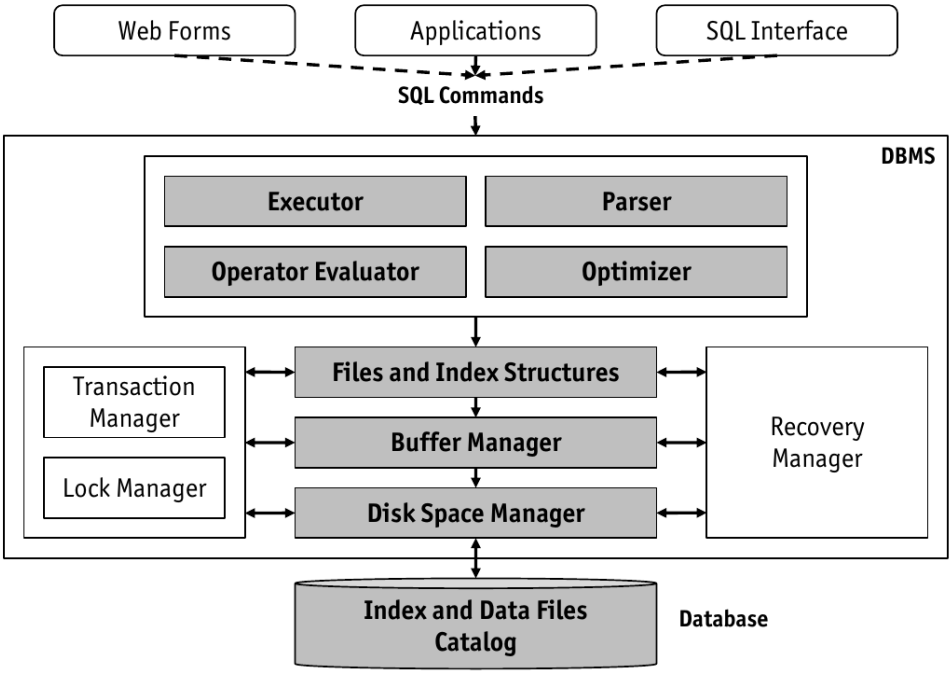
DBMS Architecture



Topic	Exercise
Introduction	Disk Storage
Disk and Buffer Management	Disk Management
File Management	Buffer Management
Tree-structured Indexing (I)	
Tree-structured Indexing (II)	B+ Trees
Hash-based Indexing	Disk-based Hash Indexes
Query Evaluation and Optimization	
External Sorting	External Sorting
Evaluating Relational Operators (I)	
Christmas Break	
Evaluating Relational Operators (II)	Relational Operators
Relational Algebra Equivalences	
Histograms	Cost and Estimation
Nested Queries	Query Optimization
Optimizer Architectures	
Physical Database Design and Tuning	Flashback

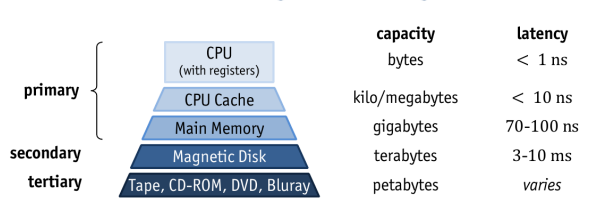
Contents

Chapter 1

Disk, Buffer & File Management

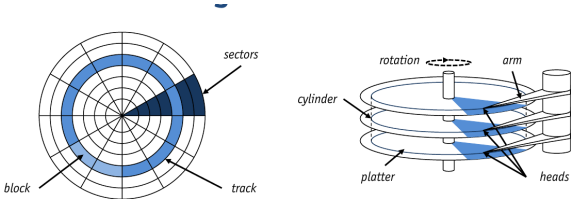
1.1 Hardware

1.1.1 Memory Hierarchy:



Only data stored in non-volatile memory is persistent across shutdowns and the primary level of memory (address space) is not large enough to map the complete data-base, thus the need for magnetic disks, SSDs, tape and the like. The main goal of the primary memory level is to hide I/O latency by using faster memory to cache a subset of all necessary data. With increasing speed and decreasing size, the cost of the memory is aproximately increasing by a factor of 100 per level.

1.1.2 Magnetic Disks:



Blocks: Data is read and written to disk one block at a time. Size is multiple of the sector size.

Sector: A sector is a single part of a track

Track: A track is a ring on a plater

Cylinder: A cylinder is the set of all tracks with the same diameter

Head: The head is mounted at the arm which is controlled by a stepper motor to move from track to track as the disk rotates

The access time t is defined as

$$t = t_s + t_r + t_t$$

where

t_s seek time (movement of disk head to desired track)

t_r rotational delay (waiting time until the desired sector has rotated under the disks head)

t_t transfer time (time taken to read/write the block)

Sequential reads are much faster as one only needs to seek and to wait for the disk to rotate one time per sequential instead of on every access as in random I/O
Optimizations made by disk manufacturers:

- Track skewing: align sector of each track sucessively to avoid rotational delay in longer sequential scans
- Request scheduling: sort the disk requests so that minimal arm movement is needed
- zoning: outer tracks are longer than inner so can be divided into more tracks

⇒ Implies I/O focusedness as disks are major bottleneck and data needs to be in main memory to compute over it ⇒ Implies distance metric for records (i.e. same block, track, same cylinder, same disk, ...

⇒ Clustering I/O ops vs. Declustered Storage

1.1.3 RAID

Redundant Array of Independent Disks, provide redundancy to improve mean time to failure, improve performance using striping, hardware and software based implementations.
Raid Levels:

0 Striping
Best Write performance, better read performance, no reliability improvements

1 Mirroring
On-line backup, no performance improvements

10 Mirroring + Striping
reasonable performance w extra reliablility; write intensive workloads, small subsystems

2 ECC
inferior to 3

3 Bit-Interleaved parity
Apropriate for large continuous block requests, bad for many small requests

4 Block-Interleaved Parity
Inferior to 5

5 Block-Interleaved Distributed Parity Good general purpose solution, best performance with redundancy for small and large r and large w ops

6 P+Q Parity
highest level of reliability, like 5 with 2 parities

Redundancy schemes: Parity Groups: Disks or disk space may be grouped and parity may only be computed and stored per group

- ECC:
Initialization: uses bit-level striping and Hamming code to compute ECC for data of n disks which is stored on n-1 additional disks
Recovery: determine lost disk by using the n-1 extra disks and correct its content from one of those
- Parity Scheme
Initialization: let $i(n)$ be the number of bits set to 1 at position n on disk; n-th parity bit is set to 1 if $i(n)$ is odd else 0
Recovery: Let $j(n)$ be the no. of bits set to 1 at pos n on the non-failed disks. if $j(n)$ odd and parity bit 1 or $j(n)$ even and parity bit is 0, n-th value on failed disk is 0, else 1

1.1.4 SSDs

Traits:

- Very low read latency (¡ 0.01ms)
- high transfer rate
- bad random write performance (worse than HDD)
- Page level read and write (only blocks, no single bits or bytes) e.g. 128 kB
- block-level delete e.g. 64 Pages = 1 block ⇒ major reason for bad random write performance: if internal fragmentation high: delete complete block reorganize pages and write the changes including addition

Outlook: SSDs and Storage Area Network.

1.2 Disk Space Manager

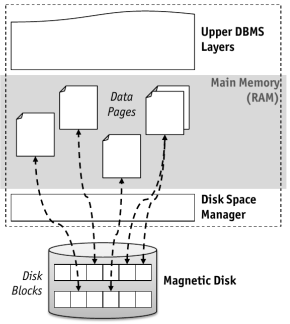
A Page is a disk block that has been brought into memory, thus pages and disk blocks equal in size. Sequences of pages map onto sequences of disk blocks. A Page is the unit of storage for all components in the system

1.2.1 Tasks

- Allocates/deallocates disk space/Pages; read/writes pages to disk
- track page locations (page no ↔ OS file + offset ↔ head, sector and track, disk)
- tracks free and used blocks
- does Segementation (aka Table spaces, Partitions,...)

Disk Space Manager

- Locality-preserving mapping
  - track page locations and block usage internally
  - page number ↔ physical location
- Abstract physical location
  - OS file name and offset within that file
  - head, sector, and track of a hard disk drive
  - tape number and offset for data stored in tape library
  - ...



tracking free and used blocks:

- Linked List of free blocks:
  1. pointer to first free block
  2. when block is freed pre/append it to free block list
  3. when block is needed take it from the list and adjust pointers
- Bitmap of free blocks
  1. reserve ceil($|blocks|/8$) bytes
  2. interpret bitwise (0 = free, 1 = used)

Segmentation/Partitioning enables a DBMS to split data store into smaller units called e.g. partitions, segments, table spaces, storage pools, ... Those are then layered e.g. n tables per m table spaces per t segments of s storage pools each beeing one logical os volume.

1.3 Buffer Manager

The BufferManager mediates between external storage (Disk space manager) and main memory using the **BufferPool**. It is a designated area of main memory which is organized by the buffer manager. Each frame in the buffer pool has the same size as a page. pages are loaded into frames as needed using **pin(pageNo)** and evicted by a policy after the page got **unpin(pageNo, dirty)**. A page is only written if it's marked dirty using **unpin(pageNo, true)**. Thus all DB transactions need to be surrounded by pin and unpin.

1.3.1 Buffer Allocation policy

Problem: How to allocate buffer frames to each transaction?

Global One BufferPool for all transactions
Good overall usage of space, all TX are taken into account
Transactions may hurt another by using up buffer frames and force others to reload their pages "extrenal page thrashing"

Local Treat all TX equal
TX cannot hurt each other
bad overall usage of space, some TX may occupy vast amounts without using them while others starve "internal page thrashing"

Mainly mixed/hybrid aproaches perform best.
Static allocation: assign buffer budget once for aech TX
Dynamic allocation: Adjust buffer budget according to some policy.

