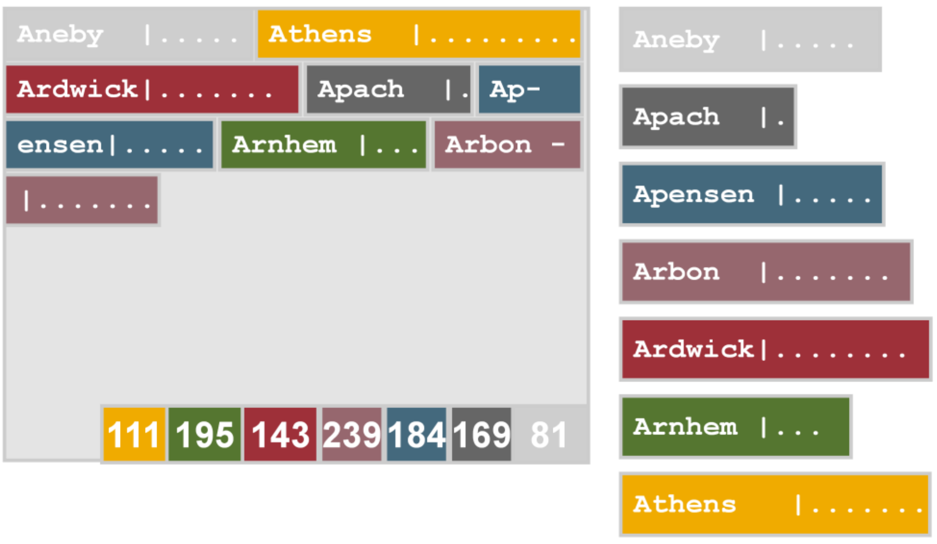
- inserted into the target page at the end of the used data area,
- sorted in the position list via an entry that, in order to minimize the number of moved bytes, contains only references to records.

The records in the data part are only sorted if a clearing operation becomes necessary. If a data page is moved into another one, a sorted block is advantageous as this makes it possible to move whole groups of records rather than copying record by record.

MaxDB data pages are organized such that the data area grows into the page from the beginning and the sorting list from the end.

Let's assume that the record fits on the page. MaxDB simply puts it at the end of the area available on the page...

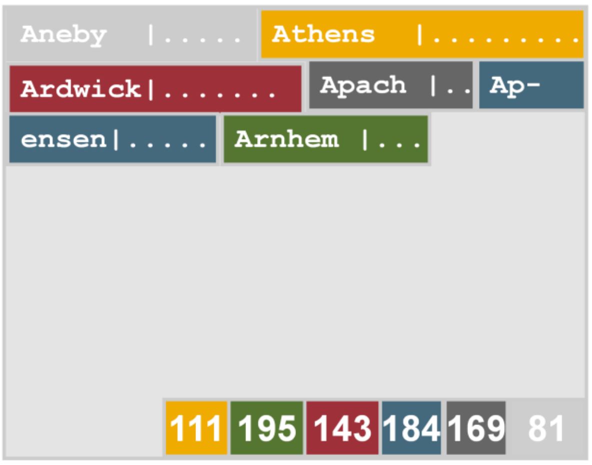
## Sort by Insertion (2)



```
INSERT INTO address (name) values ('Arbon')
```

... and then the position list is updated. The address of the new entry is written at the correct position in the position list. In our case, the correct position is position 4, which accordingly points to the seventh data record, '`Arbon`'.

## Update in Place (1)

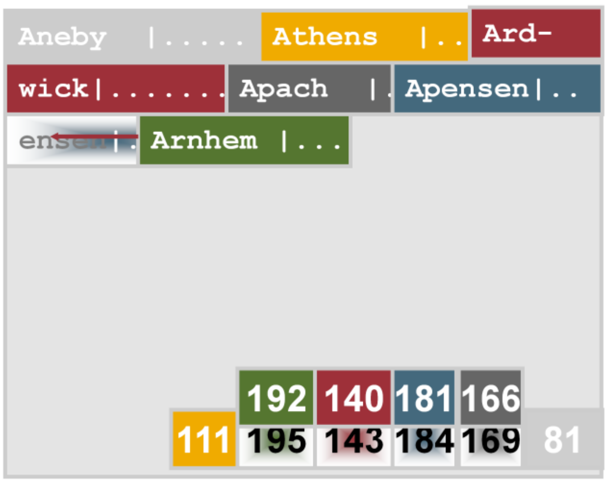


```
UPDATE address
SET street = 'AKROPOLIS 1'
KEY city = 'Athens'
```

update in place

- Records are changed directly on the target page.
- Case 1: length and key remain unchanged.
  If an UPDATE occurs and the separator is unchanged, the contents of the row are changed directly.
- Case 2: the key changes.
  If changes have been made to a key field, the UPDATE is converted into a DELETE with subsequent INSERT. If necessary, clearing operations are carried out.

## Update in Place (2)

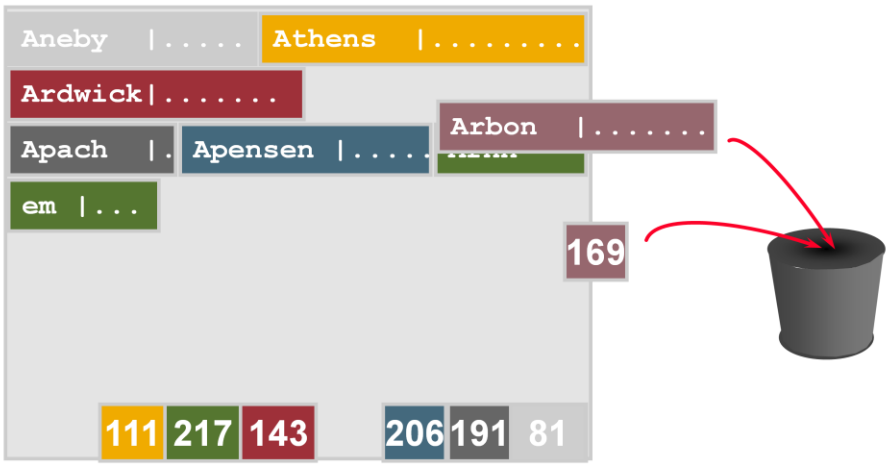


```
UPDATE address
SET street = 'Olymp 27'
KEY city = 'Athens'
```

- Case 3: The length is changed, the key remains unchanged.
  The contents of the row are changed directly, but the position of the subsequent entries is different. Thus the subsequent records need to be moved and the address information (of the subsequent records) adjusted in the position list. If necessary, clearing operations are carried out.

If it is necessary to change the tree structure, first the required space is made available by way of B* tree clearing operations or by inserting a new block; then the UPDATE is carried out as described.

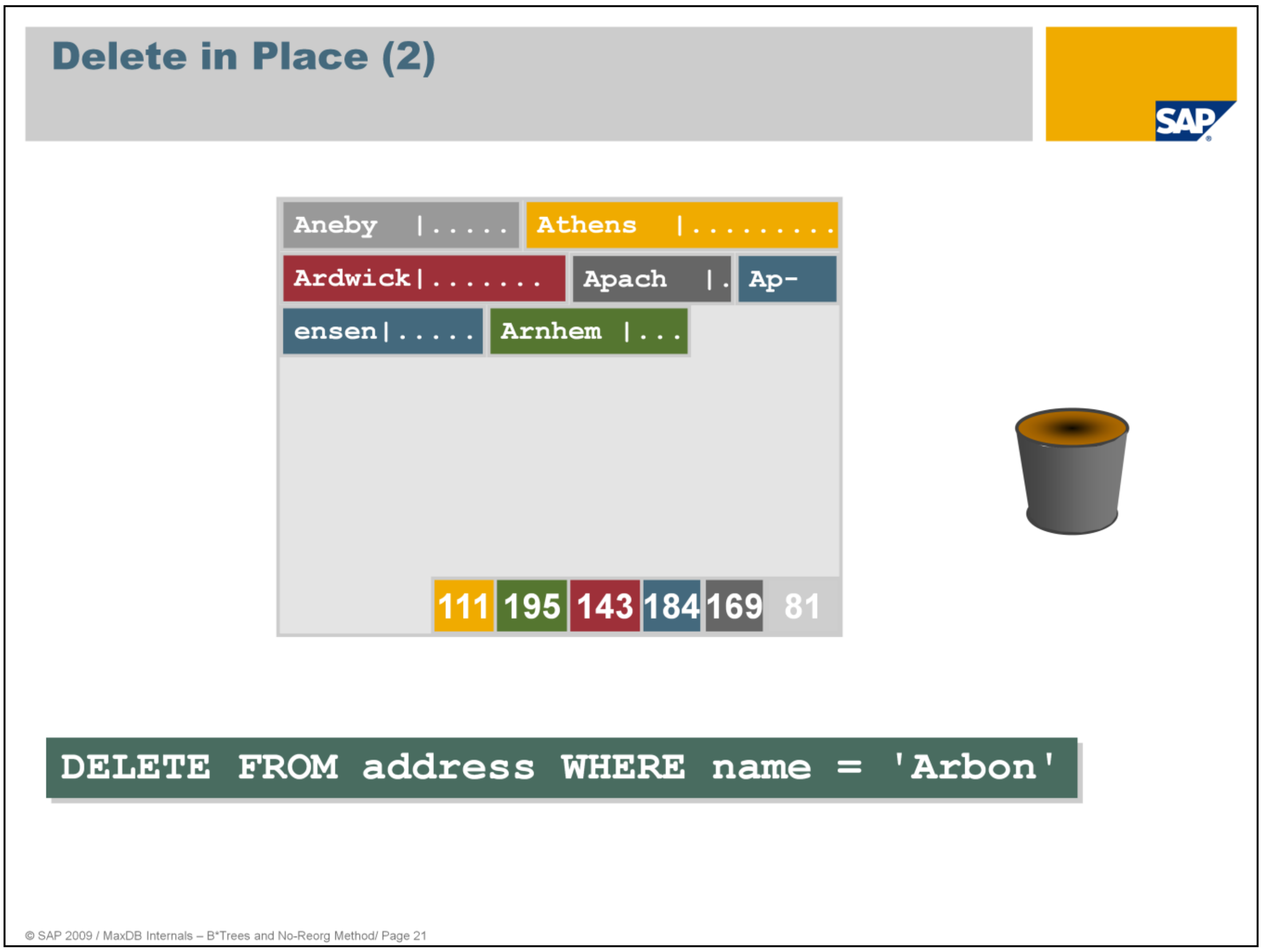
## Delete in Place (1)



```
DELETE FROM address WHERE name = 'Arbon'
```

### delete in place

- Records are changed directly on the target page.
- The positions in the sorting list must be changed on the target page for all physically subsequent records
- If a certain usage level is not reached, a B* tree clearing operation is carried out



## Delete in Place (2)

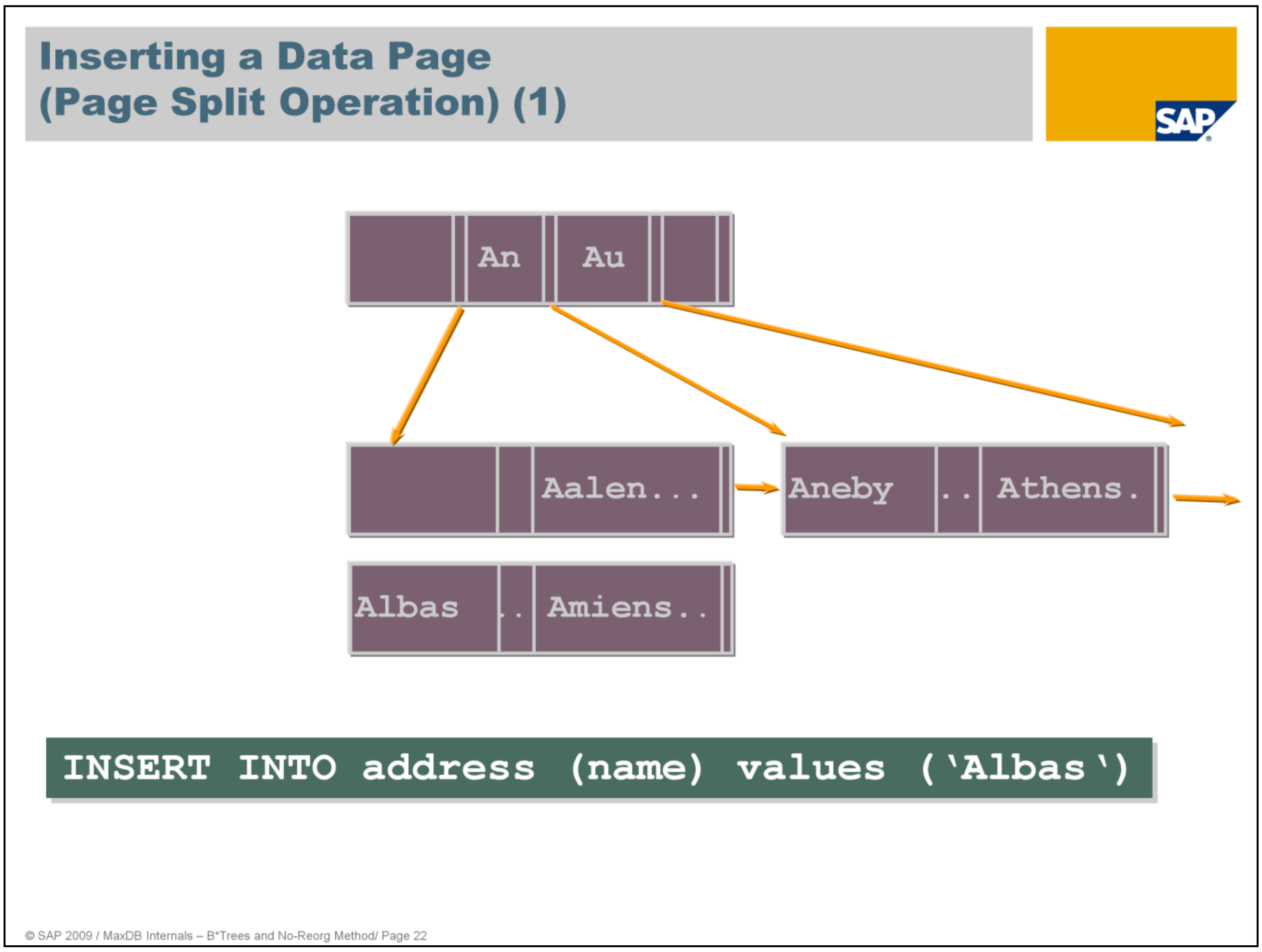
```
DELETE FROM address WHERE name = 'Arbon'
```

The records and the position list on the page are re-arranged so that the storage space used is contiguous.

All changes to pages are executed in the main memory. That makes them very fast, but also CPU-intensive.

If the fill level of a page falls below a certain mark, the tree structure is rearranged. An example of such a rearrangement will be shown later.

MaxDB offers the possibility of applying the attribute DYNAMIC to tables. Only very simplified clearing operations are carried out on these tables. Such tables require more space, but they offer noticeably higher performance. This attribute is suited to tables that are highly dynamic, in particular through random accesses and large fluctuations in the size of the table.



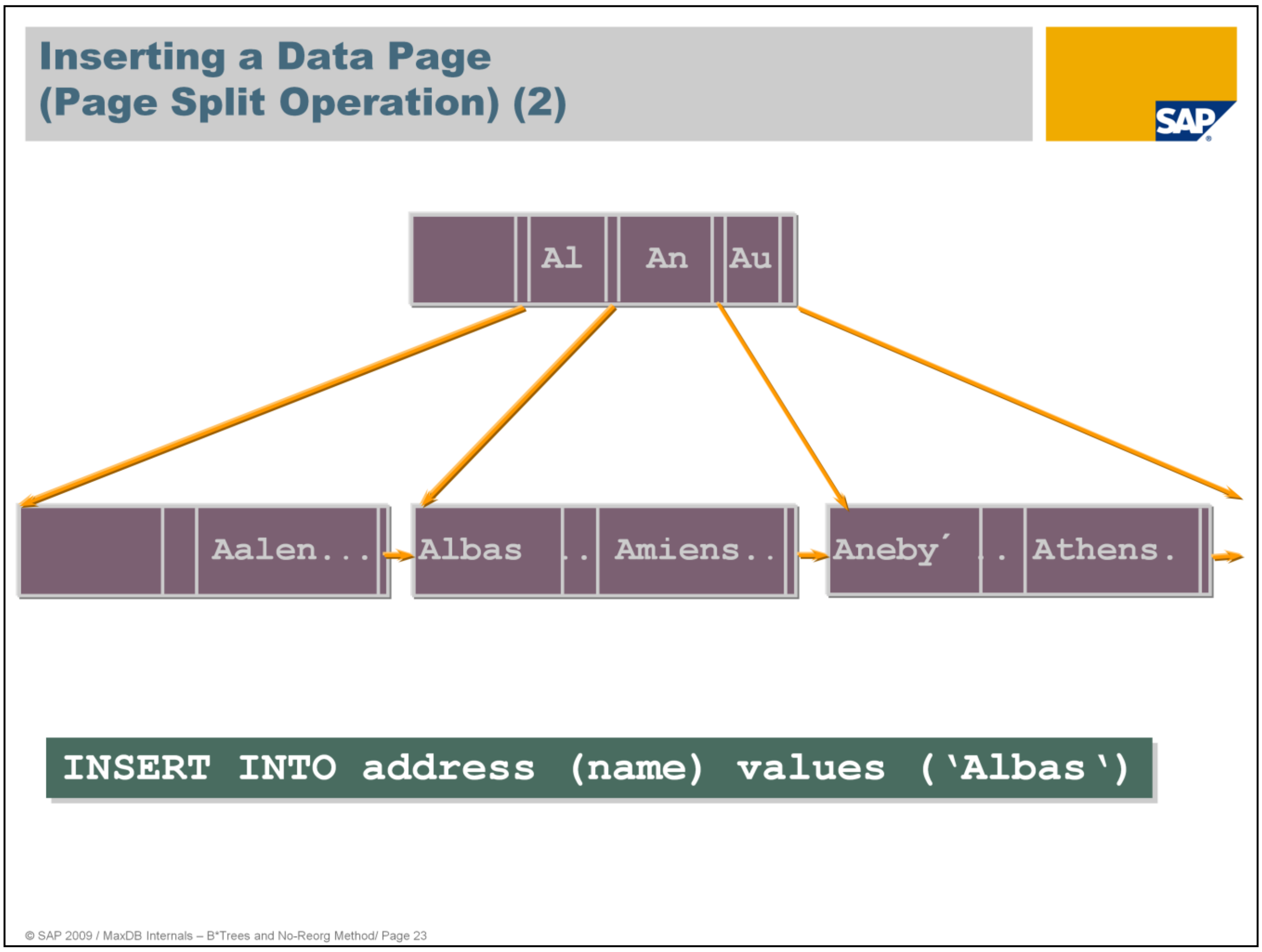
## Inserting a Data Page (Page Split Operation) (1)

```
INSERT INTO address (name) values ('Albas')
```

Now let's have a look at a simple change to the tree structure.

