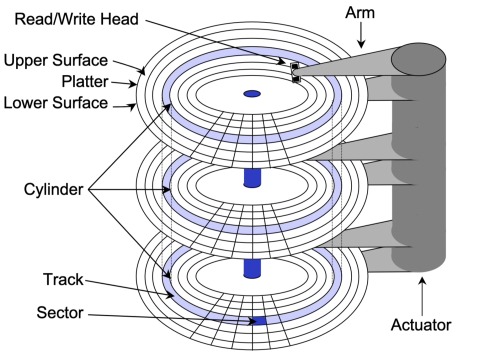
CS3223
AY22/23 SEM 2
github/jovyntls

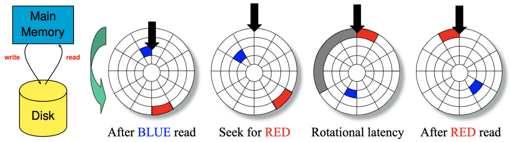
01. DBMS STORAGE

- store data on non-volatile disk
- process data in main memory (RAM) (*volatile storage*)

Magnetic HDD



- **disk access time** =
  - **seek time** $\rightarrow$ move arms to position disk head on track
  - **rotational delay** $\rightarrow$ wait for block to rotate under head
    - average rotational delay = time for $\frac{1}{2}$ revolutions
  - **transfer time** $\rightarrow$ move data to/from disk surface
    $=$ time for 1 revolution $\times$ $\frac{\text{\# of requested sectors on the same track}}{\text{\# of sectors in track}}$
- **response time** for disk access = queuing delay+access time



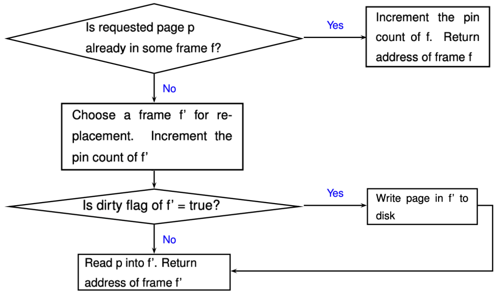
- command processing time: interpreting access command by disk controller (part of access time, considered negligible)
- small requests are dominated by seek time; large requests dominated by transfer time
- **access order**:
  1. contiguous blocks within the same track (same surface)
  2. cylinder tracks within the same cylinder
  3. next cylinder

SSD (Solid-State Drive)

- no mechanical moving parts
- advantages: ✓ significantly faster than HDD ✓ higher data transfer rate ✓ lower power consumption
- disadvantages: × update to a page requires erasure of multiple pages before overwriting page × limited number of times a page can be erased

Buffer Manager

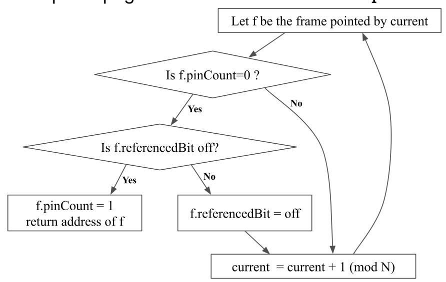
- data is stored & retrieved in **disk blocks** (pages)
  - each block = sequence of ≥ 1 contiguous sectors
- **buffer pool**: main memory allocated for DBMS
  - partitioned into **frames** (block-sized pages)
- `pin count`: number of clients using page (initialised 0)
  - >0 $\Rightarrow$ page is utilised by some transaction; don't replace
- `dirty flag`: initialised false
  - **dirty** $\rightarrow$ page is modified & not updated on the disk
  - dirty page must be written back to the disk if the transaction has committed



! unpinning: update dirty flag to true if page is dirty

replacement policies

- decide which unpinned (`pinCount==0`) page to replace
- **LRU** uses a queue of pointers to frames with `pinCount==0`
- **clock**: cheaper than LRU, used in postgres
  - `referenced bit` - turns on when `pinCount==0`
  - replace page with referenced bit off && `pinCount==0`