Examples:

- Local MRU
  Keep local LRU stack for each transaction
  keep global free list for not pinned pages
  1. allocate a page from free list
  2. allocate a page from the LRU stack of the requesting TX
  3. allocate a page from TX with largest LRU stack
- Working Set Model
  Avoid trashing by allocating just enough buffers to each TX
  observe page requests for a certain interval and deduce optimal budged from that based on the ratio of available pages

1.3.2 Buffer Replacement policy

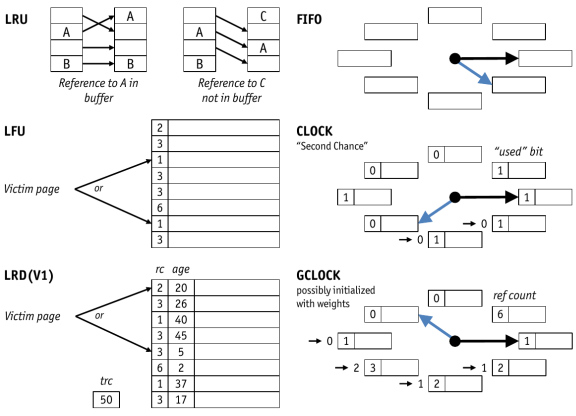
Typical Buffer Replacement Policies

DBMS typically implement more than one replacement policy

- **FIFO** ("first in, first out")
- **LRU** ("least recently used"): evicts the page whose latest `unpin()` is longest ago
- **LRU-*k***: like LRU, but evicts the *k* latest `unpin()` call, not just the latest
- **MRU** ("most recently used"): evicts the page that has been unpinned most recently
- **LFU** ("least frequently used")
- **LRD** ("least reference density")
- **CLOCK** ("second chance"): simulates LRU with less overhead (no LRU queue reorganization on every frame reference)
- **GCLOCK** ("generalized clock")
- **WS, HS** ("working set", "hot set")
- **Random**: evicts a random page

Criteria		Age of page in buffer: no	since last reference	total age
References	none	Random		FIFO
	last		LRU CLOCK GCLOCK(V1)	
	all	LFU	GCLOCK(V2) DGCLOCK	LRD(V1)
			LRD(V2)	

Criteria matrix for victim selection



Details of LRD

- Record the following three parameters
  - $trc(t)$ total reference count of transaction t
  - $age(p)$ value of $trc(t)$ at the time of loading p into buffer
  - $rc(p)$ reference count of page p
- Update these parameters during a transaction's page references (`pin` (*pageNo*) calls)
- Compute **mean reference density** of a page p at time t as

$$rd(p,t) := \frac{rc(p)}{trc(t)-age(p)}, \text{ where } trc(t) - rc(p) \geq 1$$

- **Strategy** for victim selection
  - chose page with least reference density $rd(p,t)$
  - many variants exist, e.g., for gradually disregarding old references

Hot Set with Disjoint Page Sets

Mode of Operation

1. only those queries are activated, whose Hot Set buffer budget can be satisfied immediately
2. queries with higher demand have to wait until their budget becomes available
3. within its own buffer budget, each transaction applies a local LRU policy

- Properties
  - ⊖ **no sharing** of buffered pages between transactions
  - ⊖ risk of **internal thrashing** when Hot Set estimates are wrong
  - ⊖ queries with large Hot Sets **block** following small queries (or, if bypassing is permitted, many small queries can lead to **starvation** of large queries)

Hot Set with Non-Disjoint Page Set

Mode of Operation

1. queries allocate their budget stepwise, up to the size of their Hot Set
2. local LRU stacks are used for replacement
3. request for a page p
   i. if found in **own LRU stack**: update LRU stack
   ii. if found in **another transaction's LRU stack**: access page, but do not update the other LRU stack
   iii. if found in **free list**: push page on own LRU stack
4. call to `unpin` (*pageNo*) : push page onto free list stack
5. filling empty buffer frames: taken from the bottom of the free list stack

- As long as a page is in a local LRU stack, it cannot be replaced
- If a page drops out of a local LRU stack, it is pushed onto free list stack
- A page is replaced only if it reaches the bottom of the free list stack before some transaction pins it again

Priority Hints

- **Idea**: with `unpin` (*pageNo*) , a transaction gives one of two possible indications to the buffer manager
  - **preferred page** managed in a transaction-local partition
  - **ordinary page** managed in a global partition
- **Strategy**: when a page needs to be replaced...
  1. try to replace an ordinary page from the global partition using LRU
  2. replace a preferred page of the requesting transaction using MRU
- **Advantages**
  - much simpler than Hot Set, but similar performance
  - easy to deal with "too small" partitions

Variant: Fixing and Hating Pages

Operator can **fix** a page if it may be useful in the near future (e.g., *nested-loop join*) or **hate** a page it will not access any time soon (e.g., *pages in a sequential scan*)

Prefetching

- Buffer manager can try to **anticipate** page requests
  - asynchronously read ahead even if only a single page is requested
  - improve performance by overlapping CPU and I/O operations
- Prefetching techniques
  - **prefetch lists: on-demand, asynchronous read-ahead**
    e.g., when traversing the sequence set of an index, during a sequential scan of a relation
  - **heuristic (speculative) prefetching**
    e.g., sequential n-block look-ahead (cf. drive or controller buffers in hard disks), semantically determined supersets, index prefetch, ...

1.4 Files and File-Index Structures

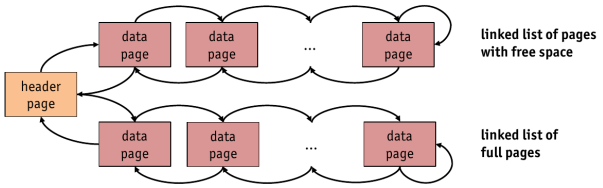
RID Each record has a unique identifier that is used like it's address/pointer. Internally the file structure must be able to map a given rid to the page and slot containing the record.

File $\xrightarrow[\text{contains}]{}$ Pages $\xrightarrow[\text{contains}]{}$ Records $\xrightarrow[\text{contains}]{}$ Fields

1.4.1 Free Slot Management

File structure needs to keep track of pages with free space

Linked List of Pages



Operation $f \leftarrow$ `createFile` (n)

1. DBMS allocates a free page (called file **header page**) and stores an entry <*n*, *header page*> to a known location on disk
2. header page is initialized to point to two doubly linked list of pages: one containing **full pages** and one containing **pages with free space**
3. initially, both lists are **empty**

Operation $rid \leftarrow$ `insertRecord` (f, r)

1. try to **find a page** p in the free list with space > $|r|$
2. should this fail ask the disk space manager **to allocate a new page** p
3. record r is **written** to page p
4. since generally $|r| \ll |p|$, p will belong to the **list of pages with free space**
5. a **unique** *rid* for r is computed and returned to the caller

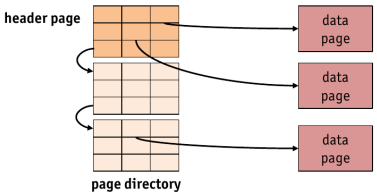
Operation `deleteRecord` (f, r)

1. may result in **moving the containing page** from the list of full pages to the list of pages with free space
2. may even lead to **page deallocation** if the page is completely free after deletion

Operation `openScan` (f)

1. **both** page lists have to be traversed

Directory of Pages



- **Header page** contains first page of a chain of **directory pages**
  - each entry in a directory page identifies a page of the file
  - |page directory| ≪ |data pages|
- Free space management is also done through the directory
  - space vs. accuracy **trade-off**: from *open/closed* flag to exact information
  - for example, entries could be of the form <*page addr p*, *nfree*>, where *nfree* indicates **actual amount of free space** (e.g., in bytes) on page p

- Keeping **exact** counter value (e.g., *nfree*) during updates may produce a performance bottleneck in multi-user operations
  - each transaction, whose update changes the amount of available free space, needs to update this meta-information in the directory
  - locking (or some other form of synchronization) needs to be applied to avoid lost updates
  - frequent updates of the same record lead to "hot data item", introducing lock-wait queues and thus reducing degree of parallelism
- Keep **fuzzy information** on available free space in directory, e.g., ⌊nfree/8⌋ (units of 8 bytes or some other granularity)
  - directory only needs to be updates for "large" changes in the available free space on a page
  - page itself contains the exact information (of course)

	Linked List	Directory
+	easy to implement	free space management more efficient
-	most pages in free space list	memory overhead

1.4.2 Record Insertion strategy

Standard Append, Best Fit, First Fit, Next Fit

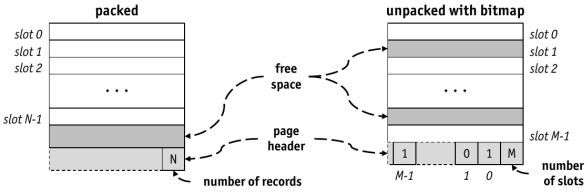
Free Space Witness

1. classify pages into buckets
2. for each bucket remember any page that falls into that one as witness
3. only perform best/first/next fit if no witness pahe is recorded for the bucket. Else insert according to witness information
4. populate witness information e.g. as side effect while searching

1.4.3 Page Formats

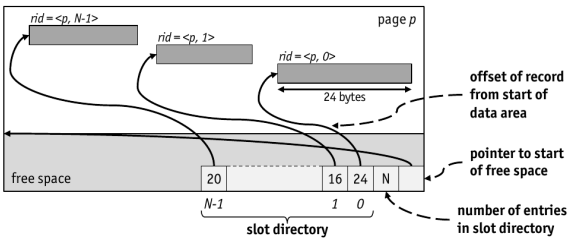
In the real world rids are PageNo + slotNo

Free Slot Bitmap



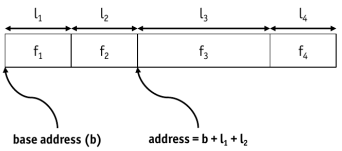
- Avoid record copying and therefore rid modifications
  - **`deleteRecord`**`(f, <p, n>)` simply needs to set bit *n* in bitmap to 0
  - **no other** *rids* affected

Variable-Length Records



1.4.4 Record Formats

Fixed-Length Fields

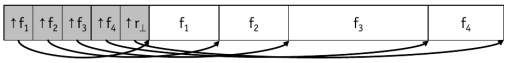


- Fixed-length record: each field has a **fixed length** and the number of fields is also **fixed**
  - fields can be stored **consecutively**
  - given the address of the record (b), the address of a particular field can be calculated using information about **lengths of preceding fields** (l_i)
  - this information is available from the DBMS **system catalog**