Let's assume that, due to an INSERT, the new data record no longer fits on the corresponding page.

A new page is then created on which the new record and half of the data records from the page that was too small for the INSERT are written. The respective records on the original page are then deleted.



## Inserting a Data Page (Page Split Operation) (2)

`INSERT INTO address (name) values ('Albas')`

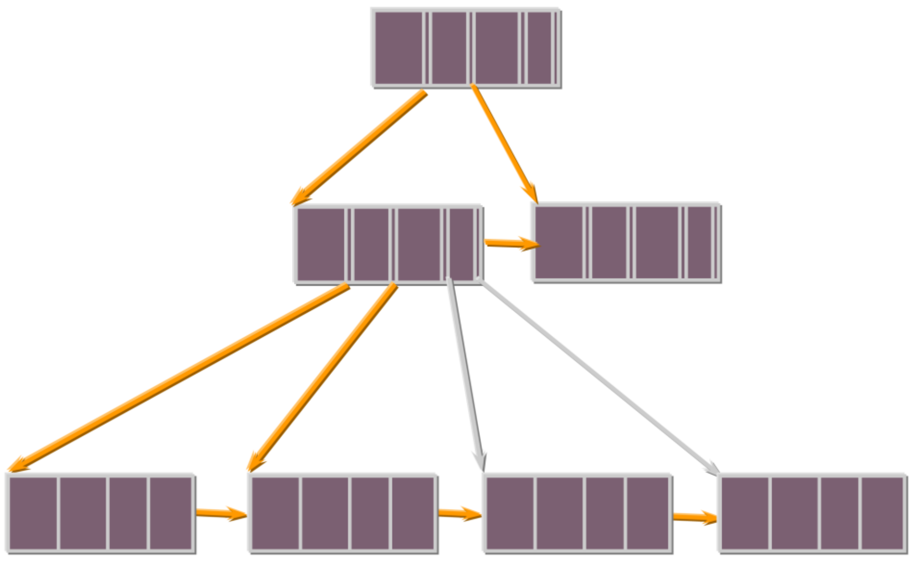
If necessary, the database system updates the pointers to the following pages.

In addition, the address and separator information for the new page is entered in the B* index page above it.

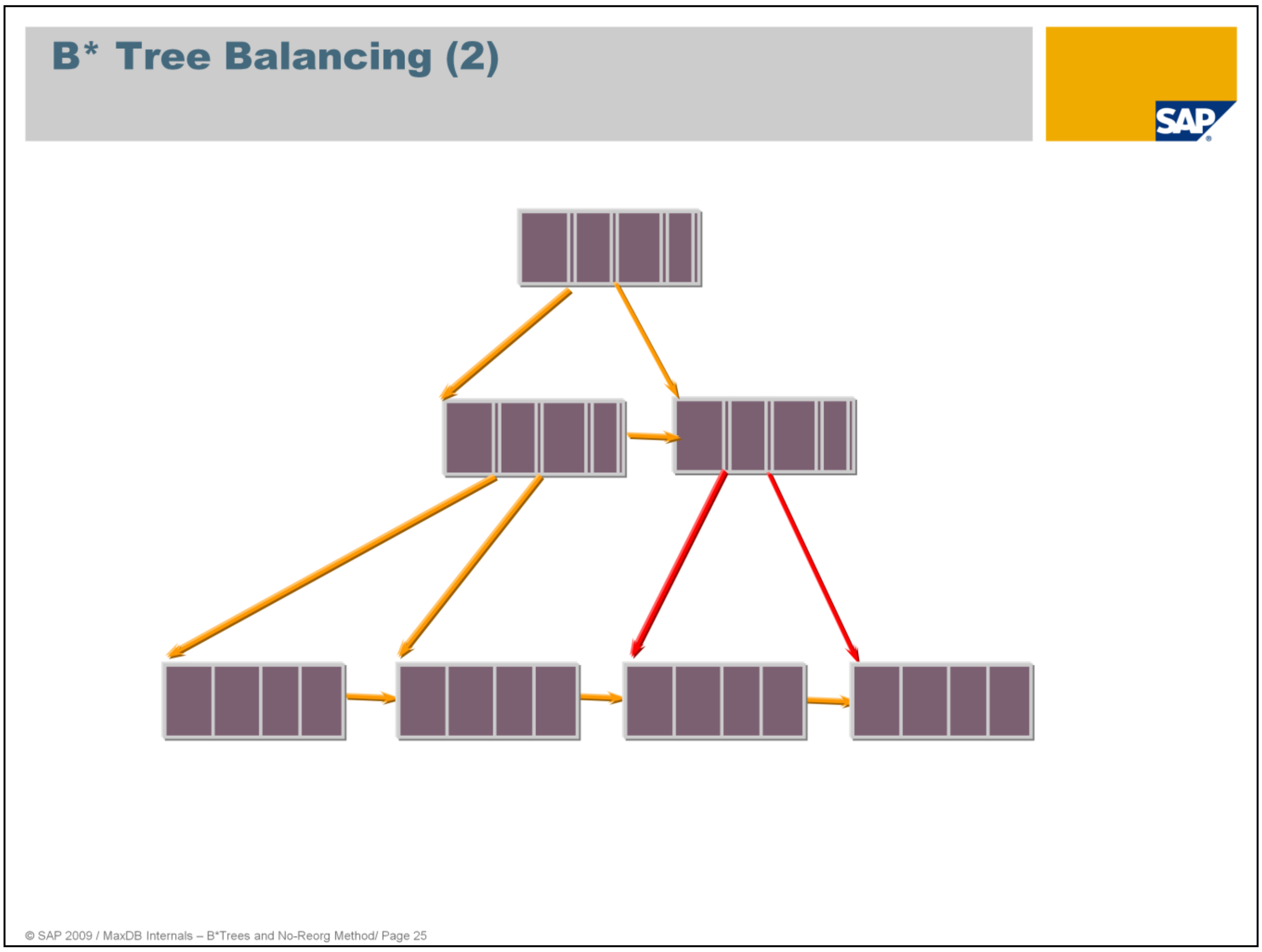
If this also does not fit on the B* index page, a new page has to be inserted.

If the B* tree is no longer able to accept the new page, that is, even in the root page there is no more space available in which to insert a new branch, the entire B* tree has to be expanded by a new level.

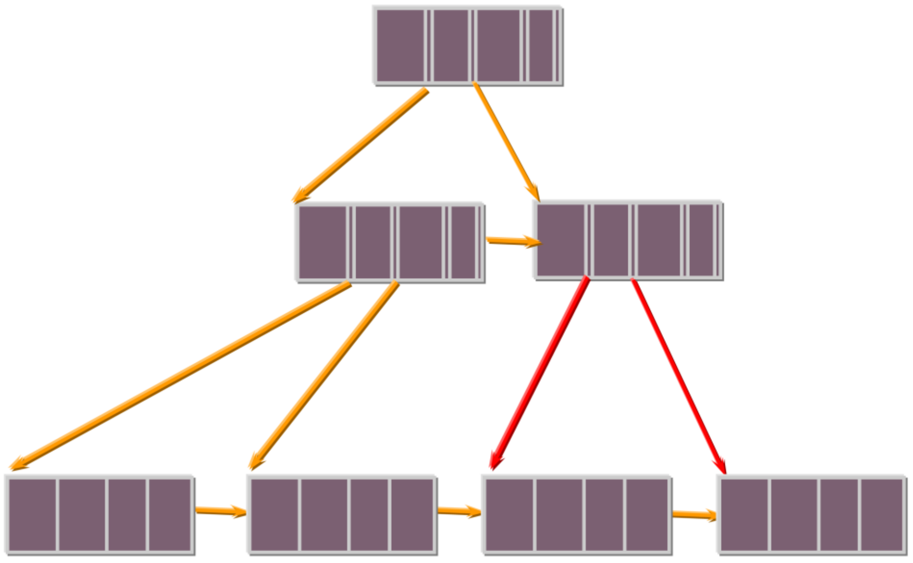
## B* Tree Balancing (1)



If the distribution of pages in the B* tree is unbalanced, that is, if there is an inordinate amount of pages on certain branches of the tree,...

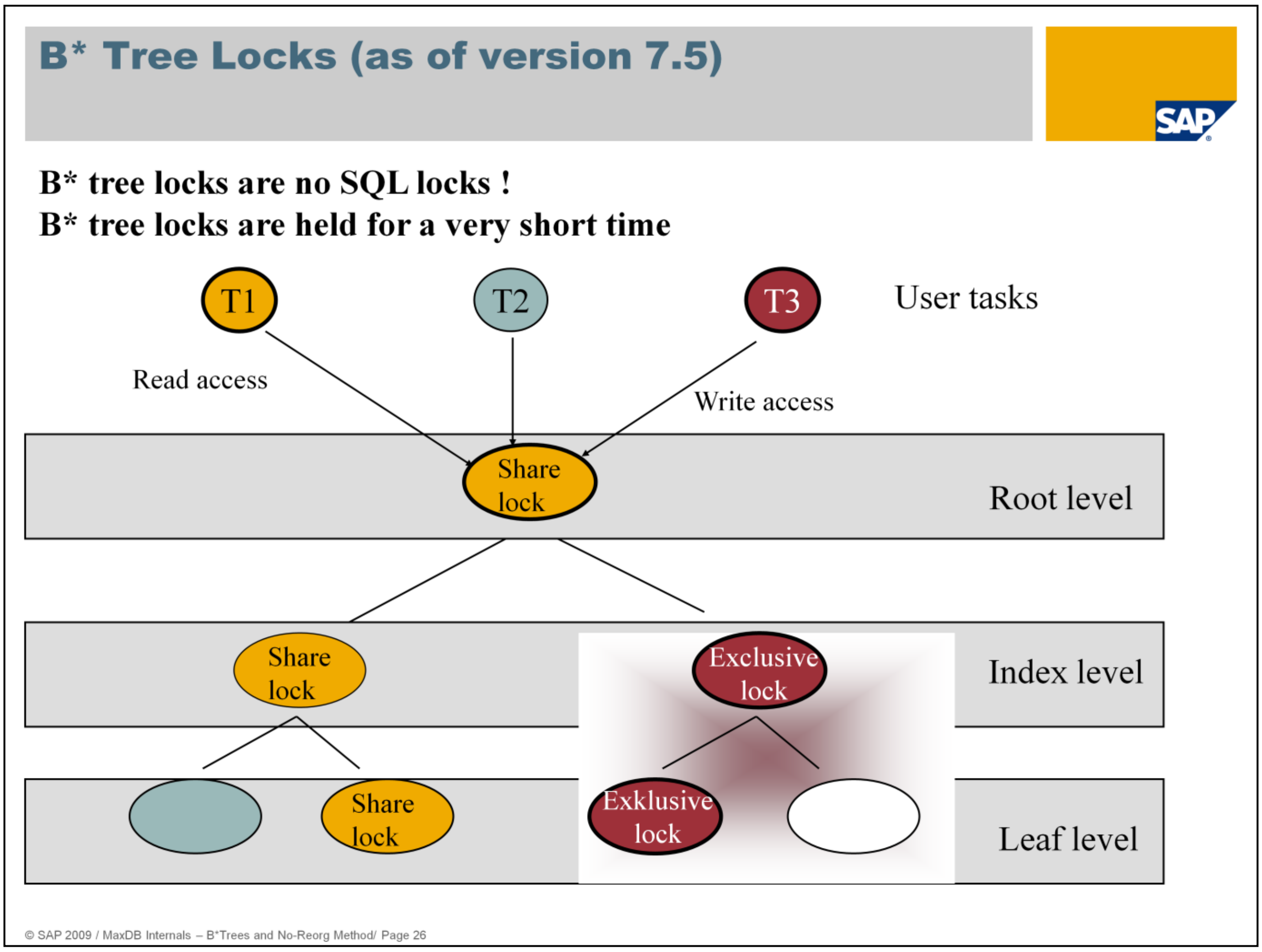


## B* Tree Balancing (2)



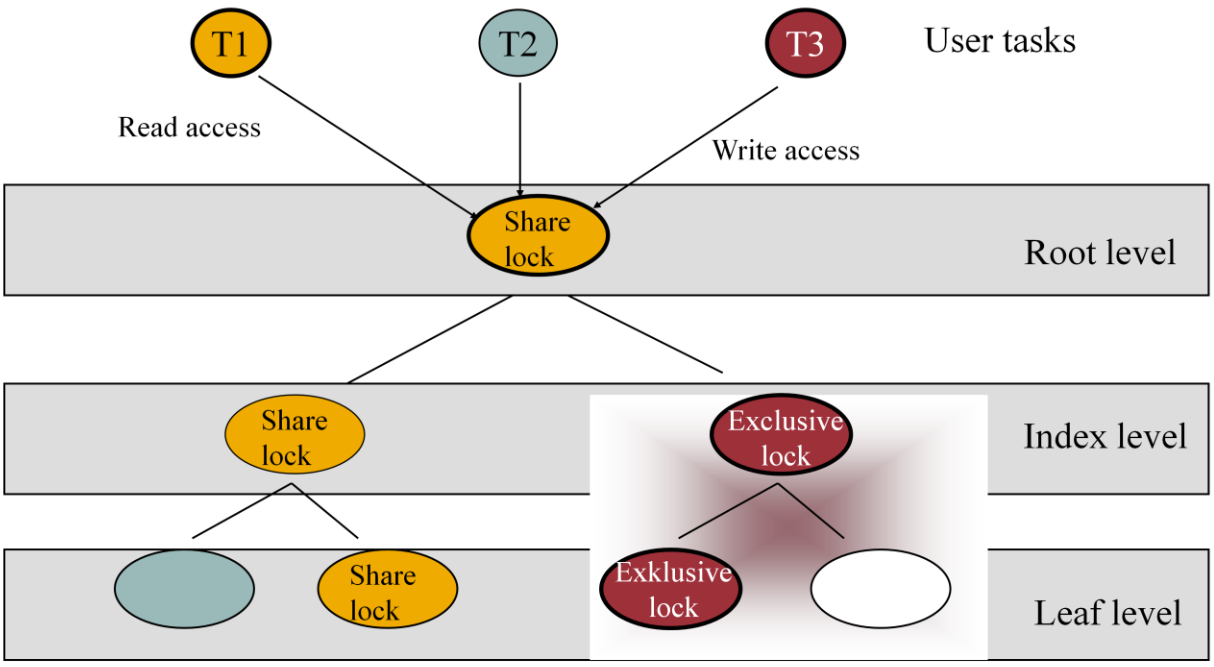
performance suffers because, on average, more accesses are needed to find data records.

Such states are recognized by MaxDB when INSERTs, UPDATEs and DELETEs are processed and the tree is rearranged in the affected subareas. This procedure is known as balancing. This involves moving records back and forth between pages in order to achieve the highest possible utilization of the pages.



## B* Tree Locks (as of version 7.5)

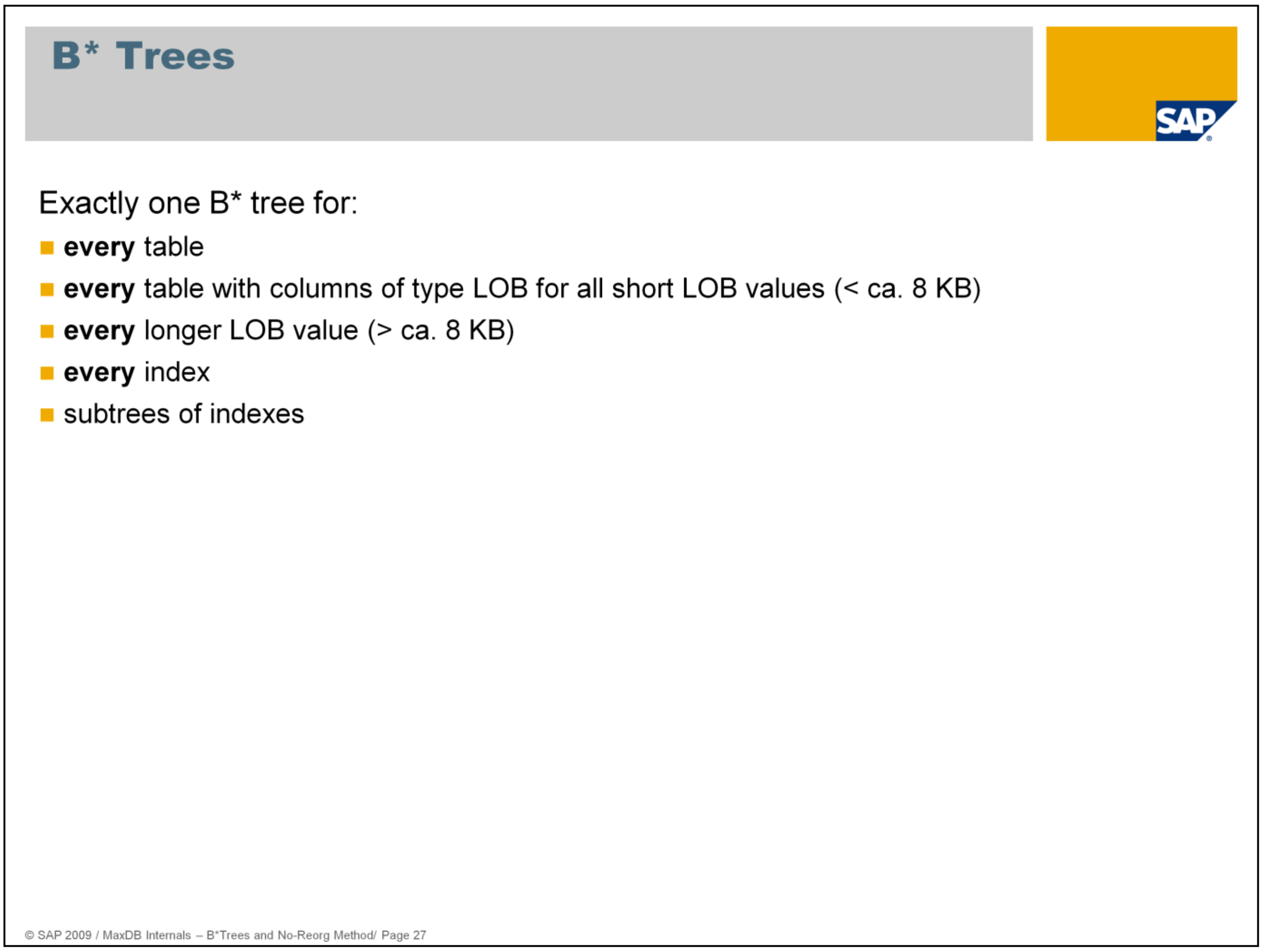
**B* tree locks are no SQL locks !**
**B* tree locks are held for a very short time**



Each time a B* tree is accessed, the respective page must be locked. As of version 7.5, these locks are no longer managed in separate lock lists but rather directly in the data cache. A lock is requested when the desired page in the data cache is accessed.

**Advantages as compared with the lock concept in versions 7.3 and 7.4:** a significant characteristic, and thus also the biggest disadvantage of the old concept, was that the locks for the pages B* tree were managed in a separate component, the so-called tree lock list. Heavy parallel access to the list could lead to collisions.