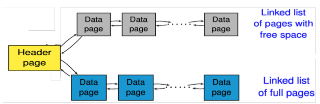


File abstraction

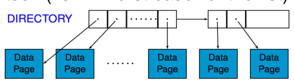
- each relation is a file of records
- each record has a unique record identifier, **RID**
- **heap file** $\rightarrow$ unordered file
  - vs sorted/hashed file: records are ordered/hashed

heap file implementations

- **linked list** implementation
  - header page: metadata about the file

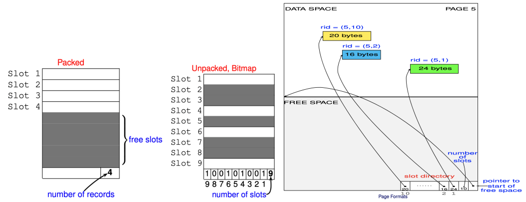


- **page directory** implementation: more efficient
  - maintain directory structure with one entry per page
    - stores address of and amount of free space on page
  - insertion: scan directory to find page with enough space to store the new record
  - insertion worst case: scan number of pages + data page itself (vs LL worst case: entire list)



Page Formats

- `RID` = (page ID, slot number)
- **fixed-length** records
  - packed organisation: inefficient deletion (transferring last record to deleted record changes RID of record)
- **variable-length** records: **slotted page organisation**



Record formats

- **fixed-length** records: store consecutively
- **variable-length** records:
  - Delimit fields with special symbols

F1	$	F2	$	F3	$	F4

  - Use an array of field offsets

o_1	o_2	o_3	o_4	F1	F2	F3	F4

Each o_i is an offset to beginning of field Fi

Data entry formats

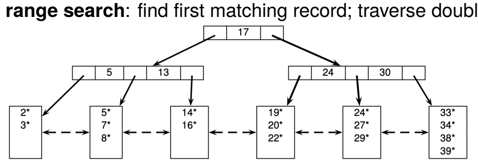
1. k* is an actual **data record** (with search key k)
2. k* is of the form **(k, RID)** - fixed length `(k, ●)`
3. k* is of the form **(k, RID-list)** - e.g. (k, {RID11, RID12})

02. TREE-BASED INDEXING

- **search key** $\rightarrow$ sequence of k data attributes, $k \geq 1$
  - **composite search key** $\rightarrow$ if $k > 1$
- **unique index** $\rightarrow$ search key is a candidate key
- **clustered index** $\rightarrow$ order of data entries $\approx$ order of records
  - **Format-1** is *always clustered*
  - *at most one* clustered index for each relation
- **dense index** $\rightarrow$ there is an index record for every search key value in the data. *unclustered index* must be dense

B$^+$-tree Index

- leaf nodes: sorted data entries (k^* is of form `(k, RID)`)
- internal nodes: stores index entries $(p_0, k_1, p_1, \ldots, p_n)$ for $k_1 < k_2 \cdots < k_n$ where p_i is the page disk address
  - each (k_i, p_i) is an **index entry**
  - for $k*$ in index subtree T_i rooted at p_i, $k \in [k_i, k_{i+1}]$
- **order** of index tree, $d \in \mathbb{Z}^+$
  1. each non-root node contains m entries, $m \in [d, 2d]$
  2. root node contains $[1, 2d]$ entries
- **equality search**: at each internal node N, find the largest k_i s.t. $k \geq k_i$. search subtree at p_i if k_i exists, else p_0
- **range search**: find first matching record; traverse doubly LL



insertion: splitting

- splitting leaf node: distribute $d + 1$ entries to a new leaf node
- if parent overflows: push the middle (d+1) key up to parent
- root node overflows: create new root (parent of current root)

insertion: redistribution (of *leaf nodes only*)

- try right sibling first, then left sibling, else use splitting
- **sibling** $\rightarrow$ two nodes at the *same level* & *same parent node*

deletion: redistribution - try right sibling, then left, else merge
deletion: merging (siblings have d entries) - try right first

- if leaf underflows: delete parent key, combine with sibling
- if internal node underflows: pull down its index entry in parent, combine with sibling, push a key back up
  - becomes the new root if parent is root & becomes empty