Variable-Length Fields

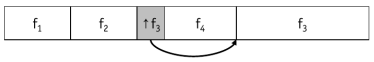
- Multiple variants exist to store records that contain variable-length fields
  1. use a special **delimiter symbol** ($) to separate record fields: accessing field f_n requires a scan over the bytes of fields $f_1 \ldots f_{n-1}$

  2. for a record of *n* fields, use an **array** of *n* + 1 offsets pointing into the record (the last array entry marks the end of field f_n)



Record Formats

- Another popular record format to support variable-length fields is a **combination** of the delimiter and array approach
  - variable-length fields are stored **at the end of the record**
  - fixed-length fields and pointers to variable-length fields are stored sequentially, starting **at the beginning of the record**



- Note that it may even make sense to use variable-length records to store fixed-length records
  - support for null values (see above)
  - schema evolution, i.e., adding or removing columns

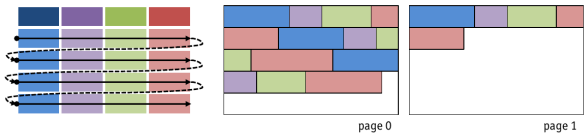
1.4.5 Alternative Page Layouts

Different layouts optimize different workloads:

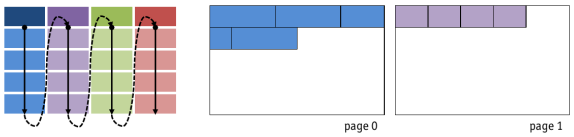
- row-major favors singular access of whole tuples (i.e. insert/update/delete, OLTP workloads)
- column-major favors table scans accessing only a subset of attributes (Scans/aggregations/analytics, OLAP workloads)
- optimally we want both ⇒ Hybrid layouts

Row-store & column Sotre aka **n-ary Sorage Model (NSM)** and **Decomposition Storage Model (DSM)**

- So far, we populated data pages in **row-wise** order

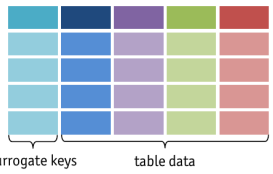


- We could also populate data pages in **column-wise** order

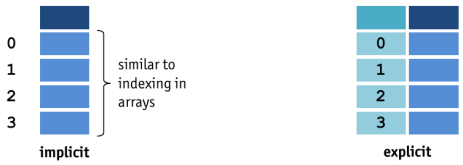


Surrogate Keys How to address in a column store

- One solution is to use **surrogate keys**



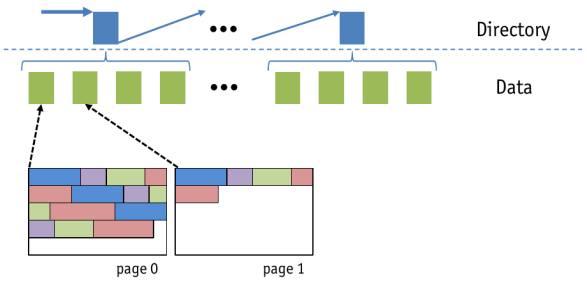
- Surrogate keys can be **implicit** or **explicit**



Binary Association Tables are tables broken into individual columns (DSM), using implicit surrogate keys to join.

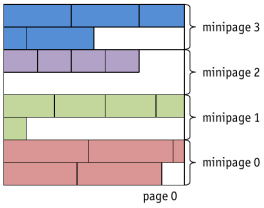
- early reconstruction: Access operator needs to know about columnar layout (and assemble the tuple as needed)
- late reconstruction: All operators need to support columnar layout

Table Files separates directory pages and data. Directory pages form a linked list while pages are listed below



Partition Attributes Across

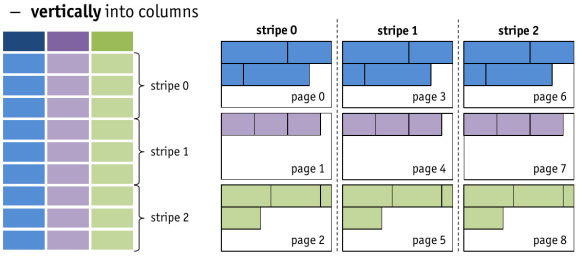
- A hybrid approach is the **Partition Attributes Across (PAX)** layout
  - divide each page into **minipages**
  - group attributes into them
- On-disk performance of NSM
- Cache friendliness/compression characteristics of DSM



Optimized Row Columnar Stripe size is used as parameter to determine how row/column oriented the layout is:

- stripe size 1: row-major
- stripe size n: column major

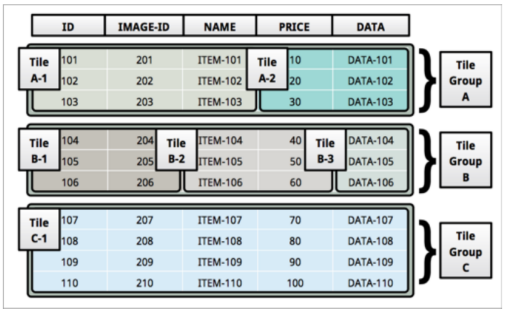
- Another hybrid approach is the **Optimized Row Columnar (ORC)** file format used by *cstore_fdw* for PostgreSQL
- ORC partitions records twice
  - **horizontally** into stripes
  - **vertically** into columns



Flexible Storage Model Abstract physical from logical storage in **tile groups**.
Data is divided into two sets:

- Hot data: insert/update/delete heavy data stored in row-major
- Cold data: mostly Read data is stored column-major

Physical tiles (tile groups) are stored on disk



1.4.6 Addressing Schemes

Direct Addressing

Relative Byte Address (RBA) uses a disk file as persistent address space, using byte offset as rid

+	very efficient to access pages and records
-	no stability wrt. moving records

Page Pointers (PP) uses disk page numbers as rid

+	very efficient to access page, locating a record within a page is also cheap (in-memory op)
-	only stable when moving records within a page

Indirect Addressing

Logical Sequence Numbers (LSN) assigns logical numbers to records and use address translation table to map to PP or RBA

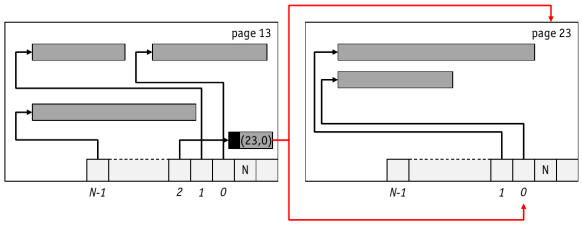
+	full stability
-	additional I/O op for table look-up (often in the buffer)

Logical Sequence Numbers with Portable Page Pointers (LSN/PPP) tries to save the look-up by using a PP. If the PP is not valid a table look-up is performed

+	full stability, if PPP valid saves one I/O
-	two additional I/O ops: one for loading the page and checking the PPP, one for the table look-up (often in the buffer)

Tuple Identifier with forwarding pointer (TID/FP) uses <PageNo, SlotNo> pair as rid, where the slotNo is an index in page-local offset array. On relocation, leave fowarding address on origin page

+	full stability
-	extra I/O if relocated, extra space for the pointer



1.5 File Organization

Cost Model :

Parameter	Description
b	number of pages per file
r	number of records per page
D	time to read a disk page
C	CPU time needed to process a record
H	CPU time taken to apply a function to a record e.g. comparison or hash

Cost of Scan :

File Org	Description	est. Cost
Heap	read all pages, process each of the records per page	$b \cdot (D + r \cdot C)$
Sorted	Same as for heap files	$b \cdot (D + r \cdot C)$
Hashed	additional free space due to overflow chain avoidance	$(100/80) \cdot b \cdot (D + r \cdot C)$

Cost of Search w. Equality :

File Org	Description	est. Cost
Heap	if equality test is on primary key, adds factor $\frac{1}{2}$	$b \cdot (D + r \cdot C)$ or $\frac{1}{2} b \cdot (D + r \cdot C)$
Sorted	Assuming equality test is on sort criterion, use bin search	$\log_2 b \cdot D log_2 r \cdot C$
Hashed	Assuming equality test on hash attribute. Directly leads to the page containing the hit	$H + D + r \cdot C$ or $H + D + \frac{1}{2} r \cdot C$

Cost of Search w. Range :

File Org	Description	est. Cost
Heap	Can appear everywhere =¿ full scan	$b \cdot (D + r \cdot C)$
Sorted	Search for equality=lower and scan sequentially until the first record with A ¿ upper	$\log_2 b \cdot D + \log_2 r \cdot C + \lfloor \frac{n}{r} \rfloor \cdot D + n \cdot C$
Hashed	Performs worst as additional space needs to be scaned	$(100/80) \cdot b \cdot (D + r \cdot C)$

Cost of Insert :

File Org	Description	est. Cost
Heap	Can be written to an arbitary page, involves reading and writing the page	$2D + C)$
Sorted	Insert into a sepcific place and shift all subsequent	$\log_2 b \cdot D + \log_2 r \cdot C + \frac{1}{2} \cdot b \cdot (2 \cdot D + r \cdot C)$
Hashed	Write to the page that the hash fn indicates	$H + D + C + D$

Cost of Delete :

File Org	Description	est. Cost
Heap	Read, delete and write	$2D + C)$
Sorted	delete and shift all subsequent	$D + \frac{1}{2} \cdot b \cdot (2 \cdot D + r \cdot C)$
Hashed	Access by rid is faster than hashing so same as heap	$D + C + D$

Summary :
There is no single file organization that performs best overall. The choice can make serious differences. Indexes may provide all of the benefits with modest overhead.

Chapter 2

Hash- and Tree-based Indexes

2.1 General Indexes

Use an auxillary structure to provide support for certain functions. Variants: 1 resembles the sorted file on attribute A, thus only one such index should exist to avoid redundant storage of records. 2 and 3 use rids where 3 groups records that match a search key k.

1. <k, $< \ldots, A = k, \cdots >$>
2. <k, rid>
3. <k, [rid_1, ...]>

Clustered & Unclustered Index: An Index is clustered if the underlying file is sorted according to the indexed key. It's unclustered if the file is not sorted at all or on another key. So there may be at most one clustered index besides redundant indexes.