**Check Data / Check Table (VERIFY):** In contrast to the SAP DB Versions 7.3 and 7.4, from version 7.5 this new concept makes it possible to execute change operations on the B* trees in parallel with Check Data or Check Table.



## B* Trees

Exactly one B* tree for:

- **every** table
- **every** table with columns of type LOB for all short LOB values (< ca. 8 KB)
- **every** longer LOB value (> ca. 8 KB)
- **every** index
- subtrees of indexes

MaxDB uses B* tree structures for the storage of all its tables.

The term "table" includes:

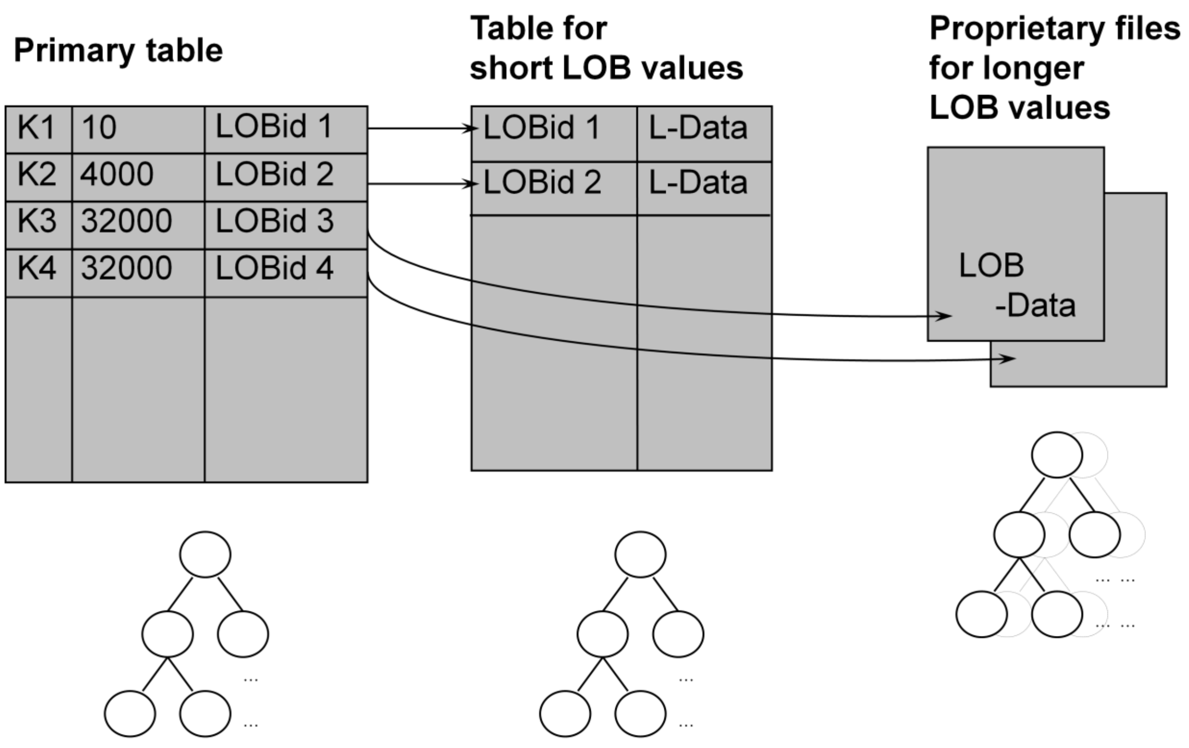
- Primary data, including the associated LOB data (LOB Large Object)
- Secondary data as required for single and multiple secondary keys.

A MaxDB table always has a primary key. This is either a user-defined key or a generated internal key. A user-defined key can be comprised of several columns (multiple key).

The user can define additional secondary keys, which can also consist of one (single index) or several (multiple index) columns.

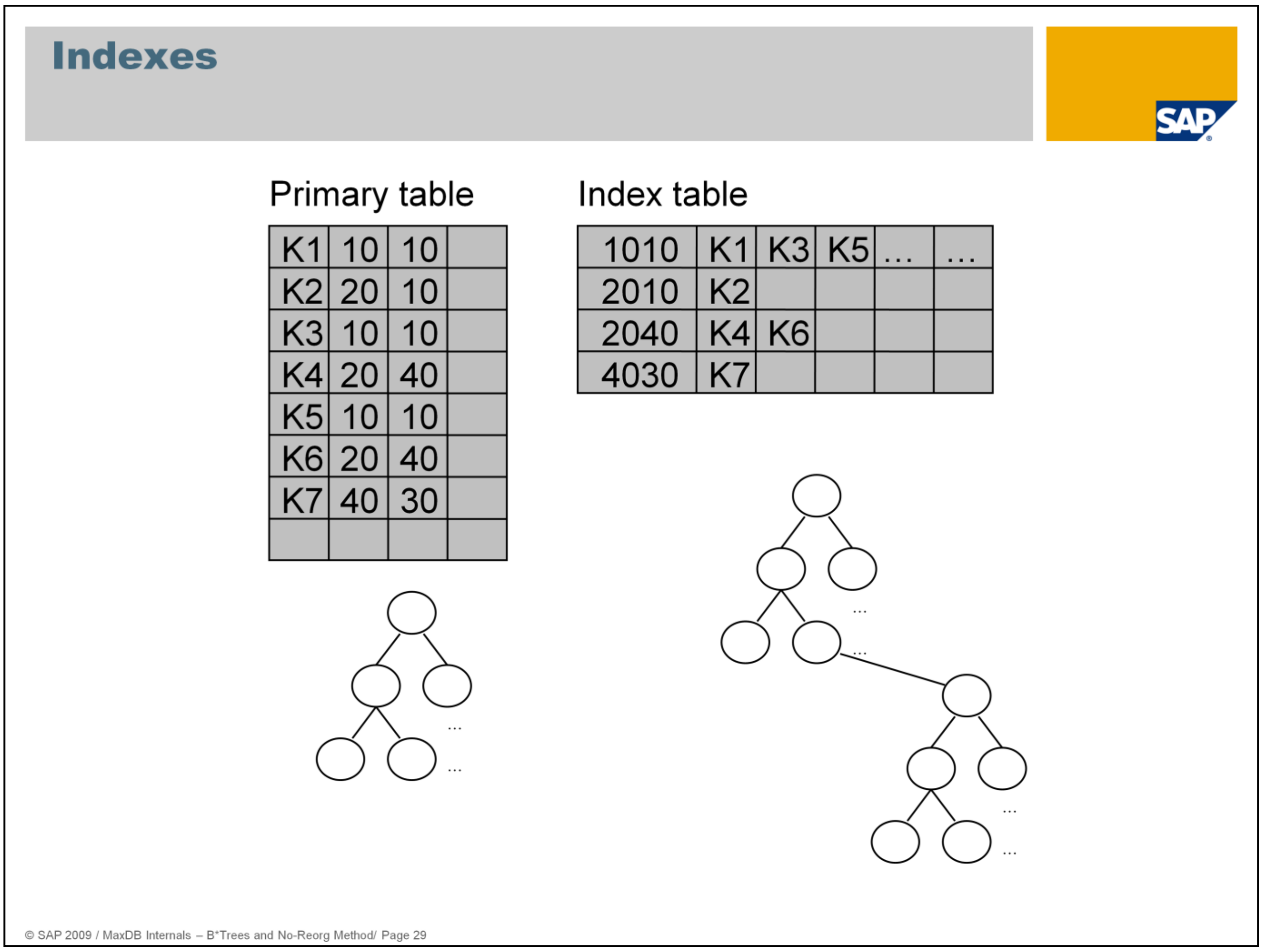
There is exactly ***one*** B* tree for the primary data of a table and also precisely ***one*** B* tree for each defined index (also known as: secondary key). If a table is defined with LOB columns, **one** additional B* tree is created for the purpose of accepting the LOB values in these columns that do not exceed a certain length. If LOB values are longer than this defined value, a new B* tree is created for every single one of these values.

## LOB Columns (Large Objects)



This illustration shows a table with a LOB column. The number column represents the length of the LOB values. There is a B* tree for primary data, a B* tree for the shorter LOB values and *n* B* trees for *n* longer LOB values.

Irrespective of their length, for LOB values the primary table always has a single entry of a fixed length which refers to the respective storage structure.



## Indexes

Primary table

| | | | |
|---|---|---|---|
| K1 | 10 | 10 | |
| K2 | 20 | 10 | |
| K3 | 10 | 10 | |
| K4 | 20 | 40 | |
| K5 | 10 | 10 | |
| K6 | 20 | 40 | |
| K7 | 40 | 30 | |
| | | | |

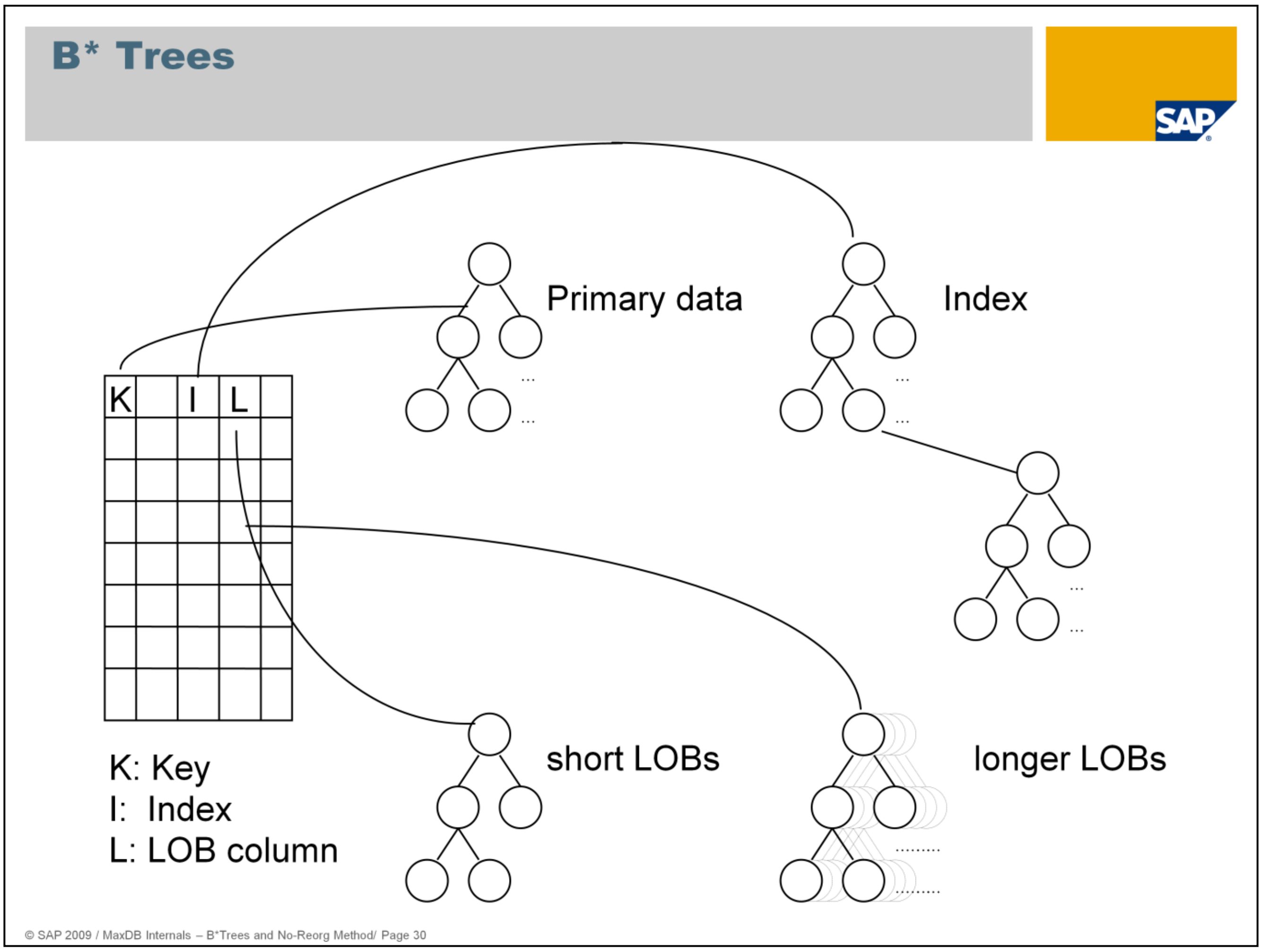
Index table

| | | | | | |
|---|---|---|---|---|---|
| 1010 | K1 | K3 | K5 | … | … |
| 2010 | K2 | | | | |
| 2040 | K4 | K6 | | | |
| 4030 | K7 | | | | |

This illustration shows an example of a table with a secondary key defined for multiple fields (2 fields). There is one B* tree for the primary data and a second B* tree for the indexed data.

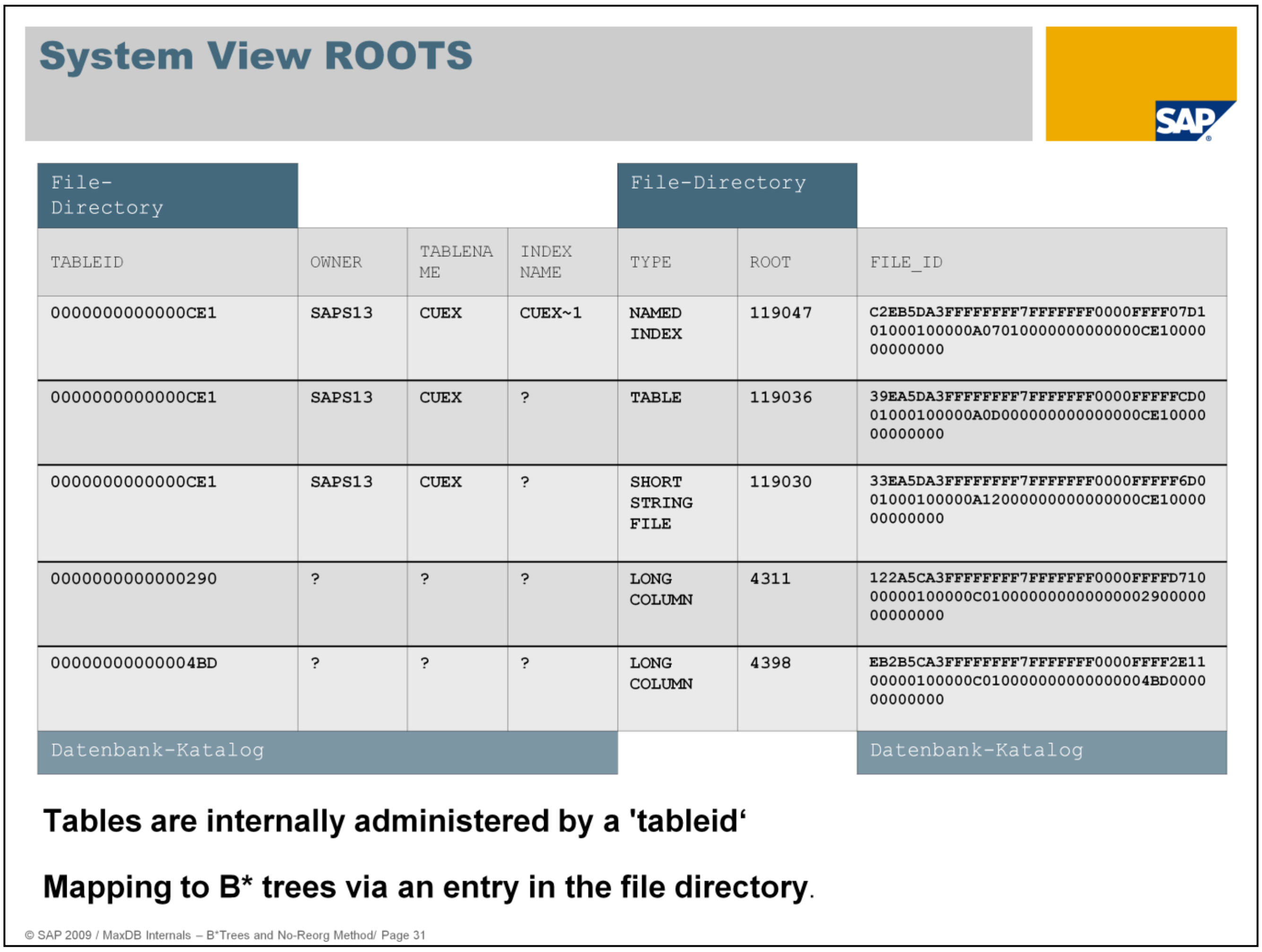
The B* index is not to be confused with the term index as it is commonly used for secondary key definitions!

If the primary key values for a secondary key value cannot be contained on one data page, MaxDB stores the primary key values, sorted, in a separate B* tree. This means that the size of the secondary key tree can be significantly decreased.



## B* Trees

This illustration, taking the example of a table that contains LOBs and for which a secondary key has been defined, depicts how the assignment to B* tree structures works.



