Database Systems
WS 08/09

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Topics (1/6)

- fundamental system concepts
- storage media
  - disk
  - flash
  - main memory
- storage management
  - principles
  - page/block mapping and replacement
- data layout - mapping data items to pages
  - vertical
  - horizontal
  - column grouping
  - hybrid mappings, PAX, fractured mirrors
  - compression
  - free memory management

Data Layout - Mapping Data Items to Pages.

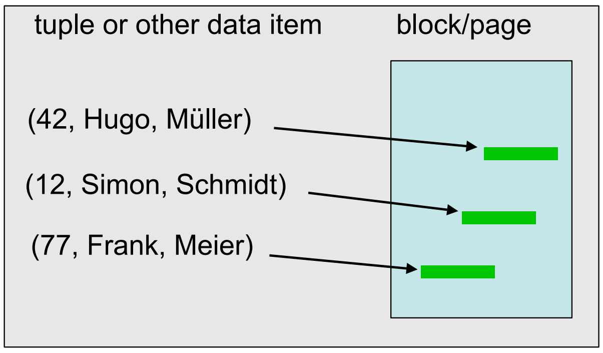
Overview

- So far we considered how to organize pages/blocks in memory and on external storage
- however, data items may be much smaller than a page
  - tuples
  - objects
  - graph nodes
  - XML nodes
  - etc.
- Therefore: we need to think about the mapping from data items to blocks/pages
- **Note:** This is not trivial and may have huge impact on overall system performance.

Data Item Management

Tasks: Mapping from data items to pages/blocks

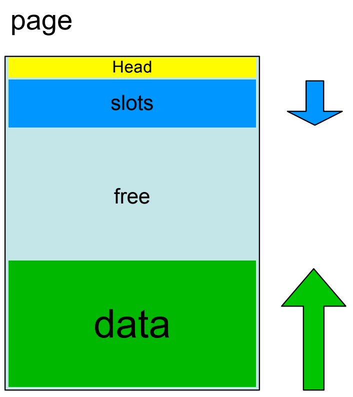
- Agenda
  - structure of a page
  - tuple addressing
  - tuple mapping
  - tuple layout
  - storage models
    - NSM
    - DSM
    - PAX
    - Fractured Mirrors
  - compression
  - long fields
  - memory management



Tuples-IDs.

Structure of a Page

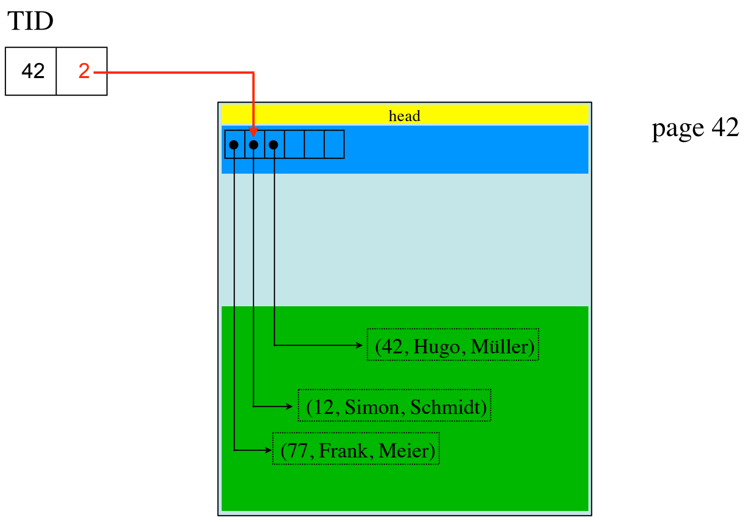
- A page consists of three parts:
  - head (meta data, e.g. page id, log sequence number: see recovery section)
  - slots (pointers to tuples)
  - data (tuple data)
- slot = (pointer, size of the tuple)
- space for slots is allocated top-down
- space for tuple data is allocated bottom-up



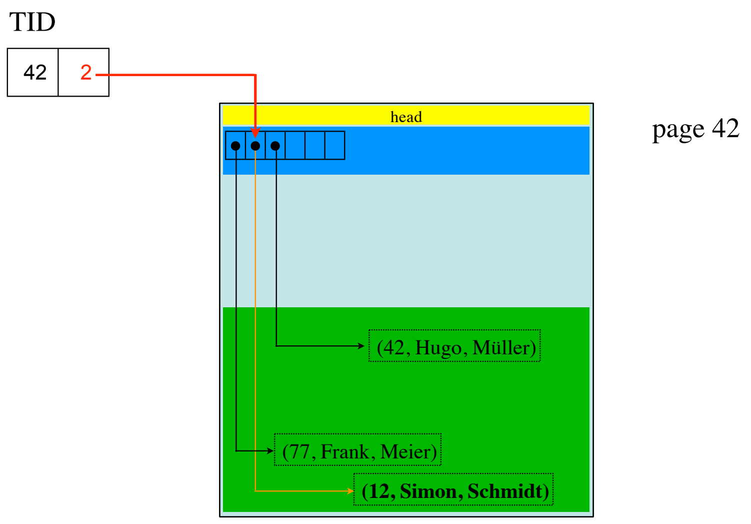
Advantage: tuple may easily migrate inside a page

Tuple IDs (TID)