A sparse index is an index where only the smallest/largest key per page is stored instead of per record. Sparse Indexes can only be created if they are clustered indexes. If all records are present in the index it's called dense.

Multi-Attribute Indexes apply the previous techniques to a combination of attribute values. This enables the lookup of all combined attributes in common or a prefix of the multi-attribute key in case of a B+Tree index.

2.2 Tree-based Indexes

Containing only one record per page those auxiliary structures recurse until all data fit onto one page in terms of representation. Thus they are very useful for range selections.

Fan-out: The average number of childrean for a non-leaf node.

2.2.1 Indexed Sequential Access Method

1. Sort the file on attribute A and store it
2. for each page maintain a pair $< k_i, p_i >$ conatining the most extreme key wrt. a comparator of a certain Page i and a pointer to that page
3. use them as array to access the right page without scanning the page

- One-level ISAM ⇒Recurse on output to obtain Multi-level ISAM
- ISAM is always static. Insert if space left or use overflow chains ⇒ search performance will dicrease over time
- since ISAM is static **it doesn't need to be locked**
- costs for searching: $\log_F N$

2.2.2 B+Tree

- Similar to ISAM but dynamic wrt. updates ⇒ no overflow chains/remains balanced
- Search performance is also $\log_F N$
- supports updates efficiently, guaranteed occupancy of 50
- non-leafes have same layout as in ISAM
- leaf nodes contain pointers to records (instead of ISAM: Pages)
- B+Tree index moves data records on split and merge, thus rid changes
  1. $k_i^* =< k_i, < \text{attr}_1, \cdots >>$
  2. $k_i^* =< k_i, \text{rid} >$
  3. $k_i^* =< k_i, [\text{rid}_1, \ldots] >$
- occupancy rule might be relaxed
- duplicates are not supported, supported as normal values (affects search, checking the siblings) or using variant 3 grouped

Searching: As in ISAM, check the key and perform bin search until leaf is reached.

Insert: look for the right place, if not full insert. If full check siblings for redistribution (and update separator if necessary). If not possible split.

Split: Create new node, redistribute keys, take first value of the second leaf as new separator and propagate the spilt upwards.

Delete: Search leaf, delete value from it. If minimal occupancy below limit, check siblings for redistribution. If not possible, merge.

Merge: Merge with sibling node, delete key from parent level pointing to second leaf and propagate upwards

Key Compression uses prefixes or smaller data types to just approximate the actual values in the leafs. Another variant is to store common prefixes only once per node e.g. iri,o,r

Bulk loading If index is created, the tree is traversed |records| times. Most DBMS provide therefore a bulk tree loading utility.

1. for each key k in the data file, create a sorted list of pages of index leaf entries (does not imply sorting the data file itself on key k for variants 2,3; var 1 creates a clustered index)
2. allocate an empty root and let the first pointer p_0 point to the first entry of the sorted list
3. for each leaf level node/list entry insert the index entry $< p_n, \min(val(n)) >$ into the rightmost index node above the leaf level

Invariants

- Order: d
- Occupancy: $d - 1 <$ |values| $< 2d + 1$. Exception: root
- Fan-out: Non-leaf holding m keys has m+1 children
- Sorted Order nodes contain elements in comparator order, all children to the left are smaler wrt. comparator than the value in the parent and the subtrees to the right.
- Balanced: All leaf nodes are on the same level
- Height: $\log_d N$

2.3 Hash-based Indexes

"Unbeatable for Equality operations", no support for range queries

Design of a hash function

1. **By division**: simply define
$$h(k) = k \bmod N$$
   - this guarantees that range of $h(k)$ to be $[0, \ldots, N-1]$
   - **prime numbers** work best for N
   - choosing $N = 2^d$ for some d effectively considers the least d bits of k only
2. **By multiplication**: extract the fractional part of $Z \cdot k$ (for a specific Z) and multiply by hash table size N
$$h(k) = \lfloor N \cdot (Z \cdot k - \lfloor Z \cdot k \rfloor) \rfloor$$
   - the (inverse) **golden ratio** $Z = {}^{2}/_{\sqrt{5}+1} \approx 0.6180339887$ is a good choice (according to D. E. Knuth, *"Sorting and Searching"*)
   - for $Z = {}^{z}/_{2^w}$ and $N = 2^d$ (w is the number of bits in a CPU word), we simply have $h(k) = msb_d(Z \cdot k)$, where $msb_d(x)$ denotes the d **most significant bits** of x (e.g., $msb_3(42) = 5$)

Hash Function Family

Given an initial hash function h and an initial hash table size N, one approach to define such a family of hash functions $h_0, h_1, h_2, \ldots$ would be

$$h_{level}(k) = h(k) \bmod (2^{level} \cdot N)$$

where $level = 0, 1, 2, \ldots$

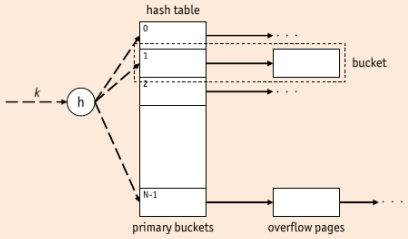
2.3.1 Static Hashing

1. Allocate a fixed area of N successive disk pages **primary buckets**
2. for each bucket install a pointer to a chain of overflow pages (init to null)
3. Define a hash function h with range $[0, N-1]$.

- search: 1 I/O
- insert & delete: 2 I/O
- Hash function should distribute evenly, overflow chains need distinct hash functions to avoid recursive collisions
- locking only required based on buckets/overflow chains

local depth d, global depth n

Static hash table



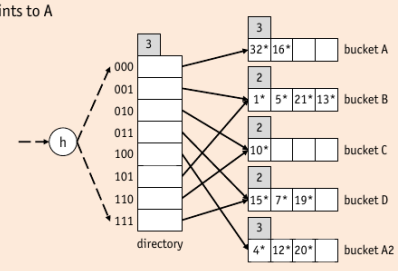
- A primary bucket and its chain of overflow pages is referred to as a **bucket**
- Each bucket contains index entries $k*$, which can be implemented using any of the variants ❶, ❷, and ❸

2.3.2 Extendible Hashing

Uses in-memory bucket directory to keep track of the actual primary buckets by adapting the hash function and the access to the buckets

Example: Insert a record with $h(k) = 20$

2. To address the new bucket, the directory needs to be **doubled** by simply copying its original pages (bucket pointer lookups now use 2 + 1 = 3 bits)
3. Let bucket pointer for $\underline{100}_2$ point to A2, whereas the directory pointer for $\underline{000}_2$ still points to A



Searching: buckets is an array of size 2^{n-1} where each entry points to a corresponding bucket

1. n = global depth
2. b = $h(k)\&(2n-1)$ // mask last n-1 bits
3. bucket = buckets[b]

Insert: If there is free space in the corresponding bucket just insert, else

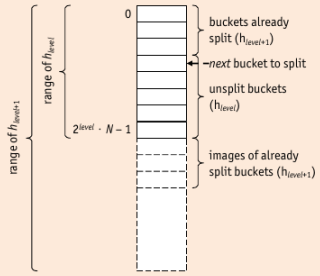
1. Split the bucket by creating a new bucket and use bit position $d+1$ to redistribute the entries where d is the local depth
2. if $d+1 > n$, $n++$ and double the directory size. The hashing uses now d+1 bits
3. let the old bucket be pointed to by 0[...] and the new be pointed to by 1[...]
4. if no value goes to the new bucket an overflow chain is initialized

Delete: Analog to insertion

2.3.3 Linear Hashing

Rehashing

With every bucket split, next walks down the hash table. Therefore, hashing via h_{level} (search, insert, and delete) needs to take **current** *next* **position** into account.



$h_{level}(k)$ { < *next*: bucket already split, **rehash**: find record in bucket $h_{level+1}(k)$
≥ *next*: bucket not yet split, i.e., **bucket found**

1. Init: level = 0, next = 0
2. current hash fn = h_{level}, active hash buckets: $[0, \ldots, 2^{\text{level}} \cdot N]$
3. whenever a certain criterion is met, split the bucket which the next pointer references (e.g. % occupancy reached in a bucket, overflow chain grew longer than x, ...

Split : All buckets with position ¡ next have been already rehashed

1. Allocate new bucket and append it at position $2^{\text{level}} \cdot N + \text{next}$
2. Redistribute entries in the bucket that next references by rehashing with $h_{\text{level}+1}$
3. next++, if next $> 2^{\text{level}} \cdot N - 1$, next = 0; level++

Insert: like in static hashing plus additional check for split criterion

Delete: like with static hashing plus if bucket$[2^{\text{level}} \cdot N + next]$.empty:

1. remove page pointed to by bucket$[2^{\text{level}} \cdot N + next]$ from hash table
2. next–, if next ¡ 0, level–, next = $2^{\text{level}} \cdot N + next$

Chapter 3

Query Evaluation

3.1 Overview

3.1.1 System Catalog

size of buffer pool, page size, information and statistics about tables, views, indexes

Information stored in the system catalog

- **Table metadata**
  - *table name*, *file name* (or some identifier), *file structure* (e.g., heap file)
  - *attribute name* and *type* of each attribute of the table
  - *index name* of each index on the table
  - *integrity constrains* (e.g., primary and foreign key constraints) on the table
- **Index metadata**
  - *index name* and *structure* (e.g., B+ tree)
  - *search key* attributes
- **View metadata**
  - *view name* and *definition*

Statistics

- **Table statistics**
  - *cardinality*: number of tuples *NTuples*(*R*) for each table *R*
  - *size*: number of pages *NPages*(*R*) for each table *R*
- **Index statistics**
  - *cardinality*: number of distinct key values *NKeys*(*I*) for each index *I*
  - *size*: number of pages *INPages*(*I*) for each index (for a tree index *I*, *INPages*(*I*) denotes the number of leaf pages)
  - *height*: number of non-leaf levels for each tree index *I*
  - *range*: minimum present key value *ILow*(*I*) and the maximum present key value *IHigh*(*I*) for each index *I*

Example

Tables

name	file	#tuples	size
Tables	...	6	1
Attributes	...	23	1
Views	...	1	1
Indexes	...	0	1
Sailors	...	40,000	500
Reserves	...	100,000	1000

Attributes

name	table	type	pos
name	Tables	string	1
file	Tables	string	2
#tuples	Tables	integer	3
size	Tables	integer	4
name	Attributes	string	1
table	Attributes	string	2
type	Attributes	string	3
pos	Attributes	integer	4
⋮	⋮	⋮	⋮
sid	Sailors	integer	1
sname	Sailors	string	2
rating	Sailors	integer	3
age	Sailors	real	4
sid	Reserves	integer	1
bid	Reserves	integer	2
day	Reserves	date	3
rname	Reserves	string	4

Views

name	text
Captains	SELECT * FROM Sailors WHERE...