## System View ROOTS

| File-Directory | | | | File-Directory | | |
|---|---|---|---|---|---|---|
| TABLEID | OWNER | TABLENAME | INDEX NAME | TYPE | ROOT | FILE_ID |
| 0000000000000CE1 | SAPS13 | CUEX | CUEX~1 | NAMED INDEX | 119047 | C2EB5DA3FFFFFFFF7FFFFFFF0000FFFF07D1 01000100000A070100000000000000CE10000 00000000 |
| 0000000000000CE1 | SAPS13 | CUEX | ? | TABLE | 119036 | 39EA5DA3FFFFFFFF7FFFFFFF0000FFFFFCD0 01000100000A0D0000000000000000CE10000 00000000 |
| 0000000000000CE1 | SAPS13 | CUEX | ? | SHORT STRING FILE | 119030 | 33EA5DA3FFFFFFFF7FFFFFFF0000FFFFF6D0 01000100000A120000000000000000CE10000 00000000 |
| 0000000000000290 | ? | ? | ? | LONG COLUMN | 4311 | 122A5CA3FFFFFFFF7FFFFFFF0000FFFFD710 00000100000C010000000000000002900000 00000000 |
| 00000000000004BD | ? | ? | ? | LONG COLUMN | 4398 | EB2B5CA3FFFFFFFF7FFFFFFF0000FFFF2E11 00000100000C0100000000000000004BD0000 00000000 |
| Datenbank-Katalog | | | | | | Datenbank-Katalog |

**Tables are internally administered by a 'tableid'**

**Mapping to B* trees via an entry in the file directory.**

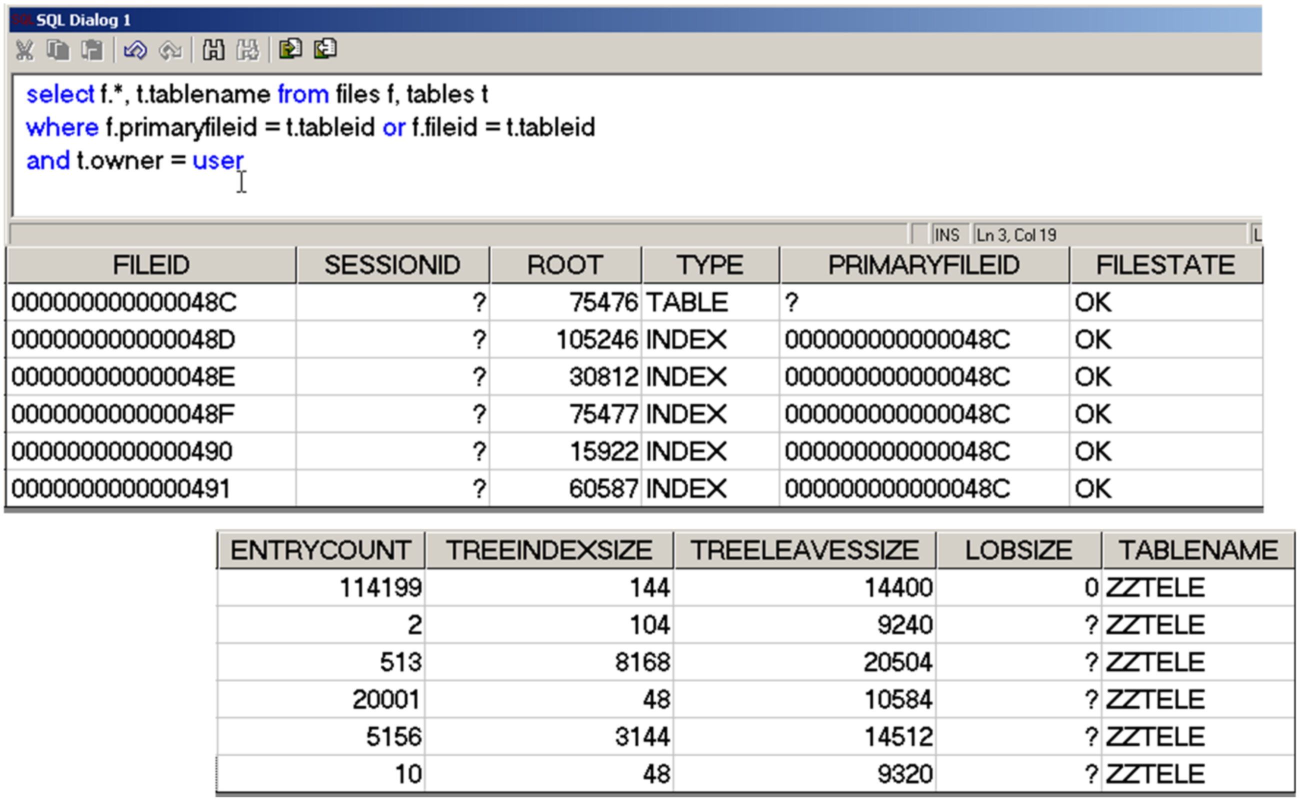
A table, which is known to the user by a name, is internally administered with a ‘tableid’. The correlation between the names and **tableid**s is registered in the database system dictionary (catalog).

There is also the database **file directory**, which contains the assignments of the root nodes of the B* trees to the tableids of the database objects. The tableids are stored in the file directory along with a type flag which indicates what contents the underlying B* tree has.

Thus a single tableid, in combination with the type flag, can be used to administer a table with all its associated B* tree entries in the file directory.

The system table ROOTS contains information from the file directory and the database catalog.

## System View FILES



SQL Dialog 1

```
select f.*, t.tablename from files f, tables t
where f.primaryfileid = t.tableid or f.fileid = t.tableid
and t.owner = user
```

INS Ln 3, Col 19

| FILEID | SESSIONID | ROOT | TYPE | PRIMARYFILEID | FILESTATE |
|---|---|---|---|---|---|
| 000000000000048C | ? | 75476 | TABLE | ? | OK |
| 000000000000048D | ? | 105246 | INDEX | 000000000000048C | OK |
| 000000000000048E | ? | 30812 | INDEX | 000000000000048C | OK |
| 000000000000048F | ? | 75477 | INDEX | 000000000000048C | OK |
| 0000000000000490 | ? | 15922 | INDEX | 000000000000048C | OK |
| 0000000000000491 | ? | 60587 | INDEX | 000000000000048C | OK |

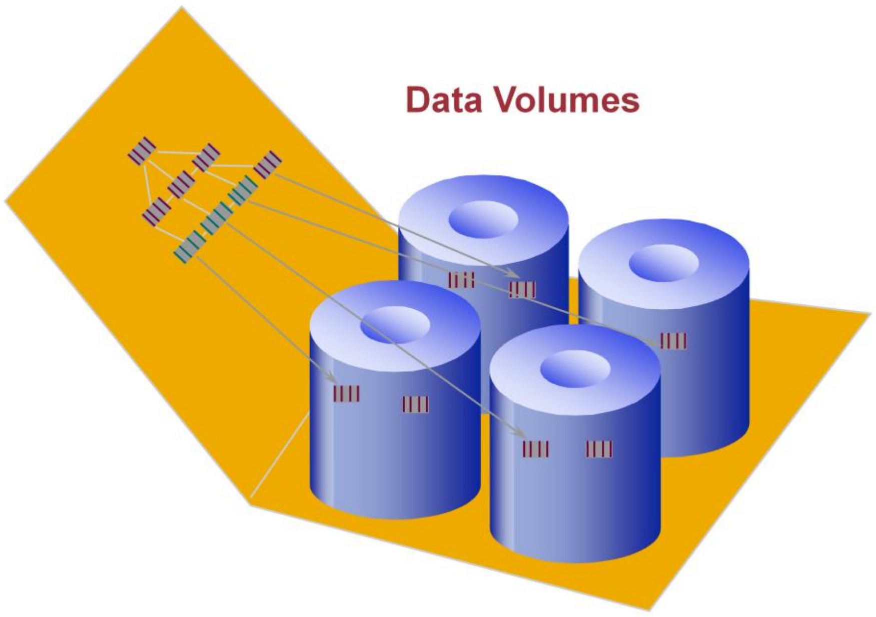
| ENTRYCOUNT | TREEINDEXSIZE | TREELEAVESSIZE | LOBSIZE | TABLENAME |
|---|---|---|---|---|
| 114199 | 144 | 14400 | 0 | ZZTELE |
| 2 | 104 | 9240 | ? | ZZTELE |
| 513 | 8168 | 20504 | ? | ZZTELE |
| 20001 | 48 | 10584 | ? | ZZTELE |
| 5156 | 3144 | 14512 | ? | ZZTELE |
| 10 | 48 | 9320 | ? | ZZTELE |

As of Version 7.6, the FILES system view displays all information in the new file directory.

The user can specify the route to the database catalog in his SQL query. The columns of the FILES view mean the following:

| | |
|---|---|
| FILEID | Corresponds to ID for tables, indexes, etc. in the catalog |
| SESSIONID | Creator session for temporary trees |
| ROOT | Root page number of the B* tree |
| TYPE | TABLE \| INDEX \| FIXED OBJECT \| VARIABLE OBJECT \| KEYED OBJECT \| KEYED OBJECT INDEX \| SHORT COLUMN FILE \| internal file type for temporary files |
| PRIMARYFILEID | FILEID of the B* tree of the table |
| FILESTATE | OK \| DELETED \| BAD \| READ ONLY |
| ENTRYCOUNT | Number of entries in the tree. For indexes, entries in subtrees are not included.<br>NULL: Value was not yet determined for migrated systems. |
| TREEINDEXSIZE | Size of index level in KB |
| TREELEAVESIZE | Size of leaf level in KB |
| LOBSIZE | Size of all BLOB values of the table |

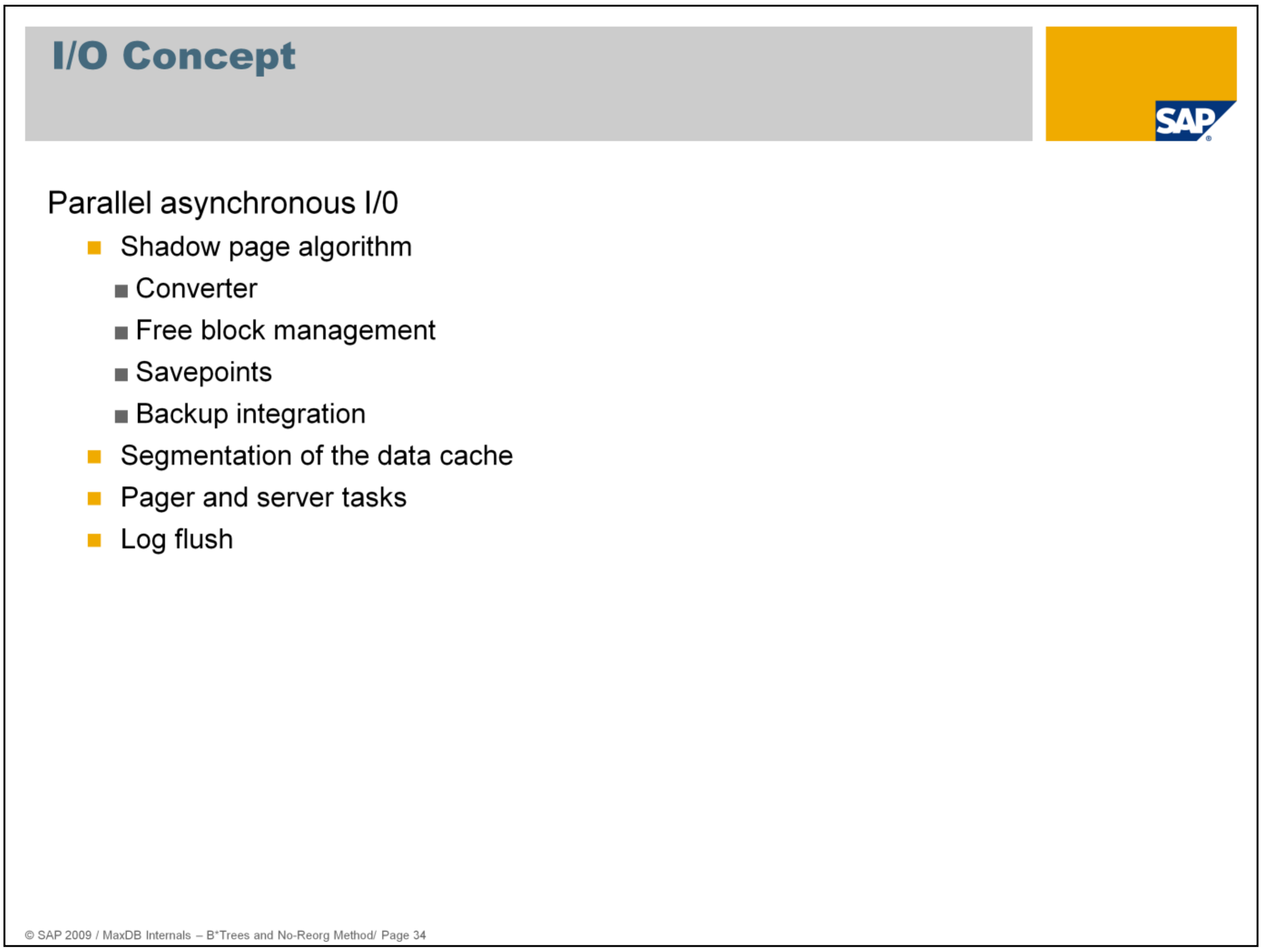
## Disk Striping



An important role in the access performance of the database is playing by the MaxDB striping mechanism, which distributes the data pages evenly on the disks. Additional striping can be performed by the hardware.

Striping guarantees even distribution of the I/O load on the available disks.

Even load balancing of all the data areas in the database also prevents individual data areas from overflowing. A table can be larger than a single data area without the need for maintenance tasks to be carried out.



## I/O Concept

Parallel asynchronous I/0

- Shadow page algorithm
  - Converter
  - Free block management
  - Savepoints
  - Backup integration
- Segmentation of the data cache
- Pager and server tasks
- Log flush

The I/O concept of the database works according to the shadow storage administration principle. The core elements are: optimized support of symmetrical multi-processor systems; the transfer of as many I/Os as possible to asynchronous execution; and highly-optimized data backup performance suited to the dimensions of modern databases.

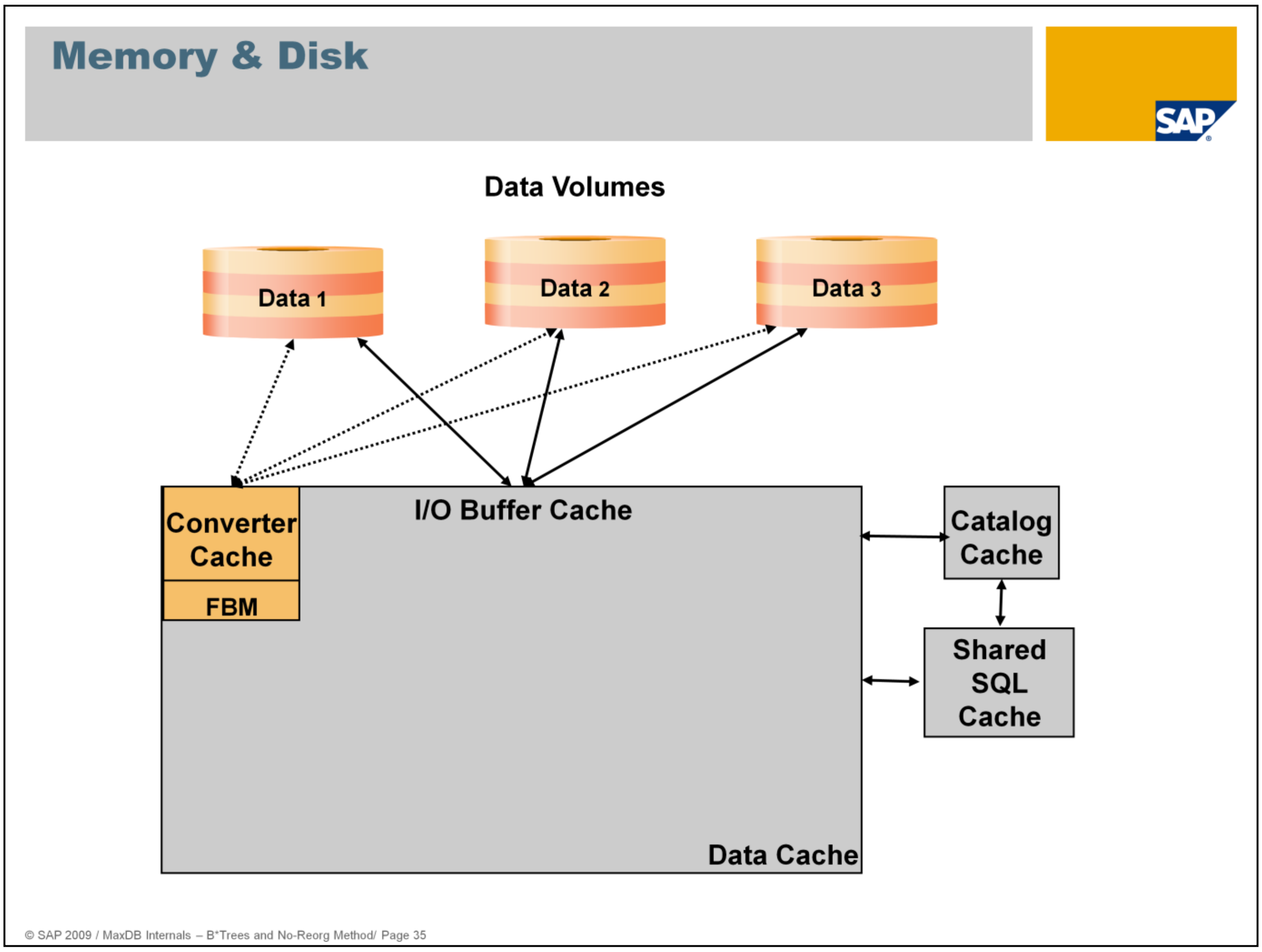
A user task should not be forced to wait for I/O processes to come to an end. All change operations are executed in the main memory. The I/O subsystem must ensure that the system always retains its ability to restart at the point of termination.

The shadow storage administration distinguishes between originals and copies. When the system is restarted after termination, the valid states of the data pages are automatically recognized. The concept is based on savepoint cycles, which are closed by a savepoint. A completed cycle is specified by the version number of its savepoint. This number is referred to as the 'savepoint version' or 'converter version'.

The different versions of the data pages that arise as a result of the savepoint cycles are administered in the converter. Here the originals and copies of the logical data pages are assigned physical blocks. Thus the location at which a logical data page is stored can change from savepoint cycle to savepoint cycle.

Another structure is employed for the administration of the data volumes (FBM: Free Block Manager). As the logical data pages no longer have a definite location in the memory, the FBM administers the states of the physical blocks. These structures enable optimal performance for data backup as well.

The data cache was optimized with regard to SMP support by the use of pager and server tasks that work in parallel.



## Memory & Disk

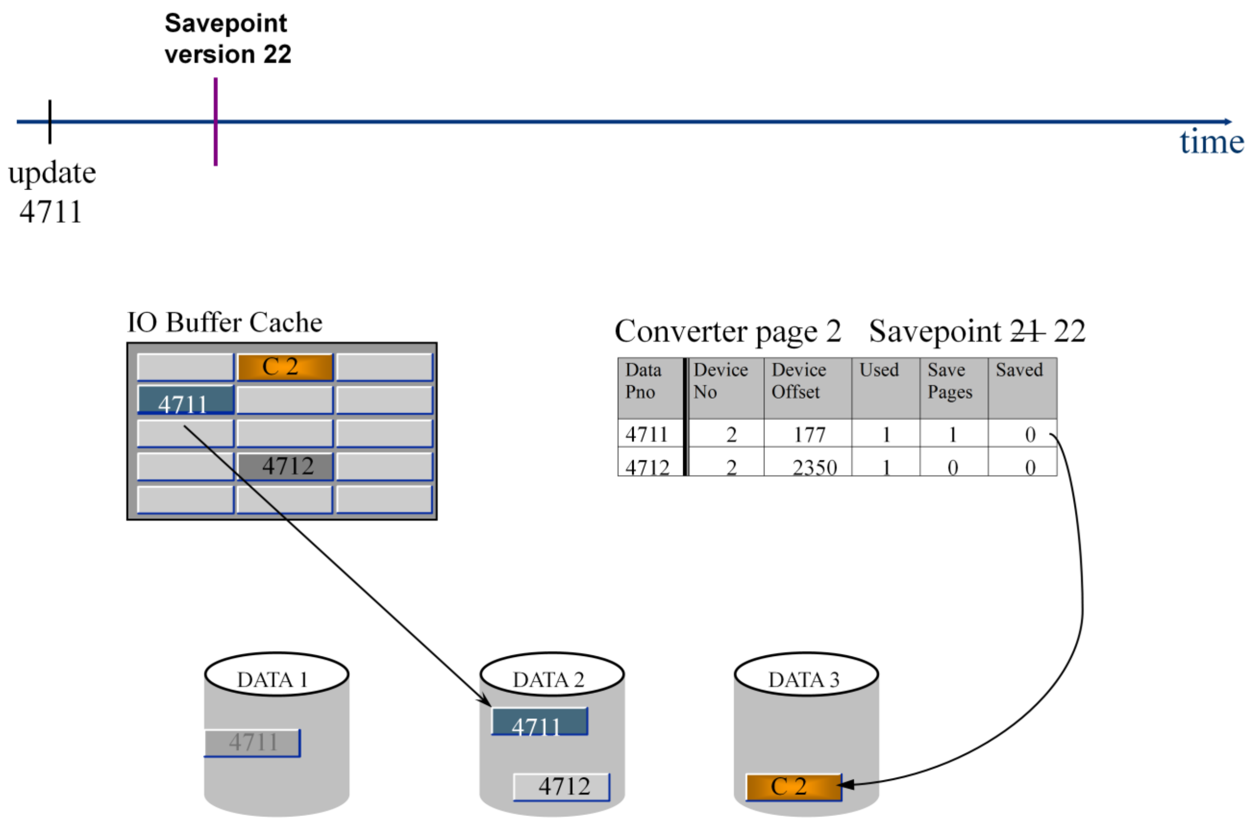
The introduction of shadow storage administration brought the launch of the converter. From Version 7.4, the converter is no longer stored in the system devspace but distributed across the data volumes. Every I/O access to a data page retrieves its information from the converter. For that reason, the complete contents of the converter are kept in the main memory (converter cache).