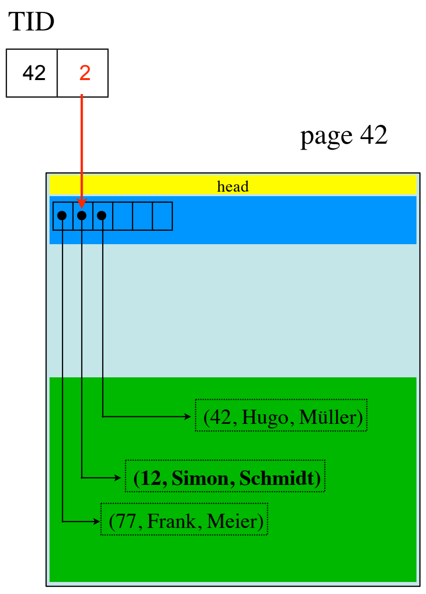
- Indirection based on tuple-ID (TID)
  TID = (page, slot)



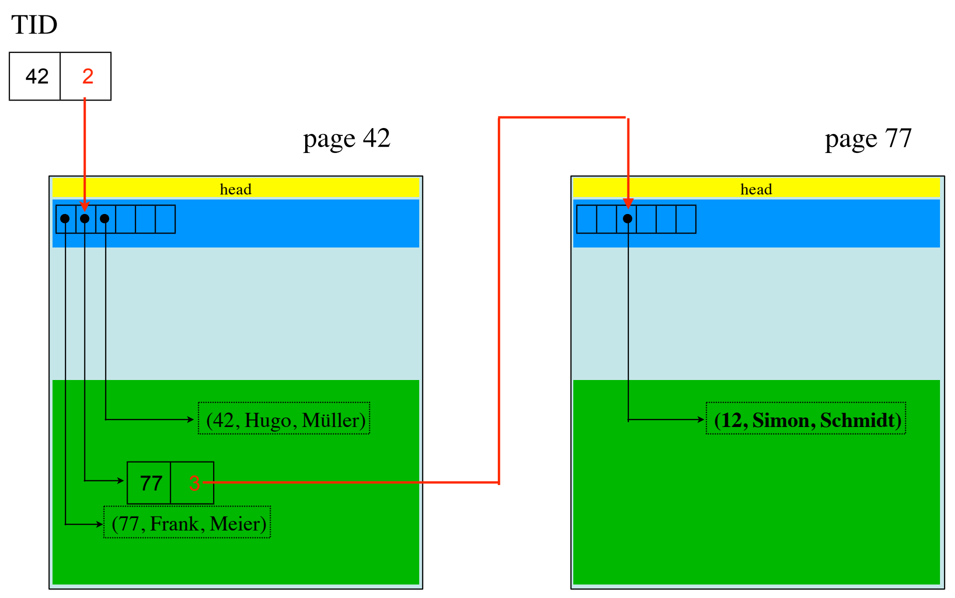
Migration of Tuples Inside a Page



Migration of a Tuple to Another Page



Migration of a Tuple to Another Page



Discussion

- access trivial if tuple does not migrate to a new page
- migration to other page using forward TIDs
- if migrated tuple migrates again: update first forwarding TID

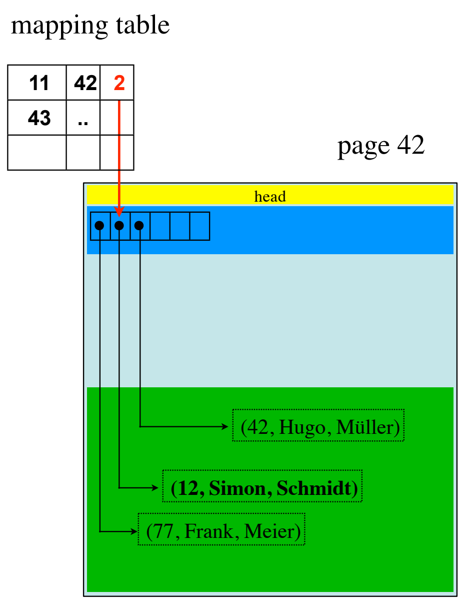
⇨ at most one indirection caused by TID

- performance
  - at least one page access required
  - at most 2 page accesses required
    (if forward TID has to be followed)

Indirect Addressing: Mapping Table

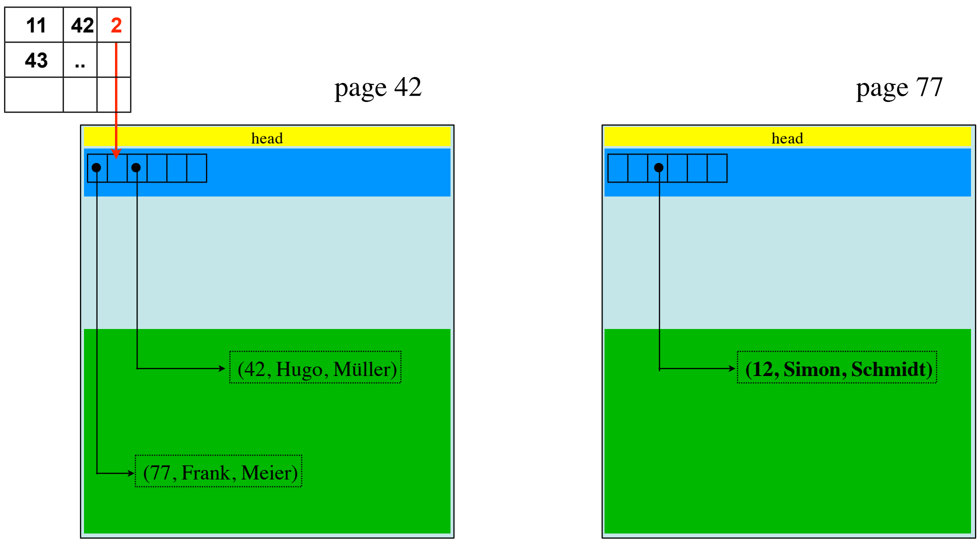
- Idea:
  - 1. keep a separate mapping table
  - 2. hide physical addresses
    (outside world only knows logical addresses)
  - no forwarding
  - if tuple needs to be moved: change entry in mapping table