Indexes

name	file	type	#keys	size
Boats	...	B+Tree	100	1

3.1.2 Access Paths

Possible access paths are

- file scan
- index with one matching selection condition
- index scan if all attributes required by the query are contained

If less than 5% are retrieved, a table scan is cheaper.

Hash vs. B+Tree Index: Hash Indexes match if selection contains equality on indexed attribute; B+Trees match if selection contains any condition on an attribute in the trees search prefix. If matches with an index were found in a CNF, those conjuncts are called **primary conjuncts**

The Selectivity of an access path is the number of index or data pages it retrieves. The most selective access path is the one that retrieves least pages.

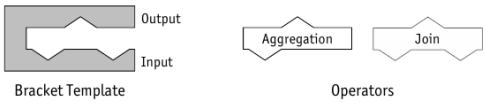
Reduction Factor: The fraction of tuples that satisfy a certain conjunct. For several conjuncts this factor is approximated, making an independence assumption. For range queries uniformity is assumed: For a tree index the reduction factor is estimated using the system catalouge: $\frac{High(T)-value}{High(T)-Low(T)}$

3.1.3 Communication and Scheduling

Pipelining streams insead of writing out the intermediate result.

Materialization writes the intermediate result to disk

Bracket Model



Bracket Template Operators

- Bracket Template
  - operating system and communication support
  - **central scheduler** can fit a single operator into the bracket on demand
- Operators
  - each operator **must** run its own thread, assumes all control within its thread, sends and receives data via networking procedures
  - essentially relies on networking procedures for pacing and flow control
  - each operator defines its own phases, synchronization points, and communication needs that must be known to the bracket implementation

Iterator Model

- To simplify the code to coordinate plan execution, all operators implement a **uniform** iterator interface
  - hides **internal implementation details** of each operators
  - assumes **pipelined evaluation** of the query plan (see next slide)

Iterator interface

open()
- initializes iterator by allocating input and output buffers
- used to pass parameters that modify operator behavior, e.g., a selection condition

next()
- calls **next** on each input operator
- executes operator-specific code to process input tuples
- places results in output buffer
- updates iterator state to keep track of how much input has been consumed

close()
- deallocates state information

Iterator Model

Iterator	open()	next()	close()	State
print	open input	call **next()** on input, format item on screen	close input	
scan	open file	read next item	close file	open file descriptor
select	open input	call **next()** on input, until an item qualified	close input	
hash join without overflow resolution	allocate hash directory, open left *build* input, build hash table calling **next()** on build input, close build input, open right *probe* input	call **next()** in *probe* input until a match is found	close *probe* input, deallocate hash directory	hash directory
merge join without duplicates	open both inputs	get **next()** item from input with smaller key until a match is found	close both inputs	
sort	open input, build all initial run files calling **next()** on input, close input, merge run files until only one step is left	determine next output item, read new item from the correct run file	destroy remaining run files	merge heap, open file descriptors for run files

3.2 External Sorting

3.2.1 Two-Way Merge Sort

Sorts files of arbitary size (here $N = 2^k$) with three pages of buffer space in multiple passes, producing a certain number of sub-files called **runs**

- **Pass 0**: Sorts each of the 2^k input page individually in main memory, resulting in the same 2^k runs
- **subsequent passes:** Merge pairs of runs into larger runs. Pass n produces $2^k - n$ runs
- pass k produces one overall sorted final run

Pass 0 (**input:** $N = 2^k$ unsorted pages, **output:** 2^k sorted pages)
1. **Read** N pages, one page at a time
2. **Sort** records, page-wise, in main memory
3. **Write** sorted pages to disk (each page results in a **run**)

This pass requires **one page** of buffer space

Pass 1 (**input:** $N = 2^k$ sorted pages, **output:** 2^{k-1} sorted runs)
1. **Open** two runs r_1 and r_2 from Pass 0 for reading
2. **Merge** records from r_1 and r_2, reading input page by page
3. **Write** new two-page run to disk, page by page

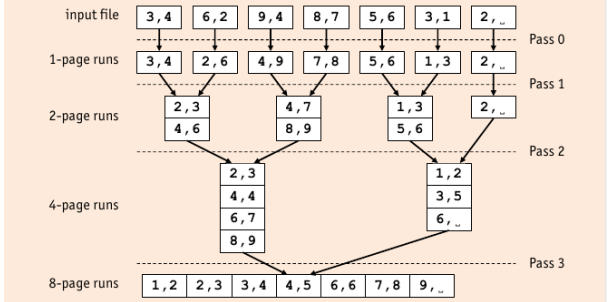
This pass requires **three pages** of buffer space

⋮

Pass n (**input:** $N = 2^{k-n+1}$ sorted runs, **output:** 2^{k-n} sorted runs)
1. **Open** two runs r_1 and r_2 from Pass $n-1$ for reading
2. **Merge** records from r_1 and r_2, reading input page by page
3. **Write** new 2^n-page run to disk, page by page

This pass requires **three pages** of buffer space

Example: 7-page file, 2 records/page, keys k shown, $\theta = <$



Costs: Each pass needs to read N pages, sort them in-memory and write them out again $\Rightarrow 2N$ I/O ops per pass
in total there are pass 0 and k subsequent pass $\Rightarrow 1 + log_2 N$ In Total Two-way Merge Sort costs

$$2N(1 + log_2 N)\text{I/O ops}$$

3.2.2 External Merge Sort

like 2-way merge sort, but reduces the number of runs by using more buffer space to avoid creating one page runs in pass 0 and reduces the number of passes by merging more than two runs at a time.

External Merge Sort

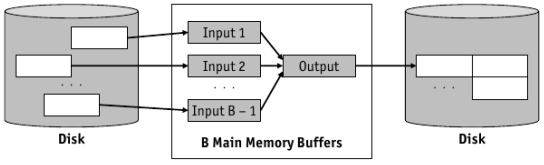
Pass 0 (**input:** N = unsorted pages, **output:** $\lceil N/B \rceil$ sorted pages)
1. **Read** N pages, B pages at a time
2. **Sort** records, page-wise, in main memory
3. **Write** sorted pages to disk (resulting in $\lceil N/B \rceil$ **runs**)

This pass uses B **pages** of buffer space

⋮

Pass n (**input:** $\frac{\lceil N/B \rceil}{(B-1)^{n-1}}$ sorted runs, **output:** $\frac{\lceil N/B \rceil}{(B-1)^n}$ sorted runs)
1. **Open** $B-1$ runs $r_1, \ldots, r_{B-1}$ from Pass $n-1$ for reading
2. **Merge** records from $r_1, \ldots, r_{B-1}$, reading input page by page
3. **Write** new $B \cdot (B-1)^n$-page run to disk, page by page

This pass requires B **pages** of buffer space

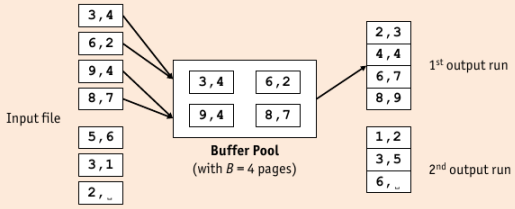


- Suppose B pages are available in the buffer pool
  - B **pages can be read at a time** during Pass 0 and sorted in memory
  - $B-1$ **pages can be merged at a time** (leaving one page as a write buffer)

N	$B=3$	$B=5$	$B=9$	$B=17$	$B=129$	$B=257$
100	7	4	3	2	1	1
1000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

Number of Passes of External Merge Sort

Example: 7-page file, 2 records/page, keys k shown, $\theta = <$, 4 buffer pages, pass 0



Costs: As in two way: read, sort, write $\Rightarrow 2N$
In pass 0 only $\lceil \frac{n}{B} \rceil$ are written thus only needs $\lceil \log_{B-1} \lceil \frac{n}{B} \rceil \rceil$ where B-1 pages are merged at the same time In Total Two-way Merge Sort costs

$$2N(1 + \lceil \log_{B-1} \lceil \frac{N}{B} \rceil \rceil)\text{I/O ops}$$

3.2.3 Optimizations

Block-grouped I/O: read blocks of b pages at once during merge. This decreases the I/O costs by factor b but decreases the fan-in thus increases the number of passes. In Total:

$$2N(1 + \lceil \log_{\lfloor \frac{B}{b} \rfloor - 1} \lceil \frac{N}{B} \rceil \rceil)\text{I/O ops}$$

N	$B=1000$	$B=5000$	$B=10,000$	$B=50,000$
100	1	1	1	1
1000	1	1	1	1
10,000	2	2	1	1
100,000	3	2	2	2
1,000,000	3	2	2	2
10,000,000	4	3	3	2
100,000,000	5	3	3	2
1,000,000,000	5	4	3	3

Number of Passes of External Merge Sort with Block Size $b = 32$

Tree of Losers

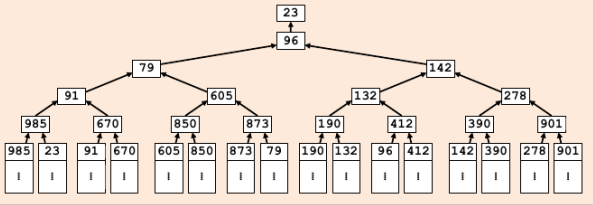
i) The tree is initially filled with one tuple from each input by propagating them up the tree. The winner at each level is moved to the parent and we record if the left or right child won. At the end of this process the first element of the array contains the smallest tuple.

ii) Now we can remove the winner and write it to the output run.

iii) After that we have to refill the tree from below. Since all input runs are sorted, the tree currently contains the smallest tuple of all inputs except for the one the removed tuple came from. We can find that input by tracing the markers of who won/lost down the tree. Then we refill the tree with the next tuple from that input.
If an input is drained, `null` can be used as the next tuple instead to mark an empty slot. We just have to make sure that `null` is compared as greater than any other tuple.
When propagating the new tuple up the tree, we again adapt the winner/loser markers.

iv) Repeat steps ii) and iii) until the *winner* becomes `null`, at which point all input runs are drained and the merge is completed.