Free block management (FBM) for free blocks in the data volumes is kept in the main memory and is reconstituted with each restart using information from the converter.

Other important caches include the data cache, which contains the most recently used data pages; the catalog cache, which contains dictionary information on the used object and, if shared SQL is not active, buffers execution plans; and the shared SQL cache, which contains executed SQL statements, execution plans and monitor data.

The next few pages will present the concept of shadow memory using examples.

## Shadow Page Algorithm (1)



Converter page 2 Savepoint ~~21~~ 22

| Data Pno | Device No | Device Offset | Used | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 2 | 177 | 1 | 1 | 0 |
| 4712 | 2 | 2350 | 1 | 0 | 0 |

In our example, the database instance is in the online operational state. The last completed savepoint cycle has the number 21.

The IO buffer contains data and converter pages.

In the converter pages, we find the positions of the data pages in the data volumes.

Data page 4711 will now be changed in the cache in savepoint cycle 22. Initially, this change does not lead to a write operation to the data volumes.

The savepoint cycle is closed with a savepoint. First, all changed pages are written to the data volumes. For data page 4711, the FBM determines position 177 in data volume 2. Data page 4711 is written to the determined position in the data volume and the position data is written to the converter page. The data page is not written at the position that was valid for savepoint 21.

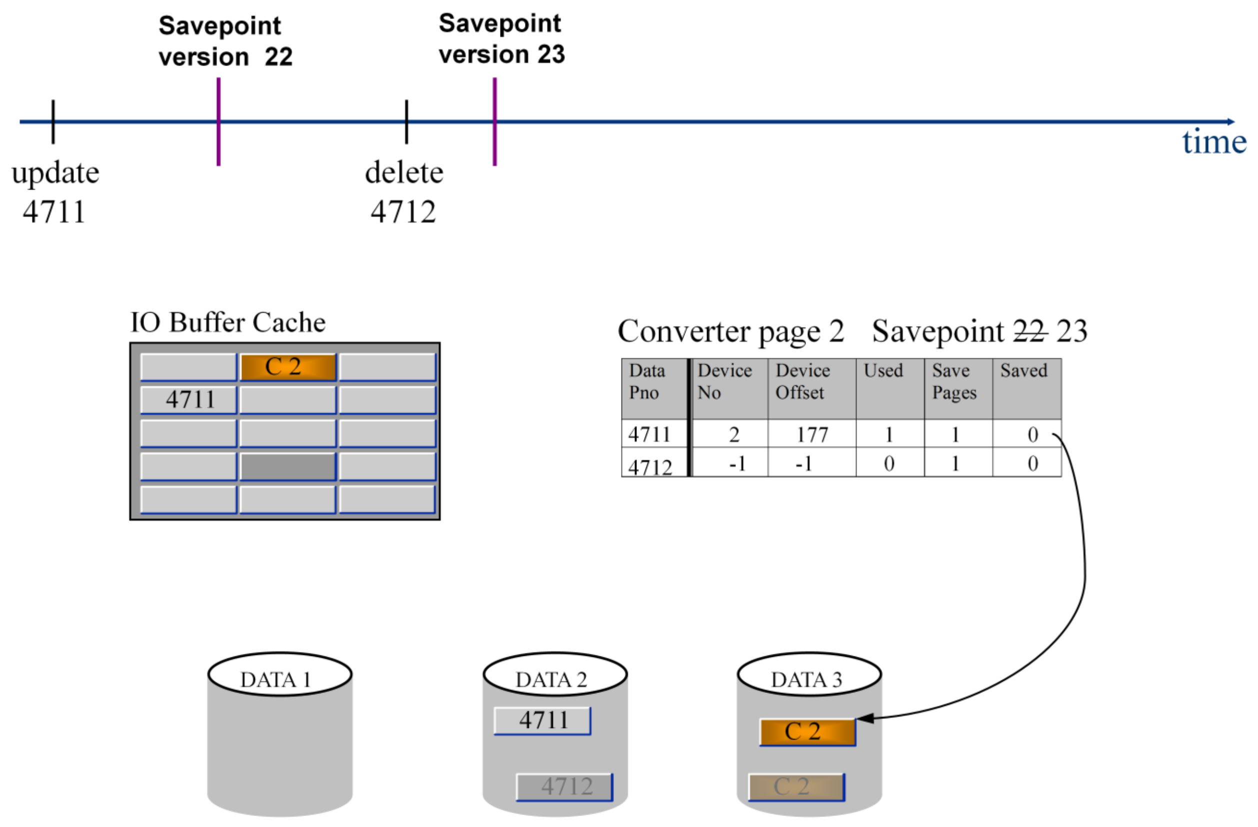
After all changed data pages have been written to the data volumes, the savepoint versions in the changed converter pages are set to the number of the savepoint cycle and the converter pages written to the data volumes.

Each converter page stores the positions of up to 1861 data pages.

A converter page contains the following information about each data page:

- the number of the data volume,
- the number of the data volume,
- a flag indicating whether the data page is in use (required to indicate used data pages that have not yet been written to a data volume),
- a flag indicating whether the data page is relevant for incremental backups,
- a flag indicating whether the datap page was already backed up in the incremental backup.
  This way the information on the data page to be saved is not lost in the case of an aborted incremental backup.

## Shadow Page Algorithm (2)



Converter page 2 Savepoint ~~22~~ 23

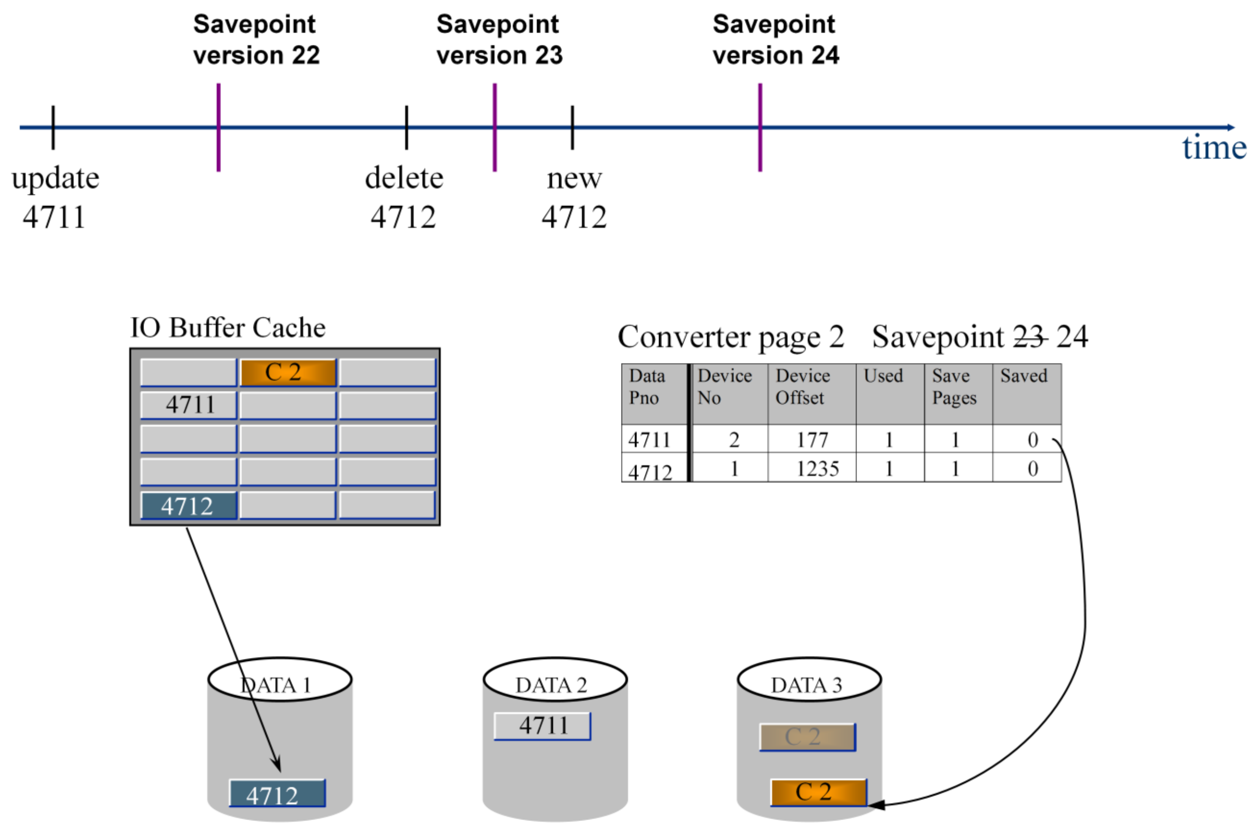
| Data Pno | Device No | Device Offset | Used | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 2 | 177 | 1 | 1 | 0 |
| 4712 | -1 | -1 | 0 | 1 | 0 |

In savepoint cycle 23, a user deletes all entries in data page 4712. Upon release, the page is immediately marked as free in the converter.

Only the converter page is re-written at the time of the savepoint. Data page 4712 is not re-written. The converter page is written to a new position in a data volume.

After the completion of the savepoint, the former position of data page 4712 in the data volumes is marked as free in the FBM.

## Shadow Page Algorithm (3)



Converter page 2 Savepoint ~~23~~ 24

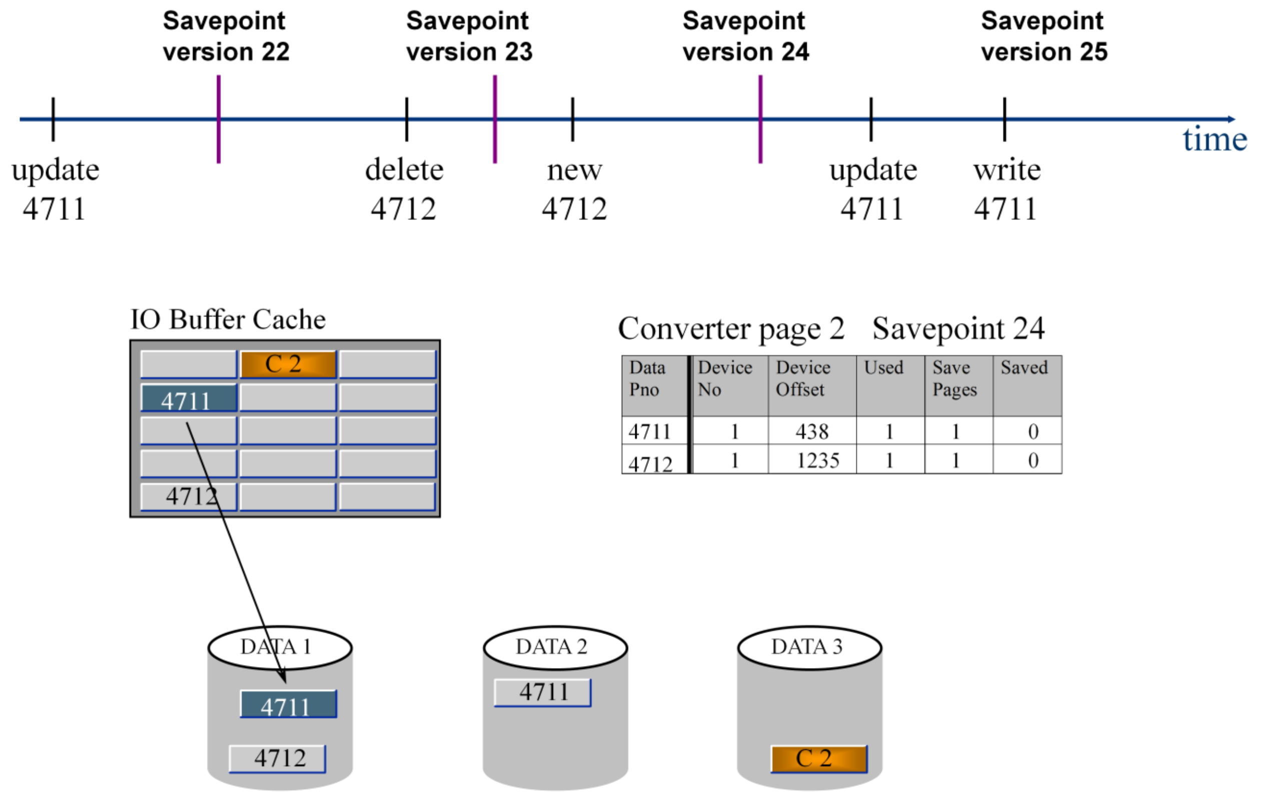
| Data Pno | Device No | Device Offset | Used | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 2 | 177 | 1 | 1 | 0 |
| 4712 | 1 | 1235 | 1 | 1 | 0 |

In savepoint 24, the database uses page 4712 for new data. The data page could already have been reassigned in savepoint cycle 23.

The new data page is marked as used in the converter. But no position for a data volume has been entered yet.

Initially, changes take place only in the cache. Upon completion of the savepoint cycle, the data page is written and its position entered in the converter. The converter page is written to a new position in a data volume.

## Shadow Page Algorithm (4)



Converter page 2 Savepoint 24

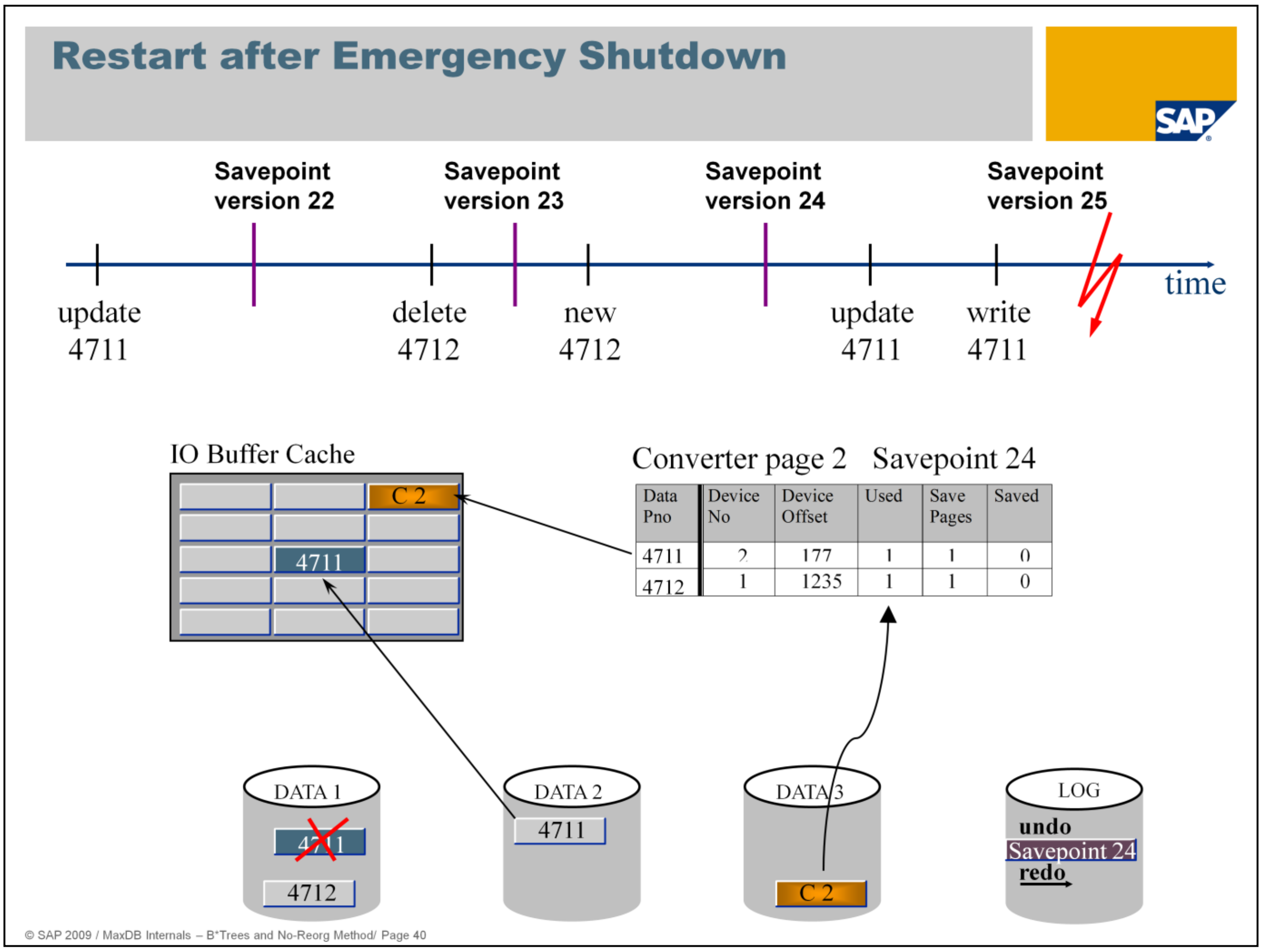
| Data Pno | Device No | Device Offset | Used | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 1 | 438 | 1 | 1 | 0 |
| 4712 | 1 | 1235 | 1 | 1 | 0 |

Data page 4711 is changed again in savepoint 25.

A data page can be written even before the completion of the savepoint cycle. The savepoint itself generally takes a few seconds as several data pages are written.

Data page 4711 is written and the new position entered in the converter page. The savepoint is not yet complete.

# Restart after Emergency Shutdown



Converter page 2 Savepoint 24

| Data Pno | Device No | Device Offset | Used | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 2 | 177 | 1 | 1 | 0 |
| 4712 | 1 | 1235 | 1 | 1 | 0 |

Before savepoint 25 is complete, an emergency shutdown occurs. The next restart reads the valid converters for savepoint 24 from the data volumes.