Migration of Tuples: Mapping Table



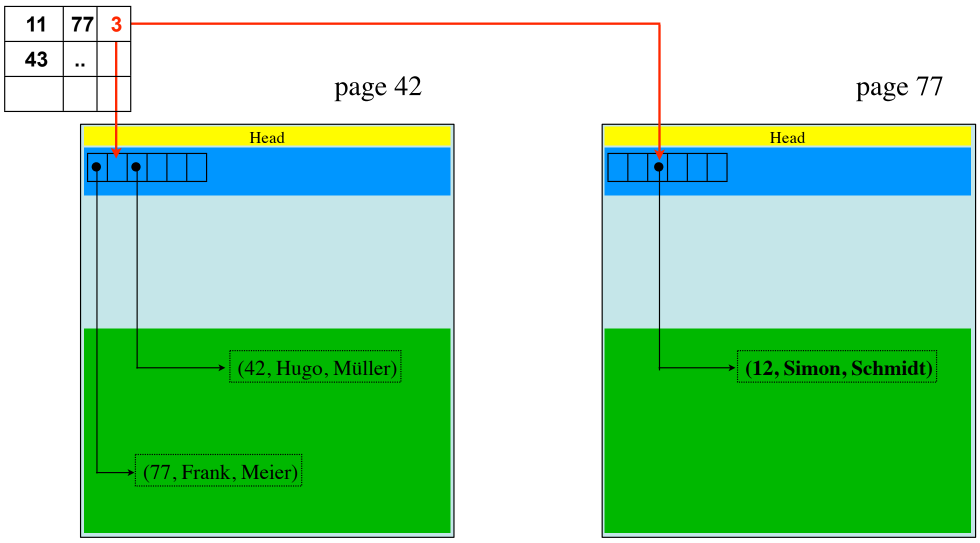
Migration of Tuples: Mapping Table

mapping table



Migration of Tuples: Mapping Table

mapping table



Mapping Table

- Drawbacks of a mapping table:
  - 2 block accesses (1 mapping table block + 1 data block)
- Advantage:
  - no space wasted for forward TIDs

Mapping Table (optimized, aka PPP)

- Drawbacks of a mapping table:
  - 2 block accesses (1 mapping table block + 1 data block)
- Optimization:
  - Access to mapping table can be avoided if frequently accessed entries are kept in a separate cache in main memory

11	42	2
43	..	

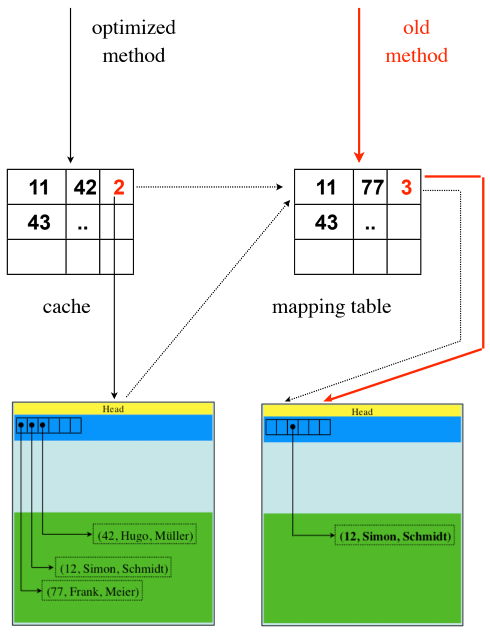
cache

11	77	3
43	..	

mapping table

Mapping Table (optimized, aka PPP)

```
Algorithm to find a tuple
    IF tuple address contained in cache:
        no I/O access on mapping table
        address := cache-address
        if tuple was not found at address:
            I/O-access on mapping table
    ELSE
        I/O-access on mapping table
```



Further Optimizations

- Observation: Mapping table corresponds to a big index page!
- So why not store the mapping

  logical tuple address $\longrightarrow$ physical tuple address

  in an index structure in the first place, e.g., a B^+-tree?
- Discussion
  - Advantages:
    - implicit ordering of entries guaranteed
    - no additional memory management required
  - Disadvantages:
    - expensive access using a multi-level tree structure (for each tuple access) --> Thus we should not do this!
    - memory usage

Tuple Layout.

How to Store Values: Data and Metadata

- Separation of data and metadata
  - **Metadata**: data in DB catalogue
    - attribute name
    - type
  - **Data**: data on each page/block
    - actual values
- Note:
  - In XML data and metadata are stored together:

```
<tuple>
  <firstname> hugo </firstname>
  <lastname> müller </lastname>
</tuple >
```

Tuple Layout

- fixed-sized part:
  - stores all values having a type of fixed size
  - e.g. numeric(10,2), date, char[42]
  - Advantage: direct addressing
    address = sizeof(type) * pos
- variable-sized part:
  - e.g. varchars
  - store size and pointer in fixed-size part
  - store actual values in variable-sized part
  - Disadvantage: indirect addressing
    address = pointer
  - Important: if variable-sized types are used for any attribute of a tuple the direct addressing of the fixed-sized part is still possible!