Example: Selection tree, read bottom-up



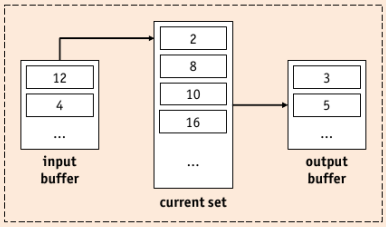
Replacement Sort

Replacement sort

1. Open an empty run file for writing.
2. Load next page of file to be sorted into input buffer. If input file is exhausted, go to 4.
3. While there is space in the current set, move a record from input buffer to current set (if the input buffer is empty, reload it at 2.)
4. In current set, pick record r with smallest key value k such that $k \geq k_{out}$, where k_{out} is the maximum key value in output buffer (if output buffer is empty, define $k_{out} = -\infty$). Move r to output buffer. If output buffer is full, append is to current run.
5. If all k in current set are $< k_{out}$, append output buffer to current run, close current run. Open new empty run file writing.
6. If input file is exhausted, stop. Otherwise go to 3.

Replacement sort

Assume a buffer pool with B pages. Two pages are dedicated **input** and **output buffers**. The remaining $B - 2$ pages are called the **current set**.

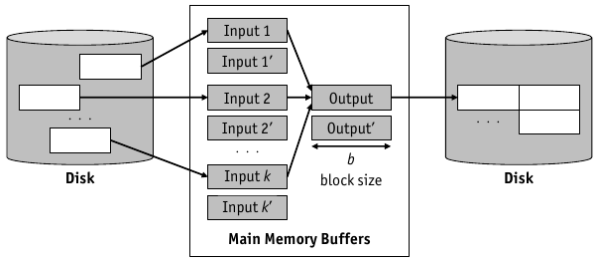


Double Buffering

Double buffering

To avoid CPU waits, **double buffering** can be used.

1. create a second **shadow buffers** for each input and output buffer
2. CPU **switches** to the "double" buffer, once original buffers is empty/full
3. original buffer is reloaded by **asynchronously** initiating an I/O operation
4. CPU **switches** back to original buffer, once "double" buffer is empty/full, etc.



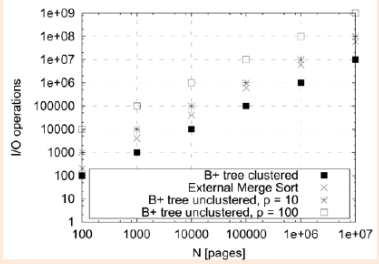
B+ Tree for Sorting Clustered B+Tree Index: just load the N pages as they are already sorted.

Expected page I/O operations for sorting

Let p denote the number of data records per page (typical values are p = 10, ..., 1000). The expected number of page I/O operations to sort using an unclustered B+ tree index is therefore $p \cdot N$ (worst case)

Assumptions in plot

- available buffer space for sorting is $B = 257$ pages
- ignore I/O to traverse B+ tree as well as its sequence set



3.3 Relational Operator Evalutation

Different operator implementations exploit different physical properties:

- availability of indexes
- sortedness of input
- size of input file
- available buffer space
- buffer replacement policy, ...

A logical Operator is an operator used in the relational algebra. A **Physical Operator** is a specific variant of a logical operator. During query processing the **Query Optimizer** choses which physical operator shall replace the logical operator based on the physical properties of the Relations intermediate results.

3.3.1 Join

Most basic variant is to calculate the cross product between the relations and apply selection according to the join predicate.

Nested Loops Join

- straight foward implementation of cross product and join equivalence
- needs only 3 buffer pages

Nested loops join

```
function ⋈^nl (R1, R2, Rout, p)
  in1 ← openScan (R1) ;
  out ← createFile (Rout) ;
  while (r1 ← nextRecord (in1)) ≠ ⟨EOF⟩ do
    in2 ← openScan (R2) ;
    while (r2 ← nextRecord (in2)) ≠ ⟨EOF⟩ do
      if p(r1, r2) then appendRecord (out, ⟨r1, r2⟩) ;
  closeFile (out) ;
end
```

Cost of $R_1 \bowtie_p^{nl} R_2$

access path	file scan (**openScan**) of R_1 and R_2
prerequisites	none (p arbitrary, R_1 and R_2 may be heap files)
I/O cost	$\underbrace{\|R_1\|}_{\text{outer loop}} + \underbrace{\|R_1\| \cdot \|R_2\|}_{\text{inner loop}}$

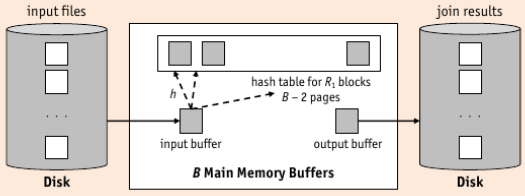
Block Nested Loops Join

- Reads both relations in blocks of b_1, b_2 pages respectively
- Costs: $\lceil \|R_1\| / b_1 \rceil \cdot \lceil \|R_2\| / b_2 \rceil$

General block nested loops join

```
function ⋈^block-nl (R1, R2, Rout, p)
  in1 ← openScan (R1) ;
  out ← createFile (Rout) ;
  foreach b1-sized block in in1 do
    in2 ← openScan (R2) ;
    foreach b2-sized block in in2 do
      for all matching in-memory tuples r1 ∈ R1 block and r2 ∈ R2 blocks,
      add ⟨r1, r2⟩ to the result out
  closeFile (out) ;
end
```

Block nested loops join with hash table



Block nested loops join with hash table

```
function ⋈^block-nl (R1, R2, Rout, p)
  in1 ← openScan (R1) ;
  out ← createFile (Rout) ;
  repeat
    B' ← min (B – 2, #remaining blocks in R1) ;      (do not read beyond ⟨EOF⟩ of R1)
    if B' > 0 then
      read B' blocks of R1 into buffer, hash record r ∈ R1 to buffer page h(r.A1) mod B' ;
      in2 ← openScan (R2) ;
      while (r2 ← nextRecord (in2)) ≠ ⟨EOF⟩ do
        compare record r2 with records r1 stored in buffer page h(r2.A2) mod B' ;
        if r1.A1 = r2.A2 then appendRecord (out, ⟨r1, r2⟩) ;
  until B' < B – 2 ;
  closeFile (out) ;
end
```

Index Nested Loops Join

- Uses index on inner Relation to avoid enumerating the corss product
- particularly usefull when index is clustered and join is very selective

Index nested loops join

```
function ⋈^index-nl (R1, R2, Rout, p)
  in1 ← openScan (R1) ;
  out ← createFile (Rout) ;
  while (r1 ← nextRecord (in1)) ≠ ⟨EOF⟩ do
    probe index on R2 using (key value in) r1 to find matching tuples r2 ∈ R2 ;
    appendRecord (out, ⟨r1, r2⟩) ;
  closeFile (out) ;
end
```

Cost of $R_1 \bowtie_p^{index\text{-}nl} R_2$

access path	file scan (**openScan**) of R_1, index access to R_2
prerequisites	index on R_2 that matches join predicate p
I/O cost	$\underbrace{\|R_1\|}_{\text{outer loop}} + \underbrace{\|R_1\| \cdot (\text{cost of } \textbf{one} \text{ index access to } R_2)}_{\text{inner loop}}$

Costs of an Index access :

- Hash Index: $1.2 \begin{cases} 1.2 & clustered \\ n & unclustered \end{cases}$
- B+Tree: $log(|R_2|) \begin{cases} 1 & clustered \\ n & unclustered \end{cases}$

Sort Merge Join

- Uses sorting to partition both input
- best-case is optimal
- integration into external sort, block-grouped I/O, double buffering, replacement sort can be applied to optimize further
- output sorted on join attribute

Sort-merge join

```
function ⋈^sort-merge (R1, R2, Rout, R1.A = R2.B)
  if R1 not sorted on A then sort it;      if R2 not sorted on B then sort it;
  out ← createFile (Rout) ;
  in1 ← openScan (R1) ;                    in2 ← openScan (R2) ;
  r1 ← nextRecord (in1) ;                  r2 ← nextRecord (in2) ;
  while r1 ≠ ⟨EOF⟩ ∧ r2 ≠ ⟨EOF⟩ do
    while r1.A < r2.B do r1 ← nextRecord (in1) ;
    while r1.A > r2.B do r2 ← nextRecord (in2) ;
    r'2 ← r2 ;                                  (remember current position in R2)
    while r1.A = r'2.B do                       (all R1 tuples with the same A value)
      r2 ← r'2 ;                                (rewind r2 to r'2)
      while r1.A = r2.B do                      (all R2 tuples with the same B value)
        appendRecord (out, ⟨r1, r2⟩) ;
        r2 ← nextRecord (in2) ;
      r1 ← nextRecord (in1) ;
  closeFile (out) ;
end
```

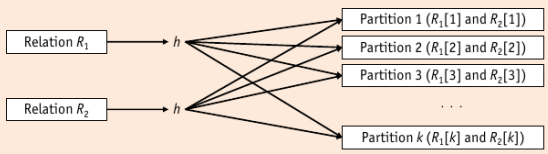
Cost of $R_1 \bowtie_{A=B}^{sort-merge} R_2$

access path	sorted file scan of R_1 and R_2
prerequisites	p equality predicate $R_1.A = R_2.B$
I/O cost	cost of sorting R_1 and/or R_2, if not sorted already, plus
	best case: $\|\|R_1\|\| + \|\|R_2\|\|$
	worst case: $\|\|R_1\|\| \cdot \|\|R_2\|\|$