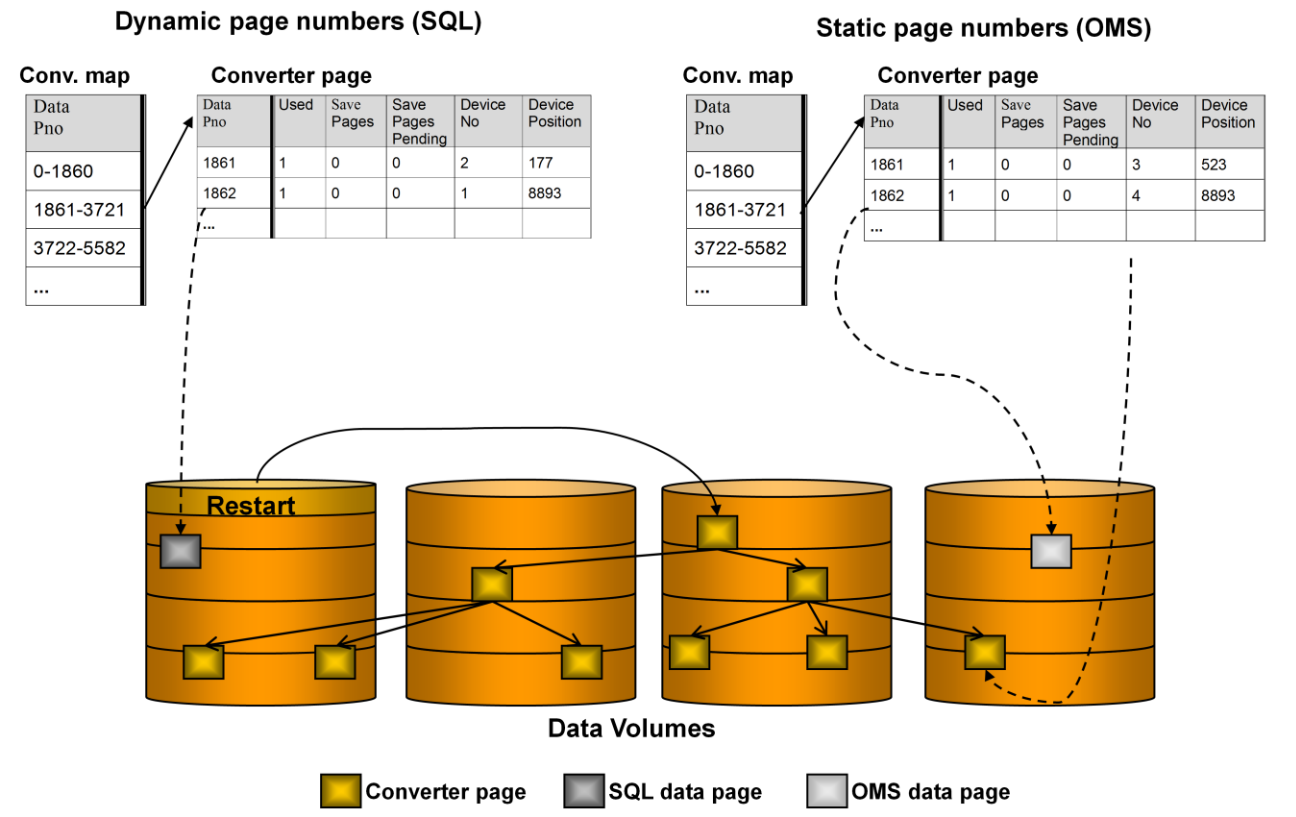
Free block management sets up when the converter is read. The position occupied by data page 4711 through the write operation in savepoint 25 is marked as free.

Data page 4711 can be read via the old valid position.

The starting point in the restart page for savepoint 24 is known. The redo log entries are redone starting from this point. The change to data page 4711 during savepoint cycle 25 will be redone if the transaction that performed the change was completed with Commit before the emergency shutdown took place.

The writing of the restart page to position 2 in data volume one completes a savepoint cycle.

## Converter



**Dynamic page numbers (SQL)**

Conv. map

| Data Pno |
|---|
| 0-1860 |
| 1861-3721 |
| 3722-5582 |
| ... |

Converter page

| Data Pno | Used | Save Pages | Save Pages Pending | Device No | Device Position |
|---|---|---|---|---|---|
| 1861 | 1 | 0 | 0 | 2 | 177 |
| 1862 | 1 | 0 | 0 | 1 | 8893 |
| ... | | | | | |

**Static page numbers (OMS)**

Conv. map

| Data Pno |
|---|
| 0-1860 |
| 1861-3721 |
| 3722-5582 |
| ... |

Converter page

| Data Pno | Used | Save Pages | Save Pages Pending | Device No | Device Position |
|---|---|---|---|---|---|
| 1861 | 1 | 0 | 0 | 3 | 523 |
| 1862 | 1 | 0 | 0 | 4 | 8893 |
| ... | | | | | |

Legend: 🟨 Converter page ▨ SQL data page ⬜ OMS data page

In versions < 7.4, the converter was implemented as a static array. The ability to enlarge an instance in online mode was limited. The limit was set with the parameter MAXDATAPAGES. This parameter defined the size of the converter. So the converter was generally larger than necessary.

From Version 7.4, the converter can grow and shrink dynamically. The converter pages are distributed across all data volumes. Upon restart, read access to the converter pages is done via a tree structure. The tree has 3 levels: a root level, an index level and a leaf level. Upon restart, the database finds the root page of the converter via the restart page at the beginning of the first data volume. It contains the positions of the index pages. For their part, the index pages contain positions of the leaf pages. The leaf pages are not necessarily sorted. From Version 7.4.3., the restart reads the converter pages in parallel.

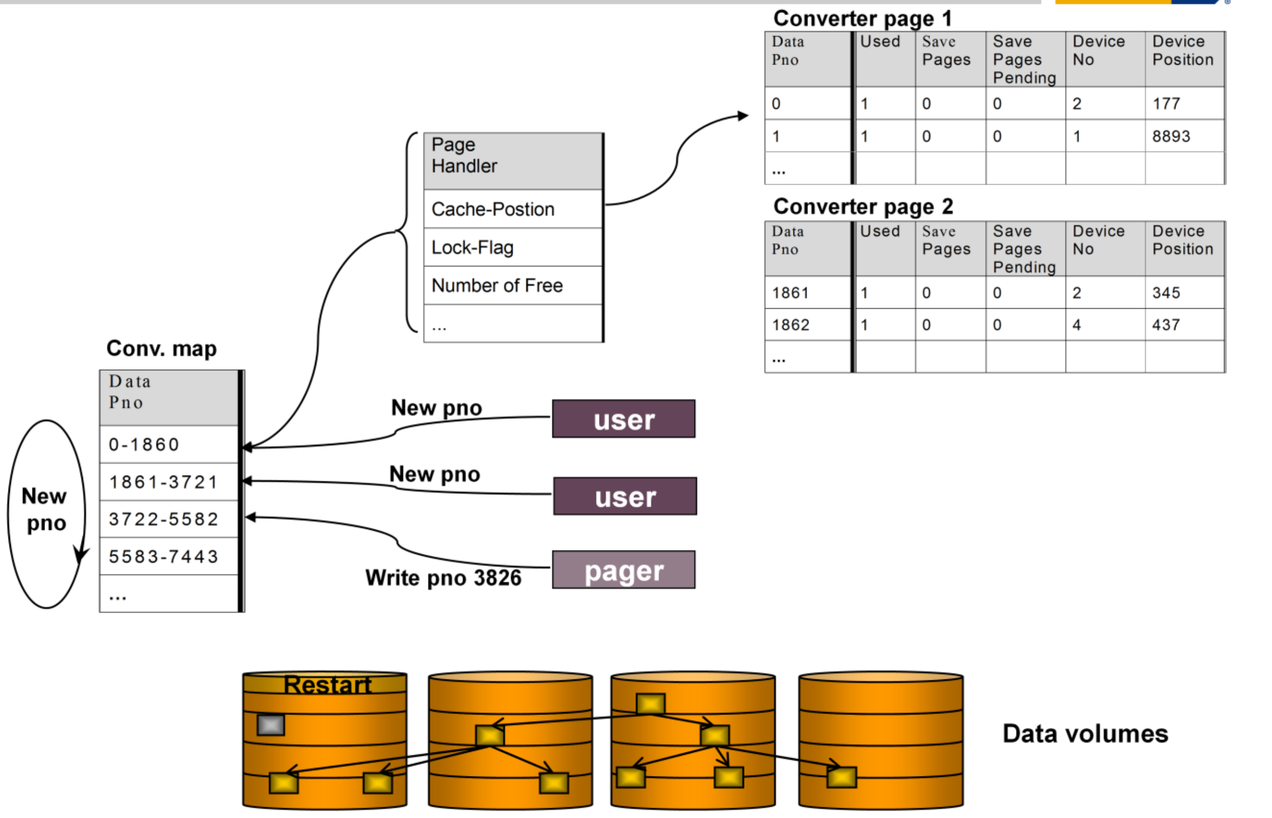
The tree as a whole contains pages for 3 converters, one each for

- Static page numbers for OMS data (live cache)
- Dynamic page numbers for permanent data that is not OMS data
- Page numbers for temporary pages

Static and dynamic data pages are handled separately for the following reasons:

- Changes to relational data are logged in the log without position information for the data records.
- Changes to OMS data are done on the basis of an object ID. The object ID contains the number of the data page that contains the object.
- Without this separation, under some circumstances it might not be possible to restore objects in a log recovery due to the corresponding data page number for relational having been assigned.

## Scalability through Converter Implementation



| Data Pno |
|---|
| 0-1860 |
| 1861-3721 |
| 3722-5582 |
| 5583-7443 |
| ... |

Converter page 1

| Data Pno | Used | Save Pages | Save Pages Pending | Device No | Device Position |
|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 2 | 177 |
| 1 | 1 | 0 | 0 | 1 | 8893 |
| ... | | | | | |

Converter page 2

| Data Pno | Used | Save Pages | Save Pages Pending | Device No | Device Position |
|---|---|---|---|---|---|
| 1861 | 1 | 0 | 0 | 2 | 345 |
| 1862 | 1 | 0 | 0 | 4 | 437 |
| ... | | | | | |

A converter page has 8192 bytes. It contains references for 1861 data pages. A database with 500 GB of used data requires a converter of roughly 278 MB.

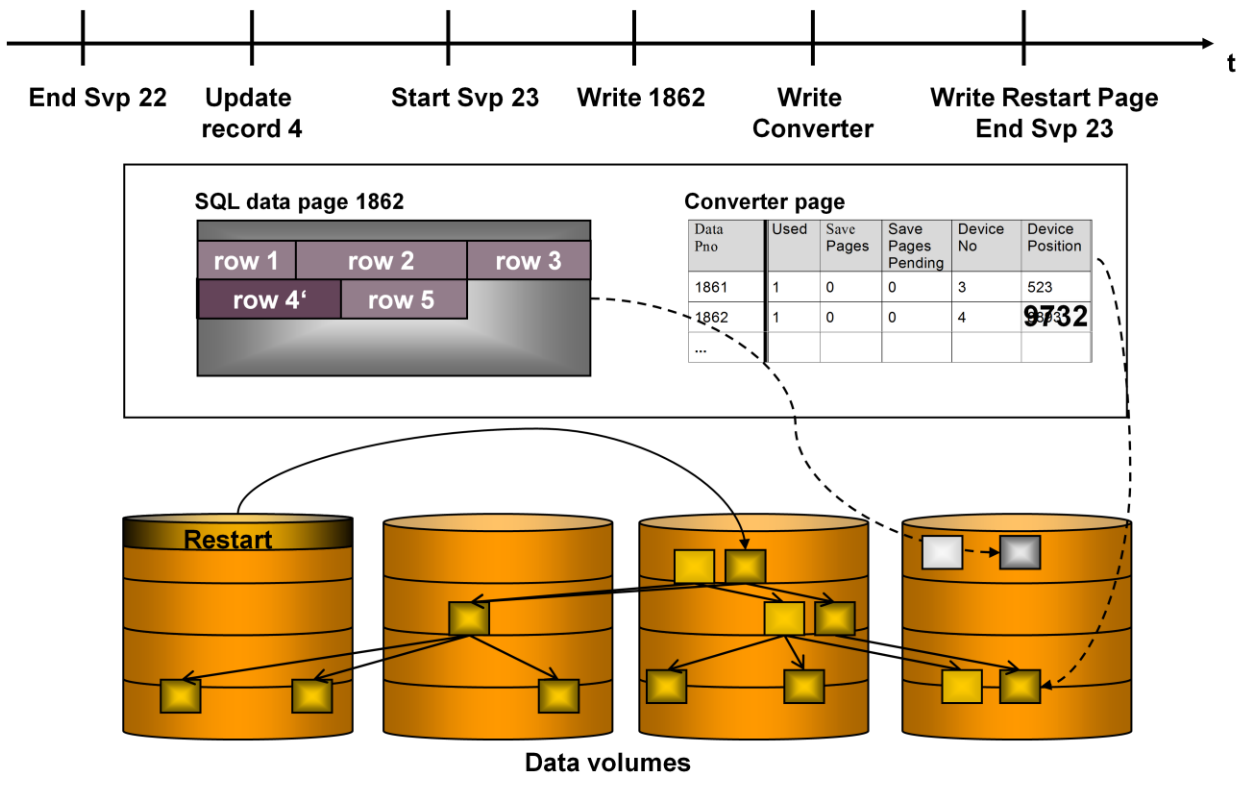
When the converter is read during the restart, a converter map is generated in the cache. The converter pages in the cache do not have fixed positions. The position of a converter page is determined via the converter map each time it is accessed.

For each converter page, the converter map contains the cache position and the number of free entries as well as administration information for the savepoint.

Accesses to converter pages are synchronized through the use of converter regions. Each entry in the converter map is assigned a region. You can set the number of regions with the parameter ConverterStripes (until 7.6 CONVERTER_REGIONS). This allows several users to access and change converter pages at the same time.

From 7.4, free page numbers are no longer determined by way of a PNO pool. They are determined directly from the converter. Free entries in the converter pages are concatenated via main memory structures. So several users working at the same time can use new pages very quickly.

## Writing to Converter during Savepoint



| Data Pno | Used | Save Pages | Save Pages Pending | Device No | Device Position |
|---|---|---|---|---|---|
| 1861 | 1 | 0 | 0 | 3 | 523 |
| 1862 | 1 | 0 | 0 | 4 | 9732 |
| ... | | | | | |

During the savepoint the database kernel writes all changed data pages to the data volumes. It enters the new positions in the converter.

The kernel writes the changed converter pages in the last savepoint phase. The pages are not written to their original positions. Because the position of the converter pages changes, the corresponding converter index and converter root are also changed.  These pages are also written to new positions.

When all changed data and converter pages have been written, the position of the converter root is entered in the restart page. The restart page for the old savepoint is overwritten in the data volume.

The savepoint is complete when the restart page is written. This ensures that the kernel can always restart from the last completed savepoint.

## Advantages of Converter 7.5 compared to 7.3

Operation without System Volume

- No hotspot on one volume
- Fast restart and fast savepoint through parallel I/O

Distinction static – dynamic converter

- Ability to recover liveCache instances

Converter in the I/O buffer cache

- Manual adaptation of the converter cache to the DB size is not  necessary

Parallel awarding of free page numbers

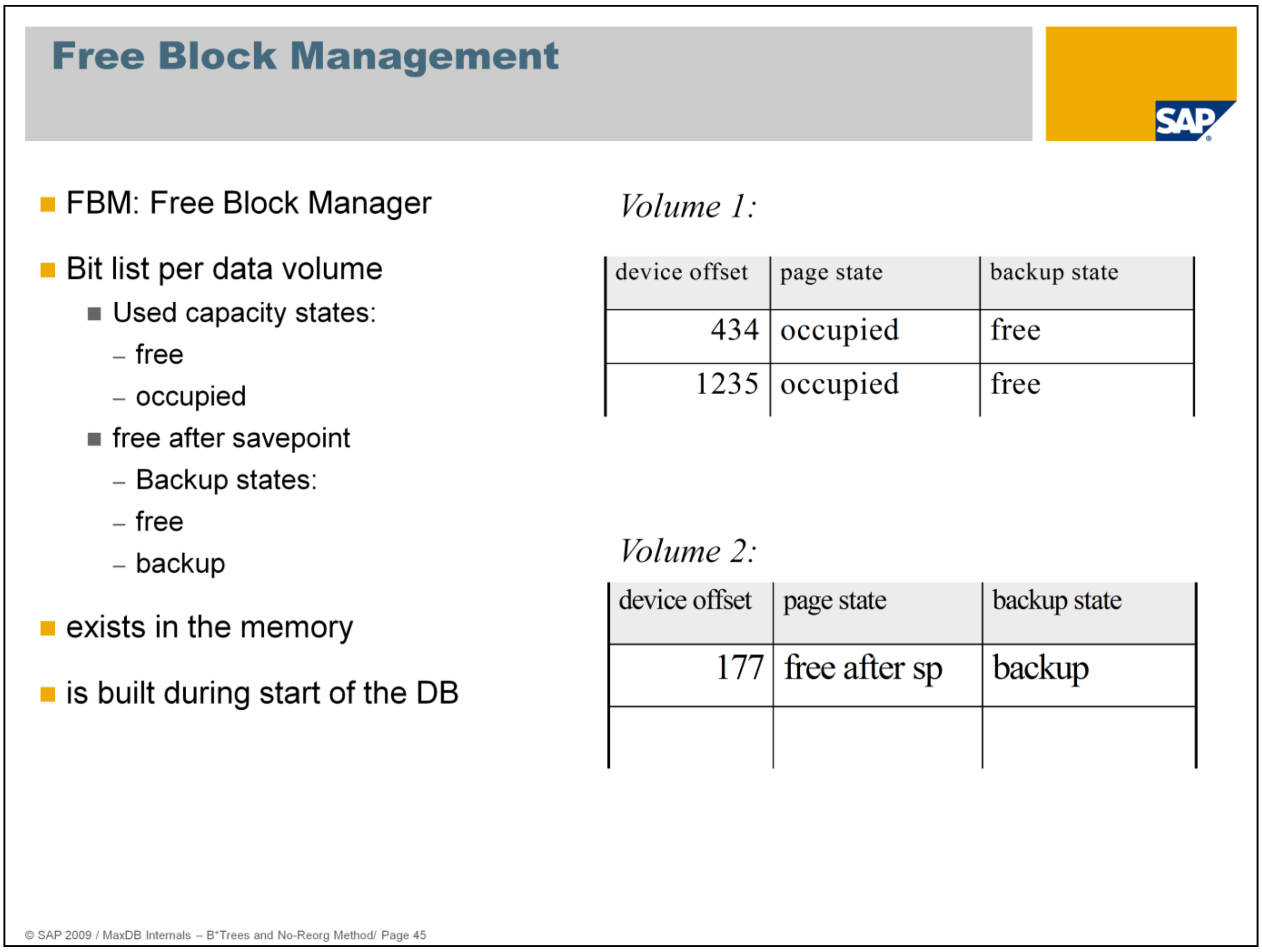
Converter may grow and shrink dynamically

- Online ADD DATA VOLUME without limitation to MAXDATAPAGES
- DROP DATA VOLUME (as of version 7.6)

Highest page number independent of the converter size

- Restore to smaller instances just with limitation to the grade of occupied pages

Snapshot support



## Free Block Management

- FBM: Free Block Manager
- Bit list per data volume
  - Used capacity states:
    - free
    - occupied
  - free after savepoint
    - Backup states:
    - free
    - backup
- exists in the memory
- is built during start of the DB

*Volume 1:*

| device offset | page state | backup state |
|---|---|---|
| 434 | occupied | free |
| 1235 | occupied | free |

*Volume 2:*

| device offset | page state | backup state |
|---|---|---|
| 177 | free after sp | backup |
| | | |

The Free Block Manager, which only exists in the memory, administers all data devices using a bit list for each device. This includes the used capacity status and the backup status. The possible statuses are:

- **Free:**
  The block is free and can be allocated.
- **Occupied:**
  The block is occupied.
- **Free after savepoint:**
  The block can be released after the current savepoint has been successfully completed.
- **Backup:**
  The block belongs to a backup that is in process. When the block has been backed up, that is, written to the backup medium, the status is reset.