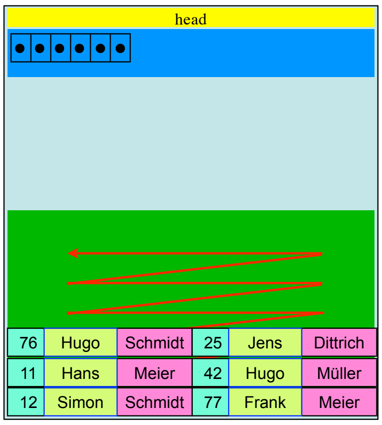
Tuple Layout

- NULL-values
  - small bitmap of fixed size at the beginning of each tuple
  - “1” if attribute is set to NULL, else “0”
  - Advantage: simple and efficient

Column, Row, and Hybrid Mappings.

Data Item Mapping

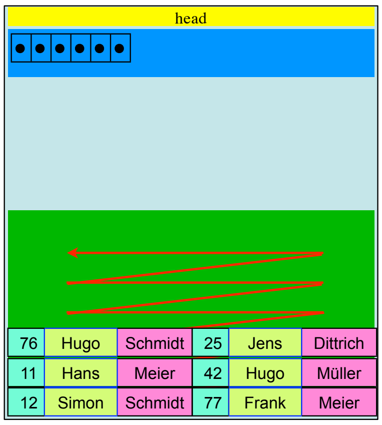
Key	fname	lname
77	Frank	Meier
12	Simon	Schmidt
42	Hugo	Müller
11	Hans	Meier
25	Jens	Dittrich
76	Hugo	Schmidt


head
76 Hugo Schmidt 25 Jens Dittrich
11 Hans Meier 42 Hugo Müller
12 Simon Schmidt 77 Frank Meier

row-wise assignment of
tuple values to page

n-ary Storage Model (NSM)

Key	fname	lname
77	Frank	Meier
12	Simon	Schmidt
42	Hugo	Müller
11	Hans	Meier
25	Jens	Dittrich
76	Hugo	Schmidt


head
76 Hugo Schmidt 25 Jens Dittrich
11 Hans Meier 42 Hugo Müller
12 Simon Schmidt 77 Frank Meier

- tuple values are assigned row-wise to page
- all attribute values of a tuple are adjacent on the page

Decomposition Storage Model (DSM)

RID	Key	fname	lname
1	77	Frank	Meier
2	12	Simon	Schmidt
3	42	Hugo	Müller
4	11	Hans	Meier
5	25	Jens	Dittrich
6	76	Hugo	Schmidt

RID	Key
1	77
2	12
3	42
4	11
5	25
6	76

RID	fname
1	Frank
2	Simon
3	Hugo
4	Hans
5	Jens
6	Hugo

RID	lname
1	Meier
2	Schmidt
3	Müller
4	Meier
5	Dittrich
6	Schmidt

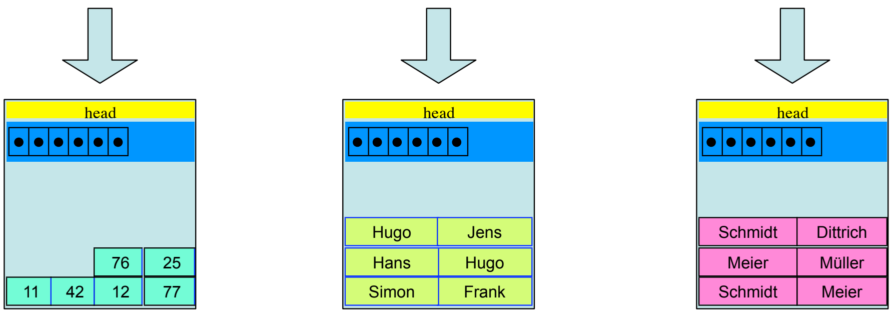
- split table into set of two-column tables
- alternatively: split table into one-column table storing the RID implicitly (array-like representation)

Decomposition Storage Model (DSM)

RID	Key
1	77
2	12
3	42
4	11
5	25
6	76

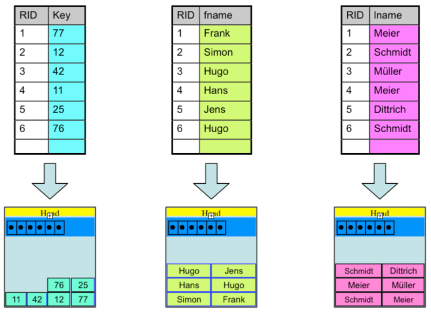
RID	fname
1	Frank
2	Simon
3	Hugo
4	Hans
5	Jens
6	Hugo

RID	lname
1	Meier
2	Schmidt
3	Müller
4	Meier
5	Dittrich
6	Schmidt



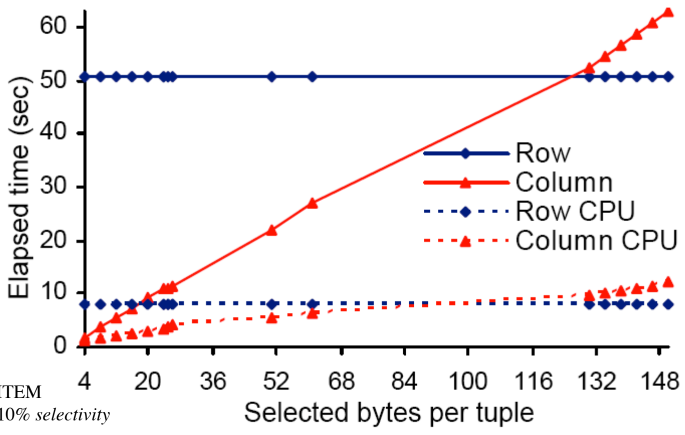
Decomposition Storage Model (DSM)

- optimized for accessing few attributes
- Advantage: very efficient when only few attributes need to be accessed
- Disadvantage: inefficient when many attributes are accessed
- Disadvantage: tuple information distributed to several pages => seeks