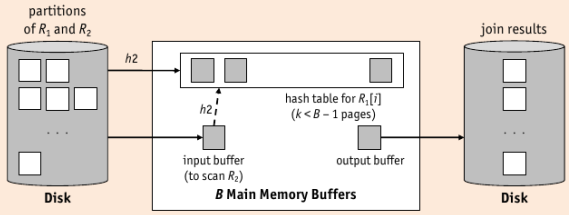
Grace Hash Join

- works only for equality predicates
- Two Phases: Partitioning and matching/probing phase
- follows divide and conquer: partition and do per partition in-memroy joins
- may be accelerated by using second hash function for probing as with the block NLJ
- Needs $B > \sqrt{f \cdot ||R||}$ Buffer pages where f is the factor of increase to maintain a hash table over the partition instead of the partition only, so that partition stays in memory

Partitioning phase of hash join



Probing phase of a hash join



Grace hash join

```
function ⋈^hash-join (R1, R2, Rout, R1.A = R2.B)
  in1 ← openScan (R1) ;                                   (partitioning phase)
  while (r1 ← nextRecord (in1) ) ≠ ⟨EOF⟩ do
    add r1 to partition R1[h(r1.A)] ;                     (flushed as page fills)
  in2 ← openScan (R2) ;
  while (r2 ← nextRecord (in2) ) ≠ ⟨EOF⟩ do
    add r2 to partition R2[h(r2.B)] ;                     (flushed as page fills)
  out ← createFile (Rout) ;
  foreach i ∈ 1, ..., k do                                (probing phase)
    foreach tuple r1 ∈ R1[i] do      (build in-memory hash table for R1[i], using h2)
      insert r1 into hash table H, using h2(r1.A) ;
    foreach tuple r2 ∈ R2[i] do      (scan R2[i] and probe for matching R1[i] tuples)
      probe H using h2(r2.B) and append matching tuples ⟨r1, r2⟩ to out ;
    clear H to prepare for next partition ;
  closeFile (out) ;
end
```

Cost of $R_1 \bowtie_{A=B}^{hash-join} R_2$

access path	file scan (**openScan**) of R_1 and R_2
prerequisites	equi-join, i.e., p equality predicate $R_1.A = R_2.B$
I/O cost	$\underbrace{\underbrace{\|\|R_1\|\| + \|\|R_2\|\|}_{read} + \underbrace{\|\|R_1\|\| + \|\|R_2\|\|}_{write}}_{partitioning\ phase} + \underbrace{\|\|R_1\|\| + \|\|R_2\|\|}_{probing\ phase} = 3 \cdot (\|\|R_1\|\| + \|\|R_2\|\|)$

3.3.2 Selection

Definition

The **selectivity** (or **reduction factor**) or a predicate p, denoted by $sel(p)$, is the faction of records in a relation R that satisfy the predicate p.

$$0 \leq sel(p) = \frac{|\sigma_p(R)|}{|R|} \leq 1$$

- Implemented using a combination of **iteration or indexing**
- may be applied on the fly in a pipelined plan
- Complex predicates may be expressed as conjuncts and disjuncts in terms of boolean logic
- three evaluation option for CNF terms:
  1. Single file scan
  2. single index that match a subset of the primary conjuncts, apply others on the fly
  3. multiple indexes each matching a subset of conjuncts, applying intersection over rid on the fly
- similar for DNF but union instead of intersection and only possible when **all** predicates are matched by index. Solution: **Bypass Selection**

No index, unsorted Data:

Selection

```
function σ (p, Rin, Rout)
  in ← openScan (Rin) ;
  out ← createFile (Rout) ;
  while (r ← nextRecord (in) ) ≠ ⟨EOF⟩ do
    if p(r) then appendRecord (out, r) ;
  closeFile (out) ;
end
```

Cost of $\sigma_p^{scan}(R_{in})$ using a sequential scan

access path	file scan (**openScan**) of R_{in}
prerequisites	none (p arbitrary, R_{in} may be a heap file)
I/O cost	$\underbrace{\|\|R_{in}\|\|}_{input\ cost} + \underbrace{sel(p) \cdot \|\|R_{in}\|\|}_{output\ cost}$

No index, sorted on selection predicate Data:

Cost of $\sigma_p(R_{in})$ using binary search

access path	binary search, then sorted file scan of R_{in}
prerequisites	R_{in} sorted on sort key k that matches p
I/O cost	$\underbrace{\log_2\|\|R_{in}\|\|}_{input\ cost} + \underbrace{sel(p) \cdot \|\|R_{in}\|\|}_{sorted\ scan} + \underbrace{sel(p) \cdot \|\|R_{in}\|\|}_{output\ cost}$

B+Tree index with predicate matching sort key

Implementing $\sigma_p(R_{in})$ using a B+ tree

- Descend the B+ tree to retrieve the first index entry that satisfies p
- If the index is **clustered**, access that record on its page in R_{in} and continue to scan inside R_{in}
- If the index is **unclustered** and $sel(p)$ indicates a **large number of qualifying records**, it pays off to
  1. read all matching index entries $k^* = \langle k, rid \rangle$ in the sequence set
  2. sort those entries on the *rid* field
  3. access the pages of R_{in} in sorted *rid* order

↳ **Note** that the lack of clustering is a minor issue if $sel(p)$ is close to 0

Cost of $\sigma_p(R_{in})$ using a clustered B+ tree index

access path	access of B+ tree on R_{in}, then sequence set scan
prerequisites	clustered B+ tree on R_{in} with key k that matches p
I/O cost	$\underbrace{\approx 3}_{B+\ tree\ access} + \underbrace{sel(p) \cdot \|\|R_{in}\|\|}_{sorted\ scan} + \underbrace{sel(p) \cdot \|\|R_{in}\|\|}_{output\ cost}$

Hash Index

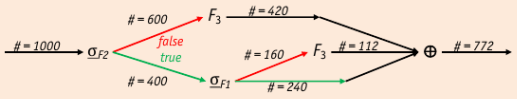
Cost of $\sigma_p(R_{in})$ using a hash index

access path	hash index on R_{in}
prerequisites	R_{in} hashed on key k, p has a term $k = c$
I/O cost	$\approx \underbrace{1.2}_{\text{B+ tree access}} + \underbrace{sel(p) \cdot \|R_{in}\|}_{\text{output cost}}$

Bypass selection avoids expensive and unselective selections by applying the most selective and the cheap selections first. I.E. the goal is to eliminate tuples early and avoid duplicates.

1. Convert selection condition to CNF
2. apply most selective/cheapest predicate first and safe disjunct tuples (true/false on predicate p_1)
3. repeat step 2 until all conjuncts are applied (when a conjunct contains disjuncts, just chain them)

Example



Mean cost per tuple ($\oplus$ disjoint union): $C_2 + (1 - s_2) \cdot C_3 + s_2 \cdot (C_1 + (1 - s_1) \cdot C_3) = 40.6$

Note that many variations are possible, e.g., for tuning in parallel environments

3.3.3 Projection

- removes unwanted attributes and eliminates duplicates
- implemented using iteration or partitioning
- without duplicate elimination can be pipelined, with needs to be materialized

1. Do a FileScan, $\forall r \in$ File: cut off uneeded attributes and append to the output
2. do duplicate elimination as follows:

Projection based on sorting

```
function π^sort(l, R_in, R_out)
  in ← openScan(R_in) ;
  out ← createFile(R_tmp) ;
  while (r ← nextRecord(in)) ≠ ⟨EOF⟩ do
    r' ← r with any field not listed in l cut off ;
    appendRecord(out, r') ;
  closeFile(out) ;
  external-merge-sort(R_tmp, R_tmp, θ) ;
  in ← openScan("run␣*␣0") ;
  out ← createFile(R_out) ;
  lastr ← ⟨⟩ ;
  while (r ← nextRecord(in)) ≠ ⟨EOF⟩ do
    if r ≠ lastr then
      appendRecord(out, r) ;
      lastr ← r ;
  closeFile(out) ;
end
```

Marriage of sorting and projection with duplicate elimination

Step ① (**projection**) and Step ② (**duplicate elimination**) can be **integrated** into the passes performed by the external merge sort algorithm.

Pass 0
1. read B pages at a time, **projecting unwanted attributes out**
2. use in-memory sort to sort the records of these B pages
3. write a sorted run of B internally sorted pages out to disk

Pass 1, ..., n
1. select $B - 1$ runs from previous pass, read a page from each run
2. perform a $(B - 1)$-way merge, **eliminating duplicates**
3. use the B-th page as an output buffer

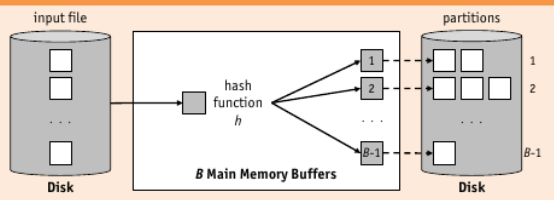
Cost of $\pi_l^{sort}(R_{in})$ using sorting for duplicate elimination

access path	file scan (**openScan**) of R_{in}
prerequisites	none (B available buffer pages)
I/O cost	$\underbrace{\|R_{in}\| + \|R_{tmp}\|}_{\text{projection}} + \underbrace{2 \cdot \|R_{tmp}\| \cdot \left(\left\lceil \log_{B-1} \left\lceil \|R_{tmp}\| / B \right\rceil \right\rceil\right)}_{\text{duplicate elimination}}$

Partitioning phase

1. Allocate all B buffer pages: one page will be the **input buffer**, the remaining B – 1 pages will be used as **hash buckets**.
2. Read the file R_{in} page by page: for each record r, **project out** the attributes not listed in list l.
3. For each such record, apply hash function $h_1(r) = h(r) \bmod (B - 1)$, which depends on **all remaining fields of** r, and store r in hash bucket $h_1(r)$.
4. If the hash bucket is **full**, write it to disk, i.e., the overflow chain of a bucket resides on disk

Partitioning phase



Duplicate elimination phase

1. For each partition, read each partition page by page (possibly in parallel), using the same buffer layout as before.
2. To each record, apply a hash function h_2 ($h_2 \neq h_1$) to all record fields.
3. Only if two records collide with respect to h_2, check if $r = r'$ and, if so, discard r'.
4. After the entire partition has been read in, append all hash buckets to the result file, which will be free of duplicates.