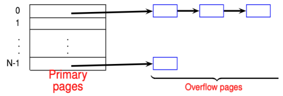
Bulk Loading a B$^+$-tree

1. sort data entries by search key and store sequentially
2. construct leaf pages with $2d$ entries
3. construct internal pages by attempting to insert leaf pages into rightmost parent page

03. HASH-BASED INDEXING

Static Hashing

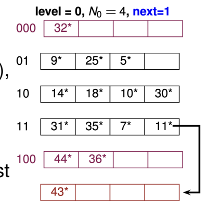
- hash record to $B_i \in B_0, \ldots, B_{N-1}$ with $i = h(k) mod\, N$
- when full, reconstruct hash table with more buckets



each bucket:
- 1 primary data page
- ≥ 0 overflow data pages

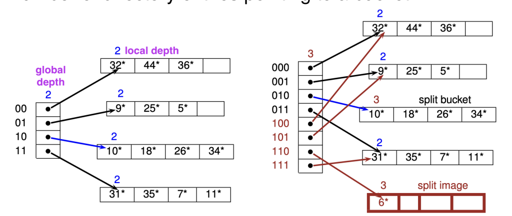
Linear Hashing (Dynamic)

- grows **linearly**: split when some **bucket overflows**
- how to split bucket B_i :
  1. add a new bucket $B_j = B_{i+N_i}$ (*split image* of B_i)
  2. redistribute entries in B_i between B_i and B_j
  3. `next++`; if `next`==N_{level}: `level++; next=0`
- file size at the beginning of round i, $N_i = 2^i N_0$
- at round i, hash x = B_x has been split ? $h_i(k)$: $h_{i+1}(k)$
- **performance**: 1 disk I/O (no overflow pages)
  - avg 1.2 I/Os (uniform distribn), worst case linear I/O cost
- removing bucket (**deletion**):
  - if next $>$ 0: `next--;`
  - else: `next=`(prev level last bucket); `level--;`



Extendible Hashing (Dynamic)

- add a new bucket whenever existing bucket overflows
  - no overflow pages unless # collisions > page capacity
- directory of pointers to buckets - 2^d entries $(b_d b_{d-1} \ldots b_1)$
  - d = **global depth** of hashed file
- **corresponding** directory entries differ only in the d^{th} bit
- entries in a bucket of **local depth** $\ell \in [0, d]$: same last ℓ bits
  - a split bucket & its image have the *same local depth*
- number of directory entries pointing to a bucket = $2^{d-\ell}$



- splitting bucket: ℓ++ (repeat until no more overflow)

- if $\ell = d$: directory doubles; $d{+}{+}$
- else $\ell < d$: redistribute and increment ℓ
- deletion: if bucket B_i becomes empty,
  - deallocate B_i and decrement ℓ-- for split image B_j
  - if each pair of corresponding entries point to the same bucket, the directory can be halved
- **performance**: at most 2 disk I/Os (for equality query)
- collisions: when 2 data entries have the same hashed value
  - use **overflow pages** if # collisions exceeds page capacity

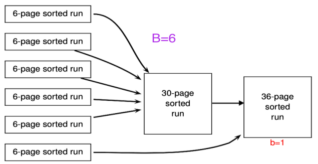
04.1 SORTING

External Merge Sort

- **sorted run** $\rightarrow$ sorted data records written to a file on disk
- divide and conquer
  1. create temporary file R_i for each B pages of R sorted
  2. merge: use $B-1$ pages for input, 1 page for output
- total I/O = $2N(\lceil \log_{B-1}(N_0) \rceil + 1)$
  - $2N$ to create $\lceil N/B \rceil$ sorted runs of B pages each
  - merging sorted runs: $2N \times \lceil \log_{B-1} N_0 \rceil$

optimisation with blocked I/O

- sequential I/O - read/write in *buffer blocks* of b pages
- one block (b pages) for output, remaining blocks for input