- Literature
  - Don S. Batory: On Searching Transposed Files. ACM Trans. Database Syst. 1979.
  - George P. Copeland, Setrag Khoshafian: A Decomposition Storage Model. SIGMOD 1985

Some Recent Study on Column Stores



select L1, L2 … **from** LINEITEM
where *predicate* (L1) *yields* 10% *selectivity*

- Tuple width: 150 bytes, 16 attributes, 9.5GB table
- Literature: Performance Tradeoffs in Read-Optimized Databases, Harizopoulos et.al, VLDB 2006

Column Stores

- Several Products
  - Sybase IQ (since early 90ies)
  - Applix
  - Monet DB (main memory)
  - SAP BI Accelerator (main memory)
  - Vertica (main memory)
  - ...
- Will become more and more important given current hardware trends
- Student in 1995: What is tape?
- Student in 2010: What is a hard disk?

Fractured Mirrors

- Idea:
  - keep both representations row-store and column store
  - depending on type of query pick appropriate store
- This idea is related to indexing.
- We will come back to this in the context of projection and bit-sliced indexes.
- Literature:
  - Ravishankar Ramamurthy, David J. DeWitt, Qi Su: A case for fractured mirrors. VLDB J. 12(2): 89-101 (2003)

Note: Intra- versus Inter-page Sequential Layout

- DSM groups data by attribute (intra-page mapping)
- effect for query processing:
  - only pages containing those attributes need to be loaded
  - total number of pages loaded is reduced
  - total amount of data loaded into the caches is reduced
- however keep in mind:
  - whether all pages pertaining to the same attribute are sequentially stored on external memory (e.g., disk) is determined at a different level: the storage manager (inter-page mapping)

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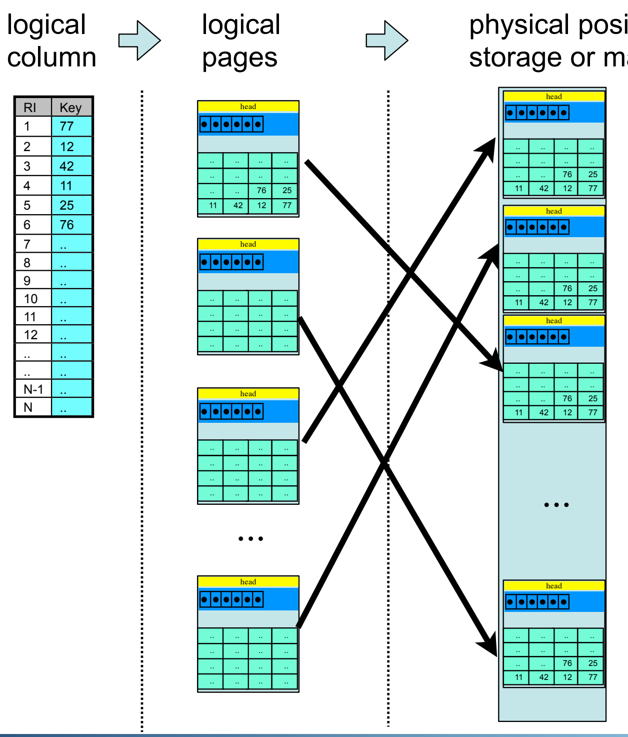
Intra-page Non-Sequential Layout



RI	Key
1	77
2	12
3	42
4	11
5	25
6	76
7	..
8	..
9	..
10	..
11	..
12	..
..	..
..	..
N-1	..
N	..

Effect: random I/O even though column is logically sequential

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Note: Intra- versus Inter-page Sequential

- Example:
  - consider you need to read all values for a given attribute a42
  - => need to read all blocks containing values for attribute a42
  - if blocks pertaining to attribute a42 are not sequentially stored on disk, this may in the worst case trigger one random I/O per block!
  - sequential layout on external storage would be great in this case...

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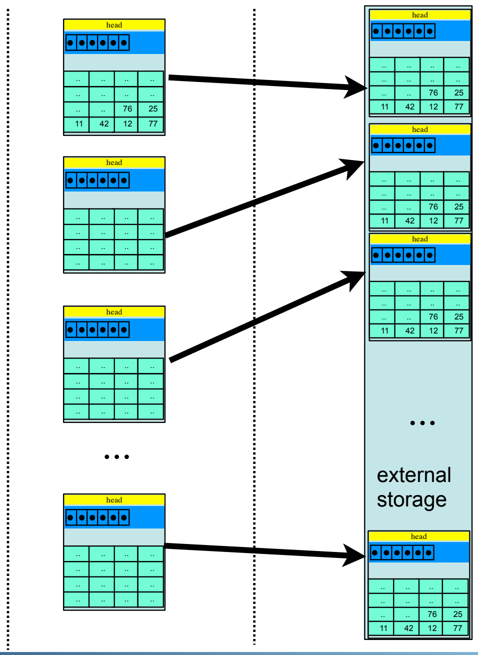
Intra-page Sequential Layout

logical column → logical pages → physical position on external storage or main memory

RI	Key
1	77
2	12
3	42
4	11
5	25
6	76
7	..
8	..
9	..
10	..
11	..
12	..
..	..
..	..
N-1	..
N	..