If a block has been selected for a backup in process, the used capacity status of a block can change. A block can only be reallocated when the used capacity and backup statuses are both "free."

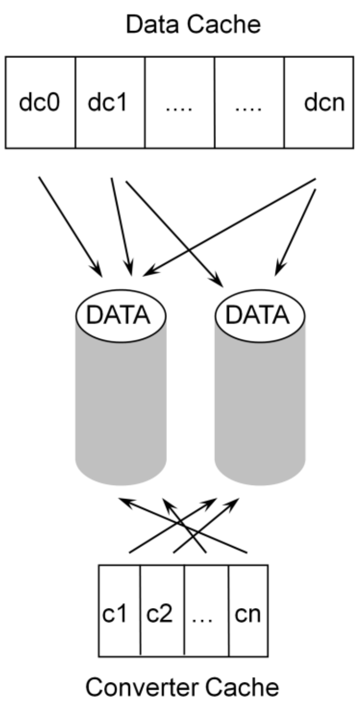
From version 7.4, the Free Block Manager is part of converter management.

## Savepoint Phases

- Write changed data pages (parallel)

- Prevent B* tree operations
- Occupy transaction regions
- Write log entry
- Remember open transactions
- Release all resources

- Write changed data pages of the 1st phase (parallel)
- Write converter pages (parallel)
- Write log info and restart page
- Increase savepoint version



The savepoint is a core function of the I/O concept. The illustration shows what happens during a savepoint.

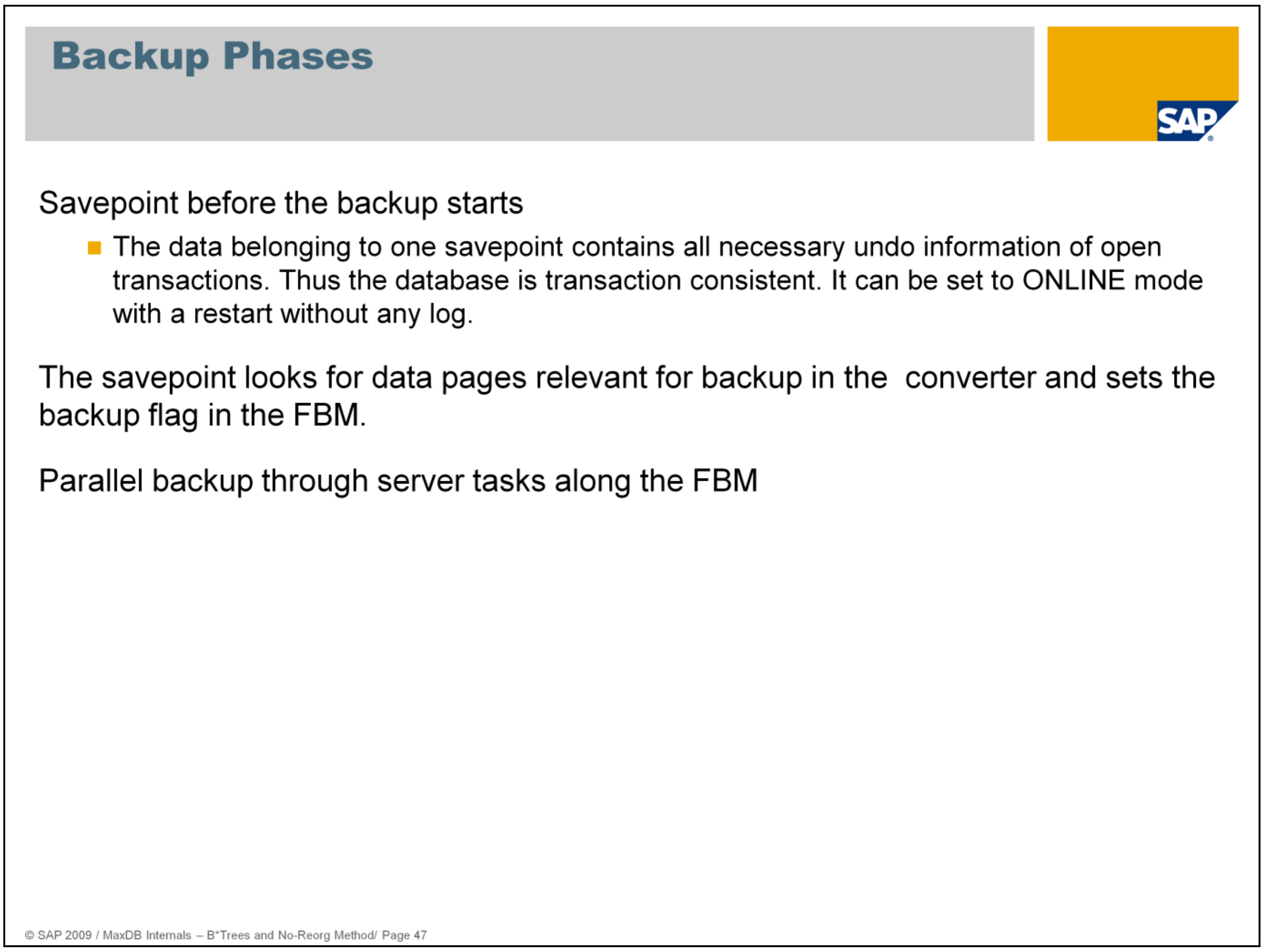
The savepoint writes the data from the data cache and the converter cache to the corresponding data volumes. Due to the size of the two caches, this cannot be carried out as a synchronous action; the system would be blocked for too long. There has to be a short phase in which the caches can be securely flushed, but this must be kept to a minimum.

The standard is for savepoints to occur at intervals of 10 minutes. To minimize the amount of data to be flushed in the protected section (marked red), the savepoint begins by flushing the data cache parallel to operation. The data cache is processed by several pagers simultaneously. The largest share of pages is flushed in this phase.

In the second phase, a flag is set which prohibits clearing operations on B* trees. It is also prohibited to open new transactions during this phase. All pages that were changed in the course of the first phase are marked as savepoint relevant. An open trans file is created for open transactions.

In the last phase, all pages that were marked during the second phase are flushed. The flags are reset. First, all changed pages are written to the data volumes. The savepoint is complete when the restart page is written. Afterwards the savepoint version (number) is updated.

The protected phase of the savepoint is generally quite short and goes unnoticed by the end user.



## Backup Phases

Savepoint before the backup starts

- The data belonging to one savepoint contains all necessary undo information of open transactions. Thus the database is transaction consistent. It can be set to ONLINE mode with a restart without any log.

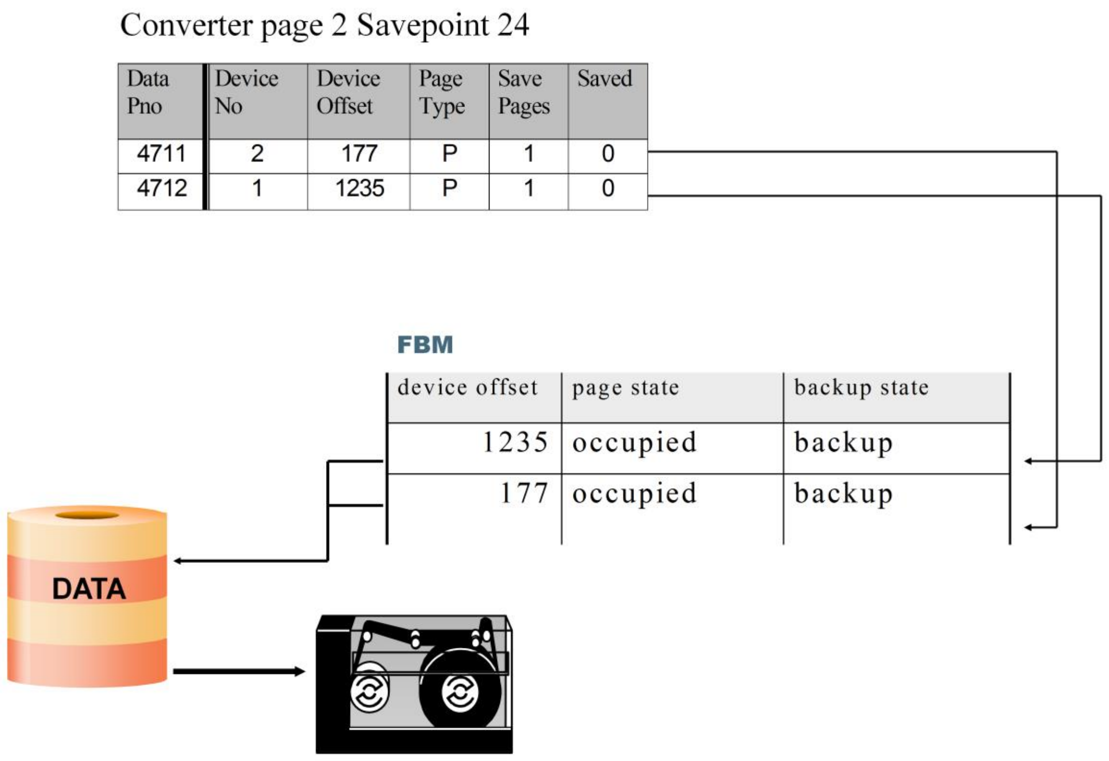
The savepoint looks for data pages relevant for backup in the  converter and sets the backup flag in the FBM.

Parallel backup through server tasks along the FBM

Data backups are carried out with a block size of 8 x 8 KB and can be parallelized.

Data backups start with a savepoint. A backup includes the data existing at the time of the savepoint. Subsequent changes are not included in the backup. The database can write further savepoints while the backup is in process.

## Backup along the FBM



Converter page 2 Savepoint 24

| Data Pno | Device No | Device Offset | Page Type | Save Pages | Saved |
|---|---|---|---|---|---|
| 4711 | 2 | 177 | P | 1 | 0 |
| 4712 | 1 | 1235 | P | 1 | 0 |

FBM

| device offset | page state | backup state |
|---|---|---|
| 1235 | occupied | backup |
| 177 | occupied | backup |

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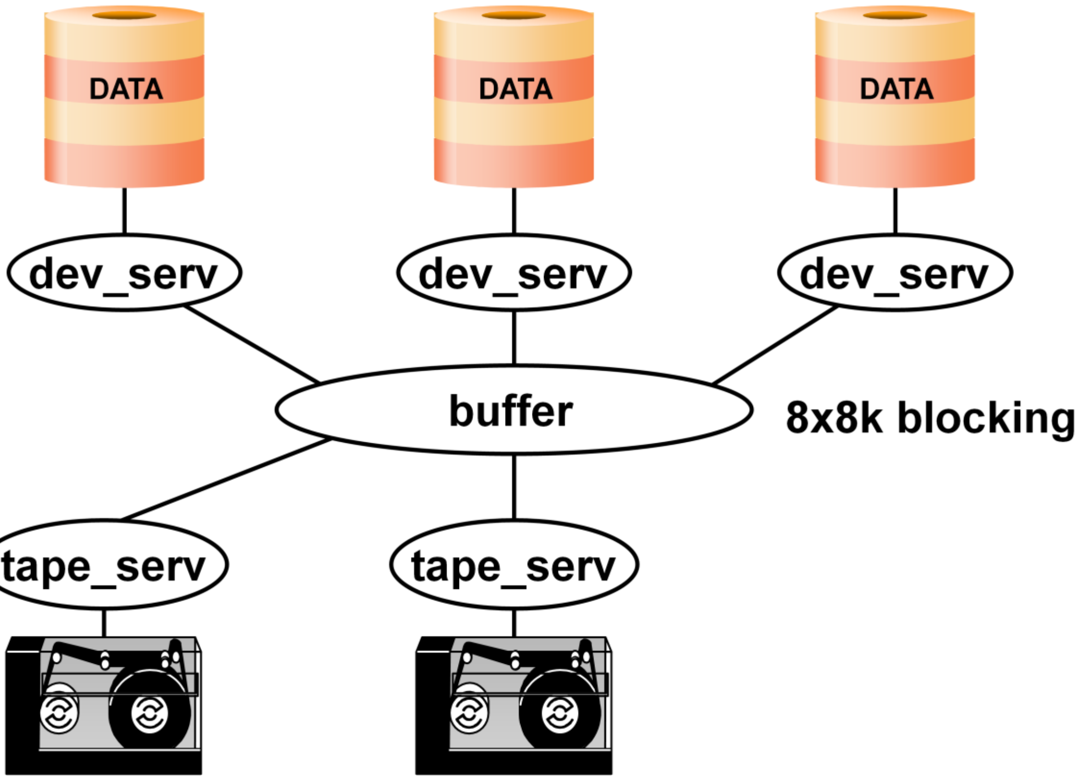
The savepoint that is executed at the start of the data backup determines the savepoint version of the backup. Through the converter, the data blocks on the data devices that are valid for this savepoint are determined for all data pages and the backup status is set in the FBM.

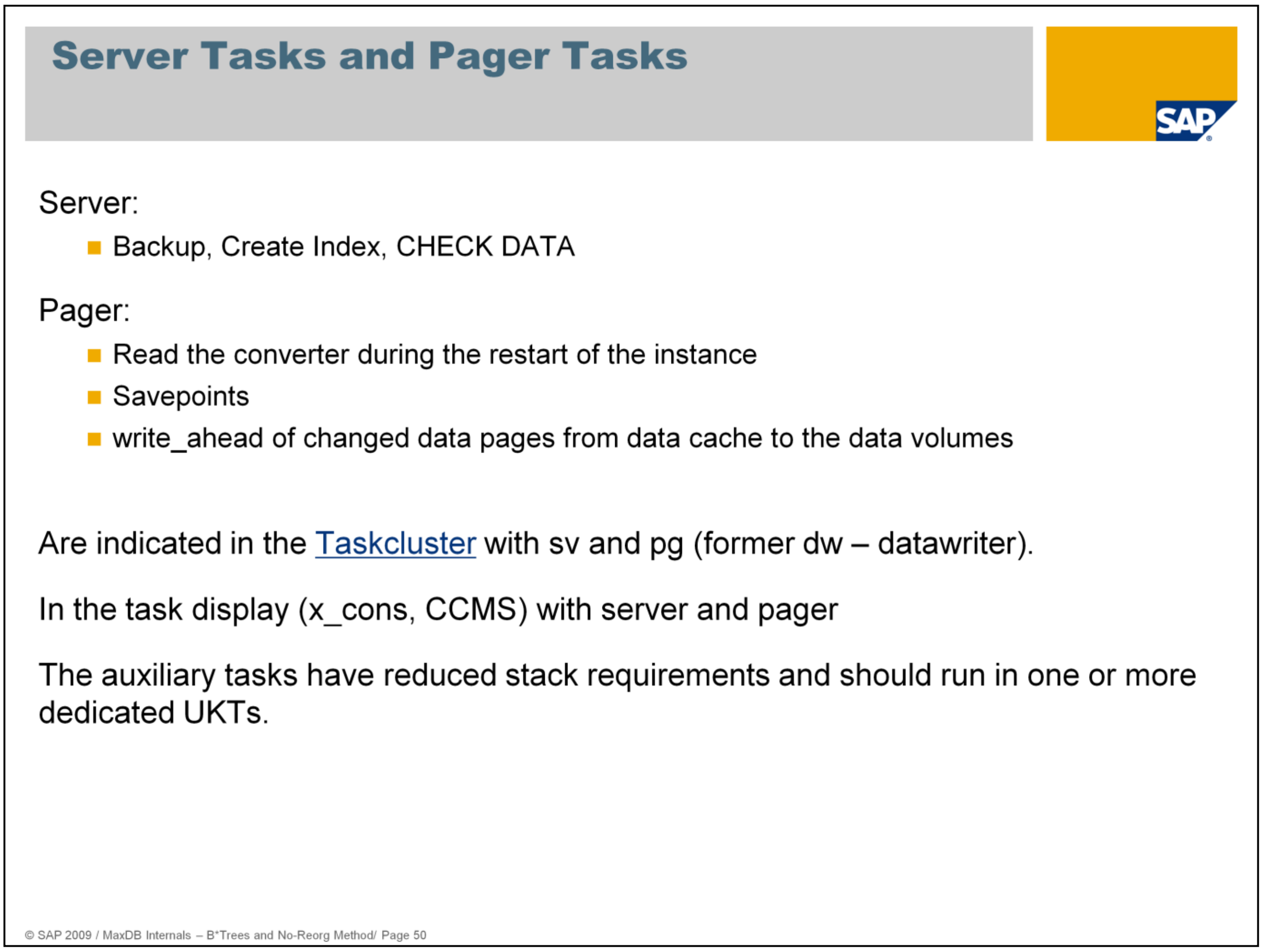
The data backup uses the bit lists of the FBM. There the data blocks are combined into 64 KB I/O units. This procedure executes one task per data volume. The backup status is reset following each block backup. Data blocks that have been freed for use can only be reallocated when the backup status has been reset.

## Parallel Backup



This illustration depicts a data transfer from the data volumes to the backup media. Each volume has a task that puts the 64 KB units into a buffer. One task per backup device reads the blocks from the buffer and stores them on the backup medium.

The limits of this process are posed either by the access speed of the data volumes, the writing performance of the backup devices or the transport layer (e.g. network) between the database server and the backup devices. As long as these limits are not reached, the process scales with any other backup device in parallel operation.



## Server Tasks and Pager Tasks

Server:

- Backup, Create Index, CHECK DATA

Pager:

- Read the converter during the restart of the instance
- Savepoints
- write_ahead of changed data pages from data cache to the data volumes

Are indicated in the Taskcluster with sv and pg (former dw – datawriter).