- number of runs merged per pass, $F = \lfloor \frac{B}{b} \rfloor - 1$
- number of passes = $\lceil \log_F(N_0) \rceil + 1$

Sorting with B$^+$-trees

- when *sort key is a prefix of the index key* of the B$^+$-tree
- sequentially scan leaf pages of B$^+$-tree
  - for Format-2/3, use RID to retrieve data records

04.2 SELECTION: $\sigma_p(R)$

- $\sigma_p(R)$: selects rows from relation R satisfying predicate p
- **access path**: a way of accessing data records/entries
  - **table scan** $\rightarrow$ scan all data pages
  - **index scan** $\rightarrow$ scan index pages
  - **index intersection** $\rightarrow$ combine results from index scans
- **selectivity** of an access path $\rightarrow$ number of index & data pages retrieved to access data records/entries
  - more selective = fewer pages retrieved
- index I is a **covering index** for query $Q \rightarrow$ if all attributes referenced in Q are part of the key of I
  - Q can be evaluated using I without any RID lookup (**index-only** plan)

Matching Predicates

- **term** $\rightarrow$ of form $R.A$ op c or $R.A_i$ op $R.A_j$
- **conjunct** $\rightarrow$ one or more terms connected by $\vee$
  - **disjunctive** conjunct $\rightarrow$ contains $\vee$
- conjunctive normal form, **CNF predicate** $\rightarrow$ comprises one or more conjuncts connected by $\wedge$

$$\overbrace{(\underbrace{\text{rating} \geq 8}_{\text{term/conjunct}} \vee \underbrace{\text{director} = \text{"Coen"}}_{\text{term/conjunct}})}^{\text{disjunctive conjunct}} \wedge (\underbrace{\text{year} > 2003}_{\text{term/conjunct}}) \wedge (\underbrace{\text{language} = \text{"English"}}_{\text{term/conjunct}})$$

B$^+$-tree matching predicates

- for index $I = (K_1, K_2, \ldots, K_n)$ and non-disjunctive CNF predicate p, I matches p if p is of the form

$$\underbrace{(K_1 = c_1) \wedge \cdots \wedge (K_{i-1} = c_{i-1})}_{\text{zero or more equality predicates}} \wedge (K_i \; op_i \; c_i), \; i \in [1, n]$$

  - *at most one* non-equality comparison operator which must be on the last attribute of the prefix (K_i)
- matching index: matching records are in contiguous pages
  - non-matching index: not contiguous $\Rightarrow$ less efficient

Hash index matching predicates

- for hash index $I = (K_1, K_2, \ldots, K_n)$ and non-disjunctive CNF predicate p, I matches p if p is of form

$$(K_1 = c_1) \wedge (K_2 = c_2) \wedge \cdots \wedge (K_n = C_n)$$

Primary/Covered Conjuncts

- **primary conjuncts** $\rightarrow$ subset of conjuncts that I matches
  - e.g. p = (age $\geq$ 18) $\wedge$ (age $\leq$ 20) $\wedge$ (weight=65) for I = (age, weight, height)
- **covered conjuncts** $\rightarrow$ subset of conjuncts covered by I
  - each attribute in covered conjuncts appears in key of I
- primary conjuncts $\subseteq$ covered conjuncts

Cost of Evaluation

let p' = primary conjuncts of p, p_c = covered conjuncts of p

B$^+$-tree index evaluation of p

1. navigate internal nodes to find first leaf page

$$\text{cost}_{\text{internal}} = \begin{cases} \lceil \log_F(\lceil \frac{||R||}{b_d} \rceil) \rceil & \text{if I is a format-1 index} \\ \lceil \log_F(\lceil \frac{||R||}{b_i} \rceil) \rceil & \text{otherwise} \end{cases}$$

2. scan leaf pages to access all qualifying data entries

$$\text{cost}_{\text{leaf}} = \begin{cases} \lceil \frac{||\sigma_{p'}(R)||}{b_d} \rceil & \text{if I is a format-1 index} \\ \lceil \frac{||\sigma_{p'}(R)||}{b_i} \rceil & \text{otherwise} \end{cases}$$