Cost of $\pi_l^{hash}(R_{in})$ using hashing for duplicate elimination

access path	file scan (**openScan**) of R_{in}
prerequisites	none (B available buffer pages)
I/O cost	$\underbrace{\|R_{in}\| + \|R_{tmp}\|}_{\text{projection}} + \underbrace{\|R_{tmp}\| + \|R_{tmp}\|}_{\text{duplicate elimination}}$

3.3.4 Set Operations & Aggregations

Set Operations: Intersection and Cross Product are implemented as special cases of join (equality on all attributes join for intersection and true for the cross product). Union and difference are implemented as special case selection (union: mainly duplicate elimination, difference: variation of duplicate elimination)

Sorting for union and difference

Implementation of $R \cup S$

1. sort both R and S using the combination of **all** fields
2. scan the sorted R and S in parallel and merge them, eliminating duplicates

As with projection, the implementation of difference can be integrated with the external sort operator.

Implementation of $R - S$ is similar. During the merging pass tuples of R are only written to the result after checking that they **do not appear** in S.

Hashing for union and difference

Implementation of $R \cup S$

1. partition both R and S using a hash function $h(\cdot)$ over the combination of **all** fields
2. process each partition i as follows
   - build an in-memory hash table, using hash function $h2(\cdot) \neq h(\cdot)$, for $S[i]$
   - scan $R[i]$; for each tuple probe the hash table for $S[i]$; if the tuple is in the hash table, discard it; otherwise, add it to the table
   - write out the hash table; clear it to prepare for the next partition

Implementation of $R - S$ is similar, but processes the partition differently. After building an in-memory hash table for $S[i]$, $R[i]$ is scanned and $S[i]$ is probed for every tuple in $R[i]$. If the tuple is **not in the table**, it is written to the result.

Aggregations There are 4 approaches: basic, using sorting, using hashing (last both only for aggregation and grouping), index only plans (if index contains all attributes needed for aggregation, group by if prefix matches index key and index is b+tree).

Basic Algorithm:

1. Scan relation, maintaining running information
2. compute aggregate using running information when finished

Using sorting (Aggregation and Grouping only):

1. Sort relation, record running information for each distinct value group and compute aggregation when sorting has finished

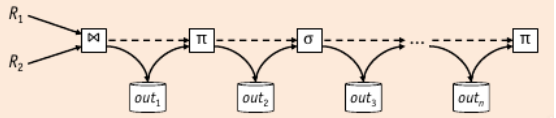
Using hashing (Aggregation and Grouping only):

1. build hash table on grouping attribute and maintain running information. compute aggreg

3.3.5 Buffering and Pipelines

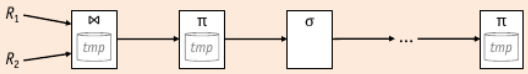
- concurrently executed operators share the buffer pool
- unclustered indexes fill the buffer pool rapidly and make pinning new pages hard to predict.
- repeated pattern of access can be speed up or be slowed down by a certain replacement policy
- all pseudo code by now assumed Materialization
- Pipelined plans can be used to avoid writing temporary files or delays to wait until some other operator has completely finished

Materialized evaluation



Pipelined Evaluation enables each operator to pass the result directly to the next operator. Each partial result may be passed, other operators can start computation as early as possible and execute in parallel.

Pipelined evaluation



Demand-driven or volcano style pipelining (open-next-close) was examined in the exercises and previously when talking about iterators.

Iterator Model

- To simplify the code to coordinate plan execution, all operators implement a **uniform** iterator interface
  - hides **internal implementation details** of each operators
  - assumes **pipelined evaluation** of the query plan (see next slide)

Iterator interface

open()
- initializes iterator by allocating input and output buffers
- used to pass parameters that modify operator behavior, e.g., a selection condition

next()
- calls **next** on each input operator
- executes operator-specific code to process input tuples
- places results in output buffer
- updates iterator state to keep track of how much input has been consumed

close()
- deallocates state information

Iterator Model

Iterator	open()	next()	close()	State
print	open input	call **next()** on input, format item on screen	close input	
scan	open file	read next item	close file	open file descriptor
select	open input	call **next()** on input, until an item qualified	close input	
hash join without overflow resolution	allocate hash directory, open left *build* input, build hash table calling **next()** on build input, close build input, open right *probe* input	call **next()** in *probe* input until a match is found	close *probe* input, deallocate hash directory	hash directory
merge join without duplicates	open both inputs	get **next()** item from input with smaller key until a match is found	close both inputs	
sort	open input, build all initial run files calling **next()** on input, close input, merge run files until only one step is left	determine next output item, read new item from the correct run file	destroy remaining run files	merge heap, open file descriptors for run files

Note that there is also data-driven pipelining:

- Producer and consumer are connected by a queue
- operators execute asynchronously, in parallel
- operators are suspended by blocking queue calls
- higher ressource requirements; systolic arrays

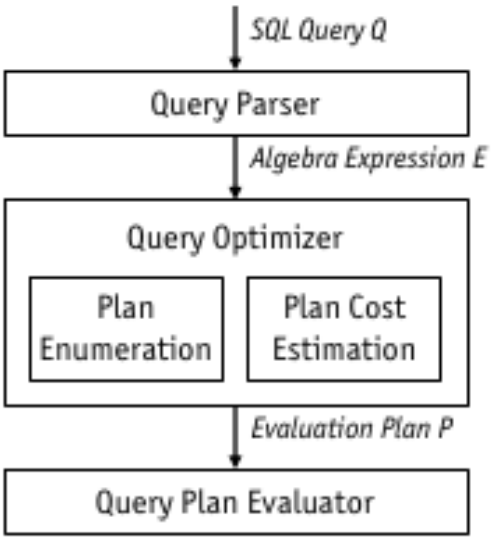
Chapter 4

Query Optimization and Database Tuning

The following steps are performed to answer a query Q:

1. Query Parser: Parse Q and derive a relational algebra expression E
2. **Rewrite optimization (logical level):** From E generate set of logical plans L transforming and simplifying E
3. **Cost-based Optimization (physical level):** Generate a set of physical plans P by annotating the plans in L with access paths and operator algorithms
4. **Plan cost estimator:** Estimate the costs of each plan and chose the best one
5. Query Plan Evaluator: Execute the plan and return the result to the UI

Search space ≡ logical level ∪ physical level



4.1 Relational Algebra Equivalences & Rewriting 20 Slides

4.1.1 Relational Algebra Equivalences

1. **Cascading selections**
$$\sigma_{c_1 \wedge \cdots \wedge c_n}(R) \equiv \sigma_{c_1}(\ldots \sigma_{c_n}(R) \ldots)$$
2. **commutativity of selections**
$$\sigma_{c_q}(\sigma_{c_p}(R)) \equiv \sigma_{c_p}(\sigma_{c_q}(R))$$
3. **Cascading Projections**
$$\pi_{c_1 \wedge \cdots \wedge c_n}(R) \equiv \pi_{c_1}(\ldots \pi_{c_n}(R) \ldots)$$
4. **Folding selections:** with $a_i \subseteq a_{i+1}$ only the last projection is needed (cutting off step by step vs. doing all cutoffs once)
$$\sigma_{a_1}(R) \equiv \sigma_{a_1}(\ldots \sigma_{a_n}(R) \ldots)$$
5. **Cross-Product and all Joins are associative** with r involves only T and S, p only involves R and S
$$(R \bowtie_p S) \bowtie_{q \wedge r} T \equiv R \bowtie_{p \wedge q} (S \bowtie_r T)$$
6. **Cross-Product and Natural Join are commutative**
$$R \times S \equiv S \times R$$
$$R \bowtie S \equiv S \bowtie R$$
7. **Selection and cross product form a join**
$$\sigma_p(R \times S) \equiv R \bowtie_p S$$
8. **Selections and joins can be combined**
$$\sigma_q(R \bowtie_p S) \equiv R \bowtie_{p \wedge q} S$$
9. **Selections commutes with Joins and cross-product** let q only involves R
$$\sigma_q(R \bowtie_p S) \equiv \sigma_q(R) \bowtie_p S$$
10. **Selections and projections distribute over joins and cross products** let p only involve R, q only involve S
$$\sigma_{p \wedge q}(R \bowtie_r S) \equiv \sigma_p(R) \bowtie_r \sigma_q(S)$$
$$\pi_a(R \bowtie_r S) \equiv \pi_{a_1}(R) \bowtie_r \pi_{a_2}(S)$$
11. **Selections and Projections commute** if the projections keeps all attributes involved in the selection predicates
$$\pi_a(\sigma_p(R)) \equiv \sigma_p(\pi_a(R))$$
12. **commutativity of Union and Intersection**
$$R \cup S \equiv S \cup R$$
$$R \cap S \equiv S \cap R$$
13. **Union and Intersection are associative**
$$(R \cup S) \cup T \equiv R \cup (S \cup T)$$
$$(R \cap S) \cap T \equiv R \cap (S \cap T)$$
14. **Projection distributes over Union**
$$\pi_a(R \cup S) \equiv \pi_a(R) \cup \pi_a(S)$$
15. **Selection, Union, Intersection and Difference are distributive**
$$\sigma_p(R \cup S) \equiv \sigma_p(R) \cup \sigma_p(S)$$
$$\sigma_p(R \cap S) \equiv \sigma_p(R) \cap \sigma_p(S)$$
$$\sigma_p(R \setminus S) \equiv \sigma_p(R) \setminus \sigma_p(S)$$
16. **Selection, Intersection and Difference are commutative**
$$\sigma_p(R \cap S) \equiv \sigma_p(R) \cap S$$
$$\sigma_p(R \setminus S) \equiv \sigma_p(R) \setminus S$$

4.1.2 Relational Algebra Rewriting

1. Break apart conjunctive selections (Rule 1)
2. Move selections down the query tree (Rules 2, 9, 15)
3. Replace selection-cross product pairs with joins (Rule 8)
4. Break list of projections apart & move them down, create new projections where possible (Rules 3, 10, 14)
5. Perform joins with the smallest expected result first

4.2 Plan Enumeration 40 Slides

4.2.1 Single-Relation Queries

4.2.2 Multiple-Relation Queries

4.2.3 Dynamic Programming

4.3 Cardinality Estimation 30 Slides

4.3.1 System Catalog

4.3.2 Histograms

4.4 Example Query Optimizers 30 Slides

System R Optimizer

4.4.1 Starburst

4.4.2 Cascades

4.5 Nested Subqueries: 30 Slides

4.6 Physical Database Design & Tuning 40 Slides