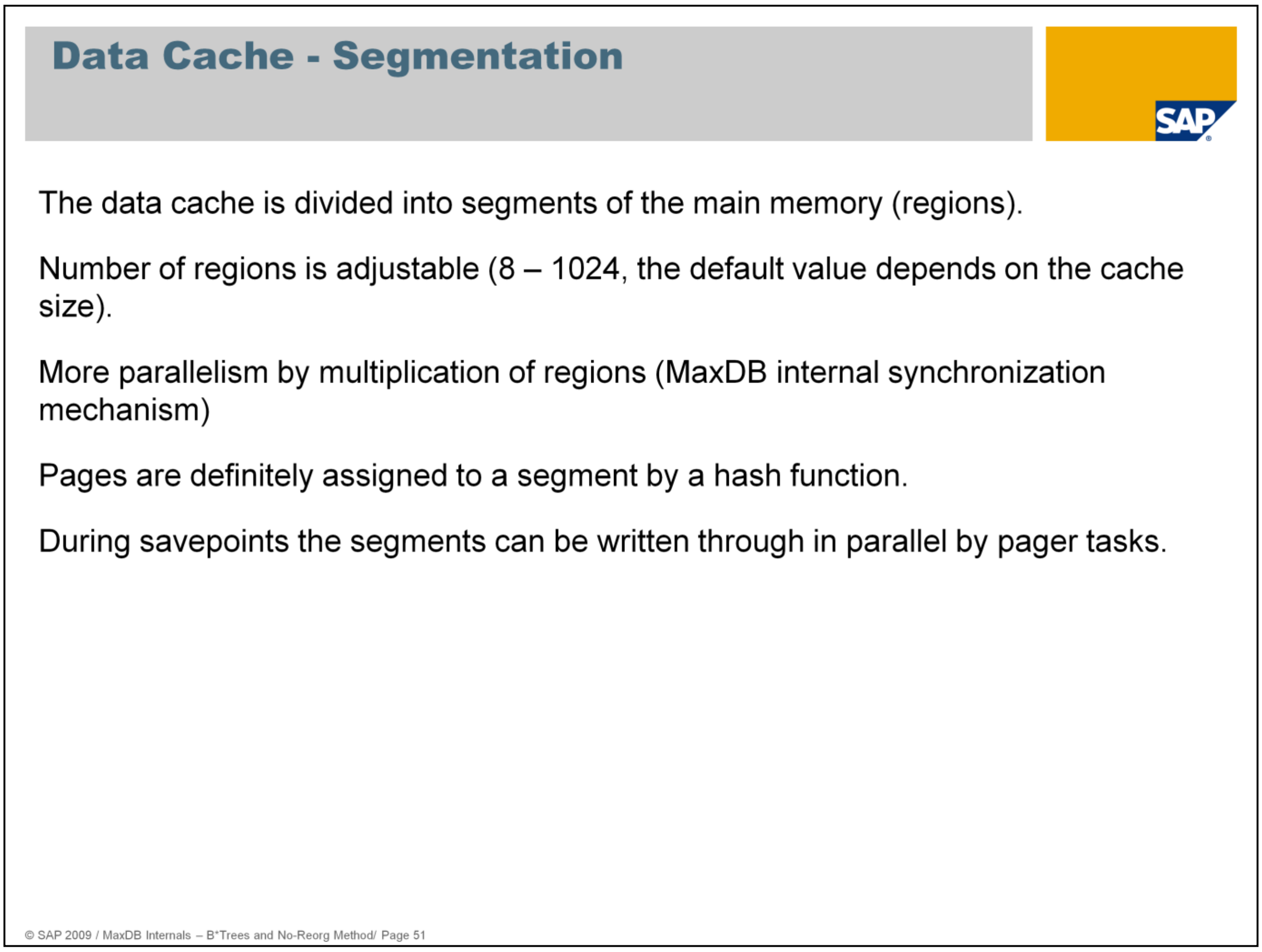
In the task display (x_cons, CCMS) with server and pager

The auxiliary tasks have reduced stack requirements and should run in one or more dedicated UKTs.

Server tasks or pager tasks have a reduced stack requirement as they do not have to carry out syntax analysis or related activities, but only process pre-translated requests.

To prevent the server tasks from negatively influencing the user tasks due to their high throughput, they are created in their own thread (UKT) in the standard.

During times in which a system is working with a moderate to low I/O load, pager tasks perform so-called write-ahead operations. This means that data pages that have been changed in the data cache are written to the data volumes ahead of time, i.e. before a savepoint or displacement. This in turn means a reduction of the burden on the first phase of the coming savepoint as there is substantially less I/O to be handled. In general, a favorable setting of the pager tasks can ensure a consistently low and largely asynchronous I/O load.



## Data Cache - Segmentation

The data cache is divided into segments of the main memory (regions).

Number of regions is adjustable (8 – 1024, the default value depends on the cache size).

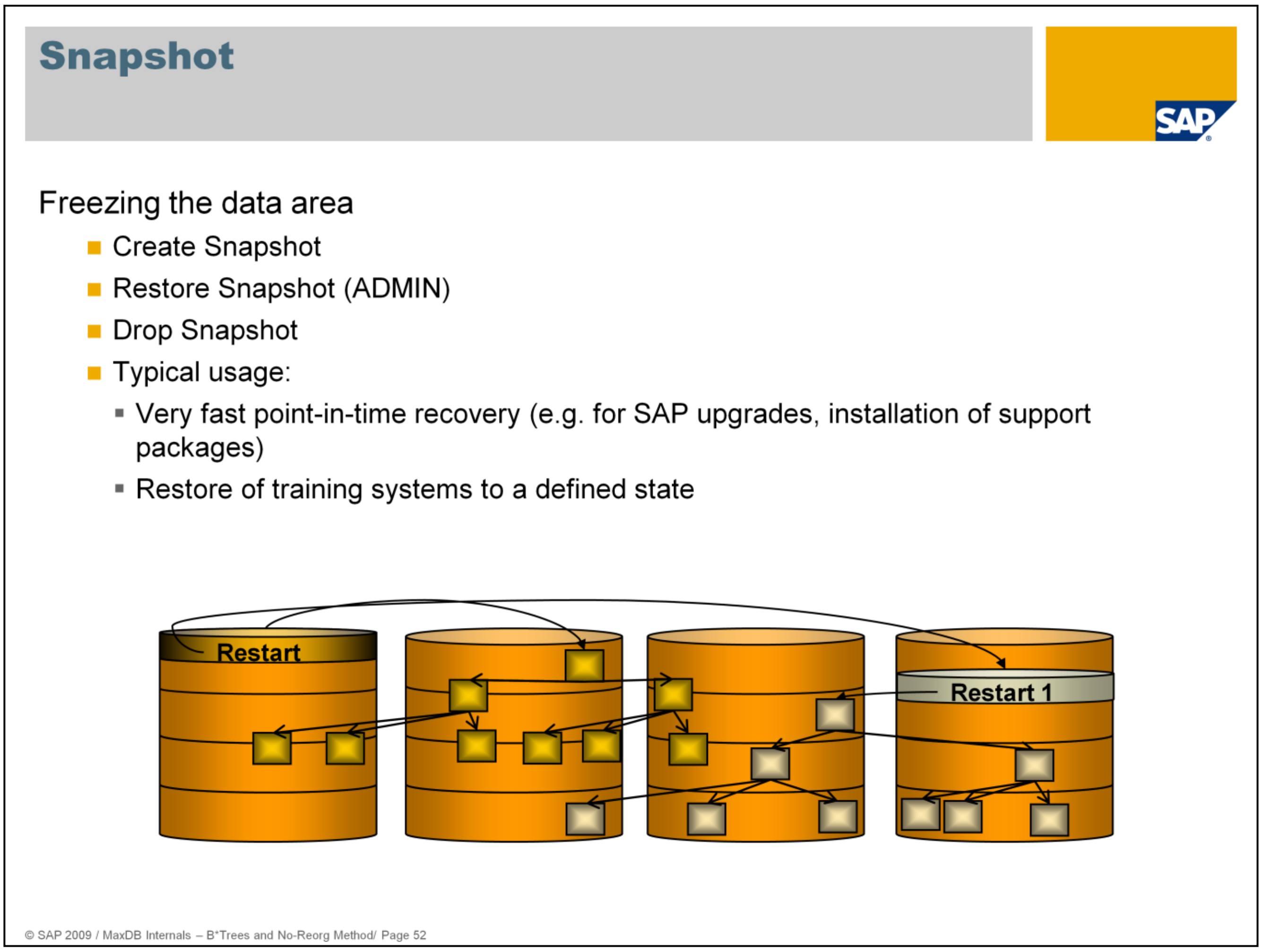
More parallelism by multiplication of regions (MaxDB internal synchronization mechanism)

Pages are definitely assigned to a segment by a hash function.

During savepoints the segments can be written through in parallel by pager tasks.

The data cache was divided into segments to enable better SMP support and to accelerate savepoints. Each segment is secured by its own region.  The data pages are uniquely assigned to a segment, that is, a data page with the page number 4711 (pno), for example, is always administered in the second cache segment.

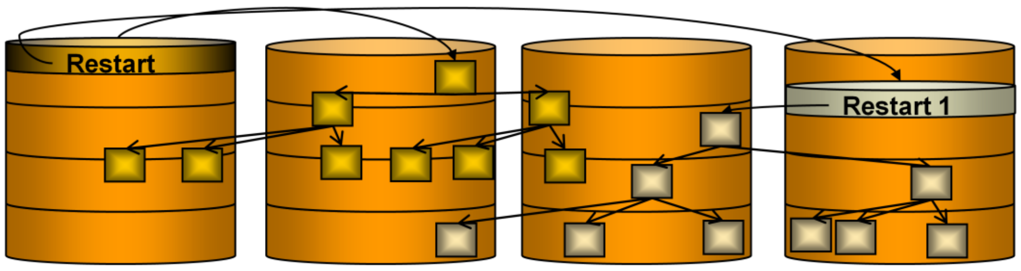
As of version 7.6.03 the number of possible segments has increased from 64 to 1024.



## Snapshot

Freezing the data area

- Create Snapshot
- Restore Snapshot (ADMIN)
- Drop Snapshot
- Typical usage:
  - Very fast point-in-time recovery (e.g. for SAP upgrades, installation of support packages)
  - Restore of training systems to a defined state



From version 7.5, you can freeze the data area of a database instance using a snapshot.

In versions 7.5 and 7.6 a snapshot is generated in the ADMIN state. As of 7.7 it is also possible to create it in ONLINE mode. Later you can reset the data to its state at the time of the snapshot and/or delete the snapshot.

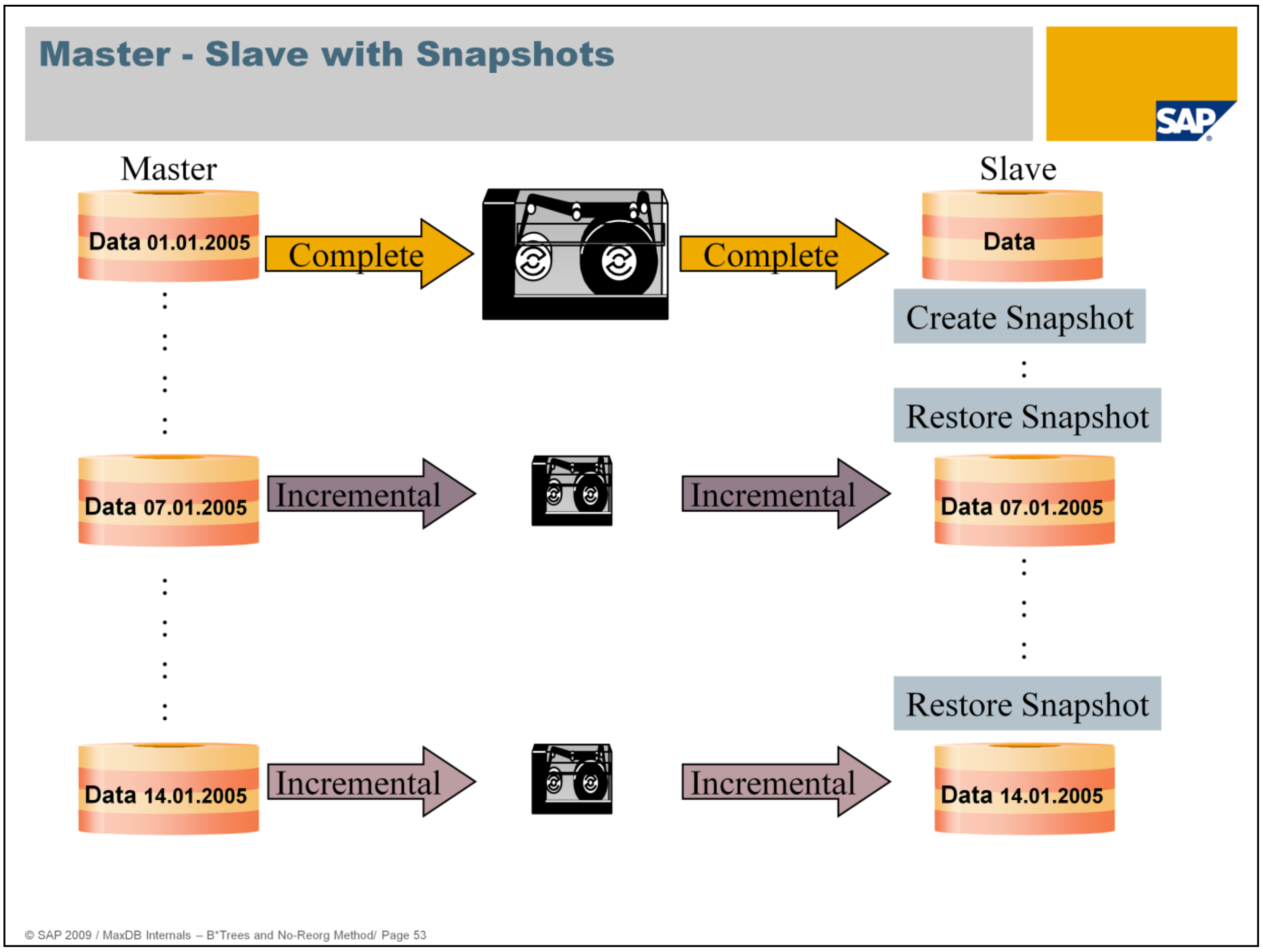
With the CREATE_SNAPSHOT command, the database kernel copies the restart page from the second block of the first data volume to another position. The complete converter is also copied. The original restart record contains a reference to the restart record that corresponds to the snapshot.

With the command RESTORE_SNAPSHOT, the current converter is deleted. All blocks that are no longer needed are marked as free in the FBM. The log is formatted such that the state HISTLOST occurs. At the next restart, the instance works with the data as they were at the time of the CREATE_SNAPSHOT.

The statement DROP_SNAPSHOT deletes the restart record and the corresponding converter that is relevant for the snapshot. The FBM marks all blocks that are no longer needed as free.

Up to 7.6 MaxDB supports only a single snapshot, as of 7.7 several snapshots can be generated. Operating the instance with one or several snapshot(s) uses more of the capacity of the data area.

## Master - Slave with Snapshots



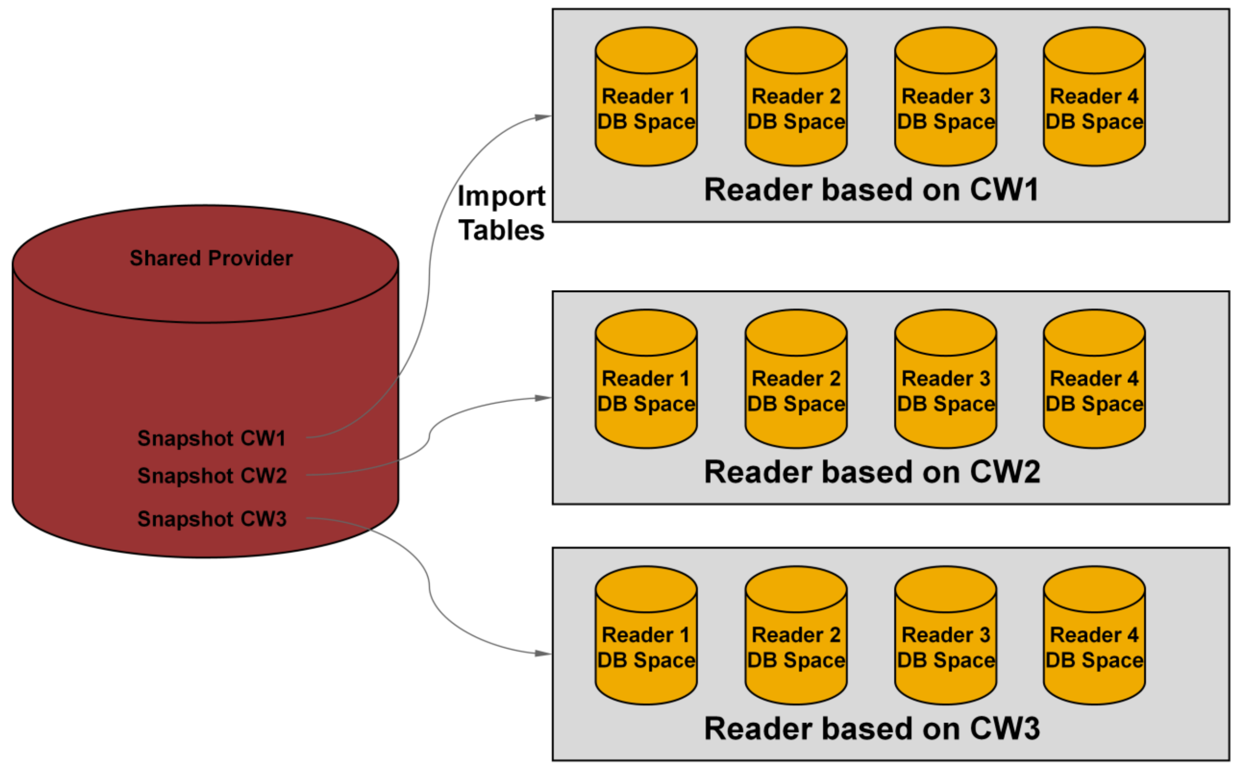
MaxDB offers the possibility of using snapshots to synchronize a master and one or more slave instances.

Create the slave instance as a homogeneous system copy using Backup/Restore. Before the first restart of the slave instance, generate a snapshot.

To transfer changes in the master instance to the slave instance, reset the slave instance to the snapshot. Then import an incremental backup from the master instance. You can reset the slave instance to the snapshot as often as you like and import incremental backups from the master instance.

This procedure works until a complete backup is created in the master instance. Then new incremental backups no longer match the snapshot in the slave instance. To synchronize it with the master, you can import a complete data backup into the slave instance.

## Import table data from a snapshot (Shared Repository)



MaxDB version 7.7 is able to administer several snapshots at the same time.You can create and drop snapshots in online mode.

An instance (reader) can access to the snapshot of another instance (provider) via the I/O interface and import tables logically.

Access to the snapshot is done in read-only mode. Changed blocks of the imported tables are stored physically in the data volumes of the reader.

In that way using a master system a lot of system copies on the level of tables or schemas, respectively, can be created. The required space of the reader is basically determined by the changed blocks.

The readers subject to the usual concept for MaxDB backups whereas only those blocks are saved that are stored in the reader. For a restore the snapshot of the accordant provider must be accessible.

The import of a snapshot and the related tables also works within the same instance if a second schema is used.

## Questions ?