Effect: sequential I/O

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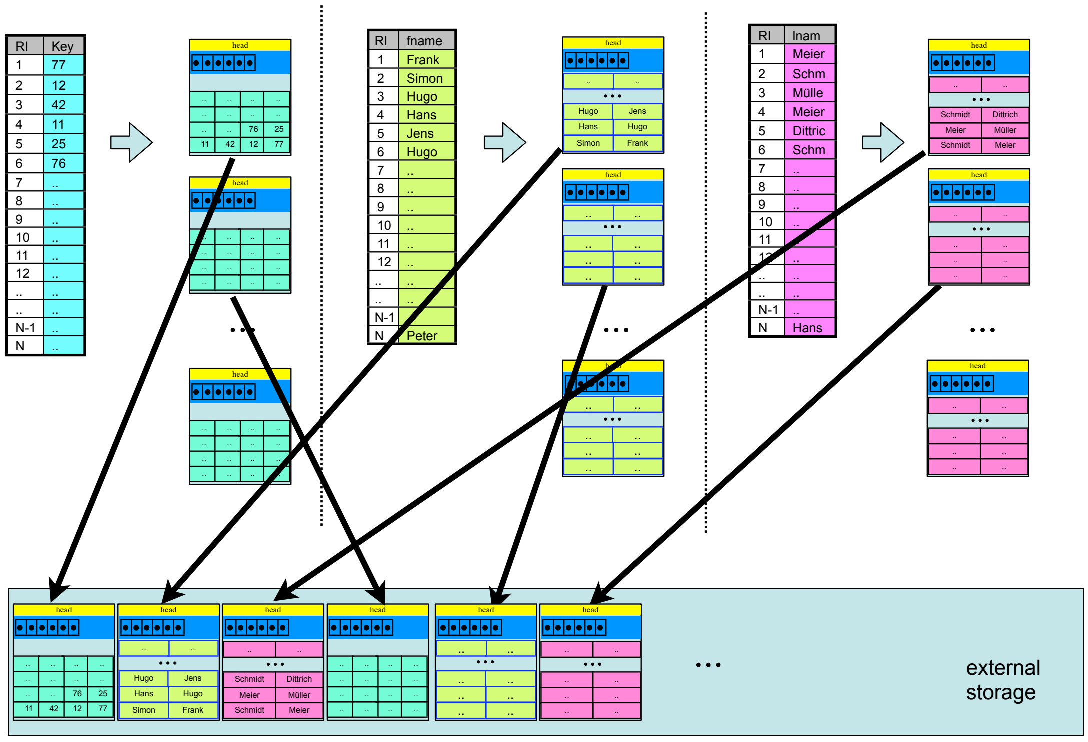
Column Grouping

RI	Key
1	77
2	12
3	42
4	11
5	25
6	76
7	..
8	..
9	..
10	..
11	..
12	..
..	..
..	..
N-1	..
N	..

RI	fname
1	Frank
2	Simon
3	Hugo
4	Hans
5	Jens
6	Hugo
7	..
8	..
9	..
10	..
11	..
12	..
..	..
..	..
N-1	..
N	Peter

RI	lnam
1	Meier
2	Schm
3	Mülle
4	Meier
5	Dittric
6	Schm
7	..
8	..
9	..
10	..
11	..
12	..
..	..
..	..
N-1	..
N	Hans



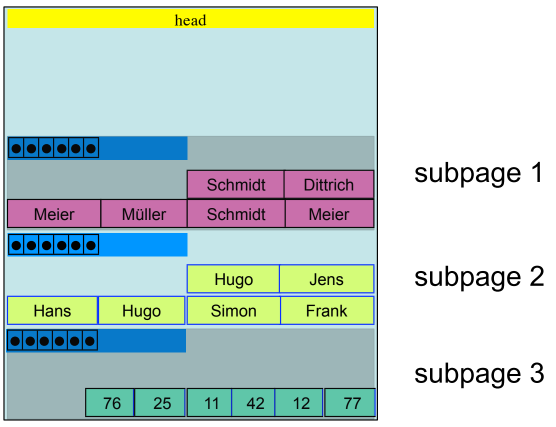
Column Grouping

- Main effect: inter-page locality among tuples (like NSM...)
- In contrast to NSM no gain in terms of I/O
- Inside a page sequential layout: good for cache hierarchy if you do main memory processing page-wise (less cache misses)
- However:
  - Consider some of the attributes are frequently accessed together
  - then you may adapt the grouping to this
  - keep frequently accessed columns grouped
  - keep infrequently accessed columns as separate columns
- In addition, if you have frequent access to attributes (a,b,c) and (e,b,f), you may even replicate b and store it in both groups.

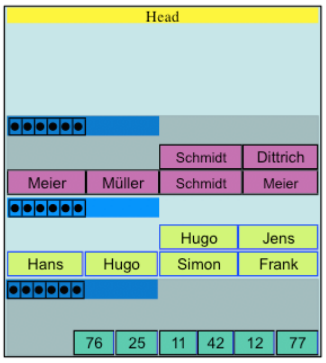
Partition Attributes Across (PAX)

- Another Idea: co-locate values of the same attribute **inside** a page

Key	fname	lname
77	Frank	Meier
12	Simon	Schmidt
42	Hugo	Müller
11	Hans	Meier
25	Jens	Dittrich
76	Hugo	Schmidt



Partition Attributes Across (PAX)



- Advantages
  - improves locality for single attributes
  - data values are reorganized inside a page only
    $\Rightarrow$ no change to the outside system
    (if appropriate information hiding was used.)
  - tuple reconstruction cheap
  - 15%-2x performance improvements when compard with NSM
- Disadvantages
  - not the best possible solution for decision support (DSS, OLAP)
  - DSM wins...
- Literature: Anastassia Ailamaki, David J. DeWitt, Mark D. Hill, Marios Skounakis: Weaving Relations for Cache Performance. VLDB 2001.