3. retrieve qualified data records via RID lookups

$$\text{cost}_{\text{RID}} = \begin{cases} 0 & \text{if I is a covering format-1 index,} \\ ||\sigma_{p_c}(R)|| & \text{otherwise} \end{cases}$$

  - reduce cost with **clustered** data records (sort RIDs):

$$\lceil \frac{||\sigma_{p_c}(R)||}{b_d} \rceil \leq \text{cost}_{RID} \leq \min\{||\sigma_{p_c}(R)||, |R|\}$$

hash index evaluation of p

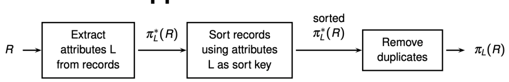
- **format-1**: cost to retrieve data records $\geq \lceil \frac{||\sigma_{p'}(R)||}{b_d} \rceil$
- **format-2**: cost to retrieve data entries $\geq \lceil \frac{||\sigma_{p'}(R)||}{b_i} \rceil$

cost to retrieve data records = $\begin{cases} 0 & \text{if I is a covering index,} \\ ||\sigma_{p'}(R)|| & \text{otherwise} \end{cases}$

05.1 PROJECTION $\pi_{A_1,\ldots,A_m}(R)$

- $\pi_L(R)$ eliminates duplicates, $\pi^*_L(R)$ preserves duplicates

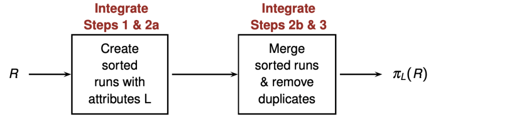
Sort-based approach



cost analysis

1. extract attributes: $|R|$ scan + $|\pi^*_L(R)|$ output temp result
2. sort records: $2|\pi^*_L(R)|(\log_m(N_0) + 1)$
3. remove duplicates: $|\pi^*_L(R)|$ to scan records

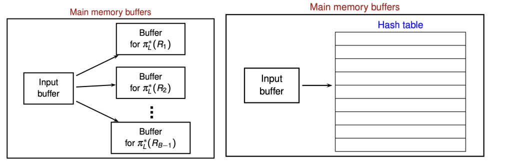
optimised sort-based approach



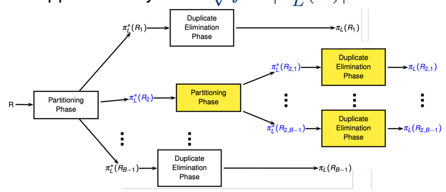
- if $B > \sqrt{|\pi^*_L(R)|}$, same I/O cost as hash-based approach
  - $N_0 = \lfloor \frac{|R|}{B} \rfloor \approx \sqrt{|\pi^*_L(R)|}$ initial sorted runs
  - $\log_{B-1}(N_0) \approx 1$ merge passes

Hash-based approach

1. **partitioning phase**: hash each tuple $t \in R$
   - $R = R_1 \cup R_2 \cup \cdots \cup R_{B-1}$
     - for each R_i & R_j, $i \neq j$, $\pi^*_L(R_i) \cap \pi^*_L(R_j) = \emptyset$
   - for each t: project attributes to form t', hash $h(t')$ to one output buffer, flush output buffer to disk when full
   - one buffer for input, $(B-1)$ buffers for output
2. **duplicate elimination** from each $\pi^*_L(R_i)$
   - for each R_i: initialise in-mem hash table, hash each $t \in R_i$ to bucket B_j with $h' \neq h$, insert if $t \notin B_j$
   - write tuples in hash table to results



- **I/O cost** (no partition overflow): $|R| + 2|\pi^*_L(R)|$
  - partitioning cost: $|R| + |\pi^*_L(R)|$
  - duplicate elimination cost: $|\pi^*_L(R)|$
- partition overflow: recursively apply partitioning
  - to avoid, $B >$ size of hash table for R_i = $\frac{|\pi^*_L(R)|}{B_1} \times f$
    - approximately $B > \sqrt{f \times |\pi^*_L(R)|}$



Projection using Indexes

- if index search key contains all wanted attributes *as a prefix*
  - **index scan** data entries in order & eliminate duplicates

05.2 JOIN $R \bowtie_\theta S$

R = outer relation (smaller relation); S = inner relation

! for **format-2** index, add cost of retrieving record

nested loop joins

- **tuple-based** nested loop join: $|R| + ||R|| \times |S|$
- **page-based** nested loop join: $|R| + |R| \times |S|$
- **block nested loop join**: $|R| + (\lceil \frac{|R|}{B-2} \rceil \times |S|)$, $|R| \leq |S|$
  - 1 page output, 1 page input, $(B-2)$ pages to read R
  - for each $(B-2)$ pages of R: for each P_S of S: check r,s
- **index nested loop join**:

$$|R| + ||R|| \times \left(\log_F(\lceil \frac{||S||}{b_d} \rceil) + \lceil \frac{||S||}{b_d ||\pi_{B_j}(S)||} \rceil \right)$$

  - joining $R(A, B) \bowtie_A S(A, C)$ with B+tree index on $S.A$
  - for each tuple $r \in R$, use r to probe S's index for match

sort-merge join

- sort R & S: $2|R|(\log_m(N_R) + 1) + 2|S|(\log_m(N_S) + 1)$
- merge cost: $|R| + |S|$ (worst case $|R| + ||R|| \times |S|$)

optimised sort-merge join

- merge sorted runs until $B > N(R, i) + N(S, j)$; then do merge and join at the same time
- I/O cost: $3 \times (|R| + |S|)$
  - if $B > \sqrt{2|S|}$, one pass to merge initial sorted runs
  - $2(|R| + |S|)$ for initial sorted runs, $|R| + |S|$ for merging

hash join

1. partition R and S into k partitions on join column
   - $\pi_A(R_i) \cap \pi_B(S_j) = \emptyset \quad \forall R_i, S_j, i \neq j$
   - $R = R_1 \cup R_2 \cup \cdots \cup R_k, \quad t \in R_i \iff h(t.A) = i$
   - $S = S_1 \cup S_2 \cup \cdots \cup S_k, \quad t \in S_i \iff h(t.B) = i$
2. join corresponding partitions:
   $R \bowtie_{R.A=S.B} S = (R_1 \bowtie S_1) \cup \cdots \cup (R_k \bowtie S_k)$

Grace hash join

for *build relation* R and *probe relation* S,

1. **partition** R and S into k partitions each, $k = B - 1$
2. **probing phase**: hash $r \in R_i$ with $h'(r.A)$ to table T
   2.1. $\forall s \in S_i, r \in$ bucket $h'(s.B)$: output (r, s) if match

- I/O cost: $3(|R| + |S|)$ (no partition overflow)
- $B > \frac{f \times |R|}{B-1} + 2$ (input & output buffer) $\approx B > \sqrt{f \times |R|}$
  - during probing, $B >$ size of each partition $+2$
- **partition overflow** if R_i cannot fit in memory
  - recursively apply partitioning to overflow partition

General join conditions

- **multiple equality-join** conditions: $(R.A = S.A) \wedge (R.B = S.B)$
  - index nested loop join: use index on some/all join attribs
  - sort-merge join: sort on *combination* of attributes
  - other algos: no change
- **inequality-join** conditions: $(R.A < S.A)$
  - index nested loop join: requires B$^+$-tree index
  - not applicable: sort-merge join (too much rewinding), hash-based joins
  - other algos: no change

NOTATION

Notation	Meaning
r	relational algebra expression
$\|\|r\|\|$	number of tuples in output of r
$\|r\|$	number of pages in output of r
b_d	number of data records that can fit on a page
b_i	number of data entries that can fit on a page
F	average fanout of B$^+$-tree index (i.e., number of pointers to child nodes)
h	height of B$^+$-tree index (i.e., number of levels of internal nodes)
	$h = \lceil \log_F(\lceil \frac{\|\|R\|\|}{b_i} \rceil) \rceil$ if format-2 index on table R
B	number of available buffer pages