How to Map Long Tuples

- Problem:
  - What if a tuple is larger than a page?
  - Example: Blobs (Binary Large Objects)
- 1. Solution
  - split tuple into pieces of size page_size
  - create index (byteoffset $\longrightarrow$ block) for pieces using a hash-table or a b$^+$-tree
- 2. Solution
  - store tuple in separate storage space (e.g. file system of the OS)
  - store only a link to the separate storage on the DB-page

Compression.

ASOK, TAKE THESE PROJECT SUMMARIES AND SUMMARIZE THEM INTO ONE SUMMARY.
AND WHEN YOU'RE DONE, TAKE THAT SUMMARY AND SUMMARIZE IT.
WHAT IS A SHORTER WORD FOR DOOMED?
www.dilbert.com
scottadams@aol.com
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Compressing Data to External Storage

- in addition to the methods shown so far, we may compress data before mapping it to external storage
- this means
  - when storing data on external storage we compress the data
  - when loading data from external storage we decompress the data
- disadvantages
  - CPU time to compress data (possibly at update time)
  - CPU time to decompress data (possibly at query time)
- advantages
  - less space used on external storage
  - less money spend for external storage
  - **better overall performance** if (de-)compress faster than gain in saved I/O

Lossless Versus Lossy Compression

- most type of information systems will require lossless compression:
  - RLE
  - type compression
  - dictionary-based compression
  - LZW
- otherwise correcteness cannot be guaranteed
- lossy algorithms may however work in cases when correctness is not required:
  - multimedia data, e.g., image search (VA-file)
  - data mining: clustering, outlier detection, sampling

Lossless Versus Lossy Compression

- also lossy indexing:
  - lossy compression considered a prefiltering step
    - retrieve candidate set with lossy index
    - compute precise result from candidates
  - has to make sure that lossy index retrieves superset of the actual result
  - otherwise: result will not be correct
- in general strong relationship between compression and indexing...
- most obvious example: huffman codes
- other examples: z-codes (see indexing slides later on)

Performance Gain Example 1

- assume
  - large sequential scan
  - 100 MB/s bandwidth
  - 3 GB data
  - => 30 seconds to scan
- compression ratio 1:3
  - just 10 seconds I/O-time to scan (1 GB to read)
  - however plus CPU time to decompress
  - can you decompress all that data within 30 sec CPU time? (note: overlap of CPU and I/O-time)
  - let‘s say we have a single 3 GHz CPU
  - thus we may spent up to **90 clocks per byte** to decompress and would still be better than uncompressed...

General Trade-Off

- De-/Compression Time versus Compression Ratio
- In general: the higher the compression ratio the more expensive it becomes to compress and decompress the data
- methods like ZIPF/LZW usually too slow
- requires a method with a “good“ trade-off
- lightweight-compression
- not the perfect space gain, yet will not ruin query performance
- choice of methods depends on storage scenario, type of information system...

Performance Gain Example 2

- assume
  - query processing algorithm operating on large amounts of data
  - algorithm needs to store temporary data on disk
  - for instance:
    - external sorting needs to store and read initial and/or intermediate “runs“
    - external partitioning needs to store and read initial and intermediate “partitions“
  - in the end: manage **external queues of data on disk**
  - again: external queues basically lead to sequential I/O
- compression ratio 1:3
  - same considerations as in Example 1
  - however: we also have to compress the data
  - therefore
  - I/O of compressed data plus CPU time for compress and decompress
  - sum of this should be faster than I/O of uncompressed data

Additional Advantage: Main Memory DB

- for some systems compression may make the difference to letting the system become a main memory system!
- For example: consider you have 300 GB uncompressed data but 100 GB of main memory only
- instead of thinking about external memory structures, you should first think of compressing the data in a way that everything fits into main memory
- the gain in terms of query performance will be so huge that almost any compression technique will work

Compression without Decompression

- so far: data needs to be uncompressed at query time
- other idea: do not decompress data but rather adapt query processing methods to directly operate on compressed data
- advantage:
  - no time lost for decompressing
- disadvantage:
  - adaption of query processing methods required
- Literature: Till Westmann, Donald Kossmann, Sven Helmer, Guido Moerkotte: The Implementation and Performance of Compressed Databases. SIGMOD Record 29(3) (2000)

Additional Advantage: Less Cache Misses

- First effect we saw: less data => less I/O on external storage (sometimes no I/O anymore) => better I/O performance
- Second effect: less data => more data fits into caches => less cache misses => better CPU performance
- Example:
  - consider you have a compression ratio of 1:3
  - L1 and L2 caches may now contain three times more data
  - => probability to get a cache misses decreases
- Note
  - you may use different compression schemes for the two levels
  - (1) main memory to caches: optimized for less cache misses
  - (2) external storage to main memory: optimized to get less I/O
- Literature: Marcin Zukowski, Sándor Héman, Niels Nes, Peter A. Boncz: Super-Scalar RAM-CPU Cache Compression. ICDE 2006

Compression Granularity

- individual attribute values
- individual tuples
- entire pages
- entire extents
- DSM may be compressed easily
- Literature (selection):
  - Meikel Pöss, Dmitry Potapov: Data Compression in Oracle. VLDB 2003.
  - Balakrishna R. Iyer, David Wilhite: Data Compression Support in Databases. VLDB 1994.
  - **Managing Gigabytes**: Compressing and Indexing Documents and Images by Ian H. Witten, Alistair Moffat, and Timothy C. Bell. 2nd edition. Morgan Kaufmann Publishing. 1999.

Free Memory Management.

Free Memory Management: Append Only

- Task: Find a free slot for a newly inserted tuple

- Naive implementation (append only):
  - only consider the last created page
  - if tuple fits into this page: OK
  - Else: create a new page
- Discussion
  - very efficient insert
  - poor memory usage (deletes?)

Append Only(n)

- Generalization of append only:
  - only consider the n last created pages
  - if tuple fits into one of this pages: OK
  - Else: create a new page
- Discussion
  - very fast insert
  - still: poor memory usage (deletes?)

Best Fit, First Fit, Next Fit

- Best Fit:
  - start search from the beginning of the page list
  - find optimal page
  - Cost = linear search in list
- First Fit:
  - start search from the beginning of the page list
  - take the first page that fits
  - disadvantage: pages at the beginning of the list will soon be full (waste of time to search through these pages)
- Next Fit:
  - like first fit, but: start search from the last position

Hybrid Approaches HY(n,u)

- Algorithm:

  If memory usage better than u:

      use append only(n)

  Else

      use Next Fit

- Discussion: acceptable compromise?

Free Memory Table

- Idea: for each page: store available memory
- Implementation: extra table in segment either
  1. providing accurate memory information

page	1	2	3	4	5	
bytes avail.	f_1	f_2	f_3	f_4	f_5	

2 byte/entry

2 byte/entry

or 2. providing approximate memory information

page	1	2	3	4	5	
bytes avail.	f_1	f_2	f_3	f_4	f_5	

2 byte/entry

k bits/entry

memory available >= $(f_i / 2^k)$ * page_size

Space Map

- Drawback of free memory table: linear search to find suitable page
- Solution "space map":
  - inversion of the free memory table

page	1	2	3	4	5	
bytes avail.	f_1	f_2	f_3	f_4	f_5	

$\Rightarrow$

bytes avail.	f_4	f_2	f_3	f_5	
page	4	1,2	3	5	

  - index on " bytes avail." attribute
  - binary search
  - works for accurate and approximate variant

Space Map

- Trade-off: granularity vs. memory needed
- Trade-off: granularity vs. performance
- Advantage: efficient search for best fit: O(log n)
- Disadvantage: maintenance cost for space map

Defragmentation.

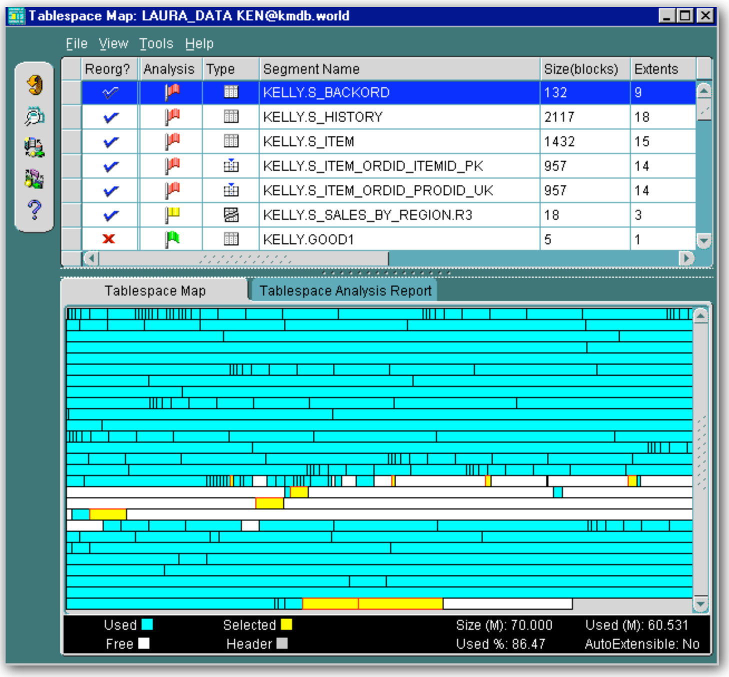
Fragmented Data Layout

- in the long run update and insert operations will lead to fragmentation
- similar problems as for file systems in operating systems:
  - fragmented data on disk may be a major bottleneck in overall system performance
  - my current Macbook is a negative example:
    (Note I really love Macs but the current version of the storage system is just crap.)
  - massive slow-down due to tons of random I/O operations
  - rule of thumb: if we decrease numer of random IOs, we increase overall system performance

How to Defrag

- physical layout on external memory should be optimized for access patterns
- we have already seen an example with columns
- in general: sequential layout is a good idea
- however, you may use any layout which gives the best performance
- Example
  - booting an operating system in single threaded mode
  - this will always lead to the **same** sequence of page accesses
  - so why not record the block sequence once
  - then layout blocks sequentially on disk
  - effect for next boot: no random I/O at boot time
  - I am not aware of any OS doing this. It would be so simple.

Example: Oracle Tablespace Map



Tablespace Map: LAURA_DATA KEN@kmdb.world

File View Tools Help

Reorg?	Analysis	Type	Segment Name	Size(blocks)	Extents
✓			KELLY.S_BACKORD	132	9
✓			KELLY.S_HISTORY	2117	18
✓			KELLY.S_ITEM	1432	15
✓			KELLY.S_ITEM_ORDID_ITEMID_PK	957	14
✓			KELLY.S_ITEM_ORDID_PRODID_UK	957	14
✓			KELLY.S_SALES_BY_REGION.R3	18	3
✗			KELLY.GOOD1	5	1

Tablespace Map | Tablespace Analysis Report

Used 🟦 Selected 🟨 Size (M): 70.000 Used (M): 60.531
Free ⬜ Header ⬜ Used %: 86.47 AutoExtensible: No

- visualizes data layout
- helps you to understand performance problems
- allows you to defrag data

- source: http://www.oracle.com/technology/products/oracle9i/datasheets/oem_tuning/tuning.html

Next Topic: Indexing.