UNIVERSITÄT MANNHEIM

Database Technology
Query Processing

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Today

- We're still opening the mysterious RDBMS black box
  - We can query a database
  - e.g., queries across multiple tables

- Today
  - How are those queries executed?
  - Which parts are evaluated first?
  - How are sorts carried out?
  - ...

Outline

- Overview
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations
- Evaluation of Expressions

Motivation

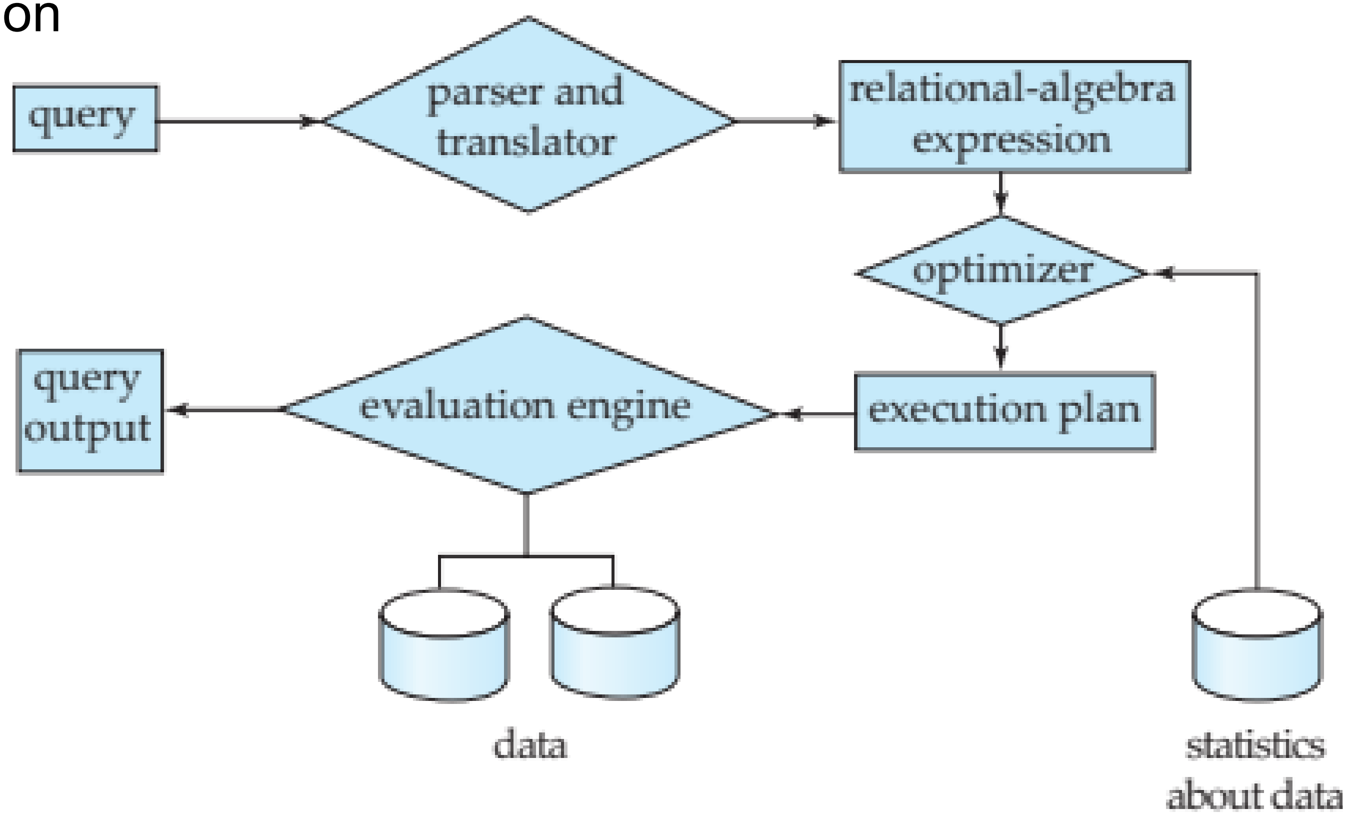
- Suppose you are a RDBMS
  - and you are asked to execute

    ```
    SELECT name, building, salary
    FROM instructor, building
    WHERE instructor.dept_name = department.dept_name
    AND salary>75000
    ORDER BY name
    ```

- How do you want to proceed?
  - Start with instructor or building relation?
  - Sort instructor by name table first, or filter by salary first?
  - …

Basic Steps in Query Processing

1) Parsing and translation
2) Optimization
3) Evaluation



Basic Steps in Query Processing

- Parsing and translation
  - translate the query into its internal form
  - this is then translated into relational algebra
  - parser checks syntax, verifies relations
- Evaluation
  - The query execution engine takes a query evaluation plan,
  - executes that plan,
  - and returns the answers to the query

Basic Steps in Query Processing

- A relational algebra expression may have many equivalent expressions
  - e.g., $\sigma_{salary<75000}(\Pi_{name,salary}(instructor))$ is equivalent to

    $\Pi_{name,salary}(\sigma_{salary<75000}(instructor))$
- Each relational algebra operation can be evaluated using one of several different algorithms
  - Correspondingly, a relational-algebra expression can be evaluated in many ways
- Annotated expression specifying detailed evaluation strategy is called an **evaluation plan**
  - e.g., can use an index on *salary*
    to find instructors with salary < 75000,
  - or can perform complete relation scan and discard instructors with salary $\geq$ 75000

Query Optimization

- **Query Optimization**: Among all equivalent evaluation plans choose the one with lowest cost
  - Cost is estimated using statistical information from the database catalog
  - e.g. number of tuples in each relation, size of tuples, etc.
- Today's lecture:
  - How to measure query costs
  - Algorithms for evaluating relational algebra operations
  - How to combine algorithms for individual operations in order to evaluate a complete expression
- Next week's lecture
  - How to optimize queries,
  - i.e., how to find an evaluation plan with lowest estimated cost

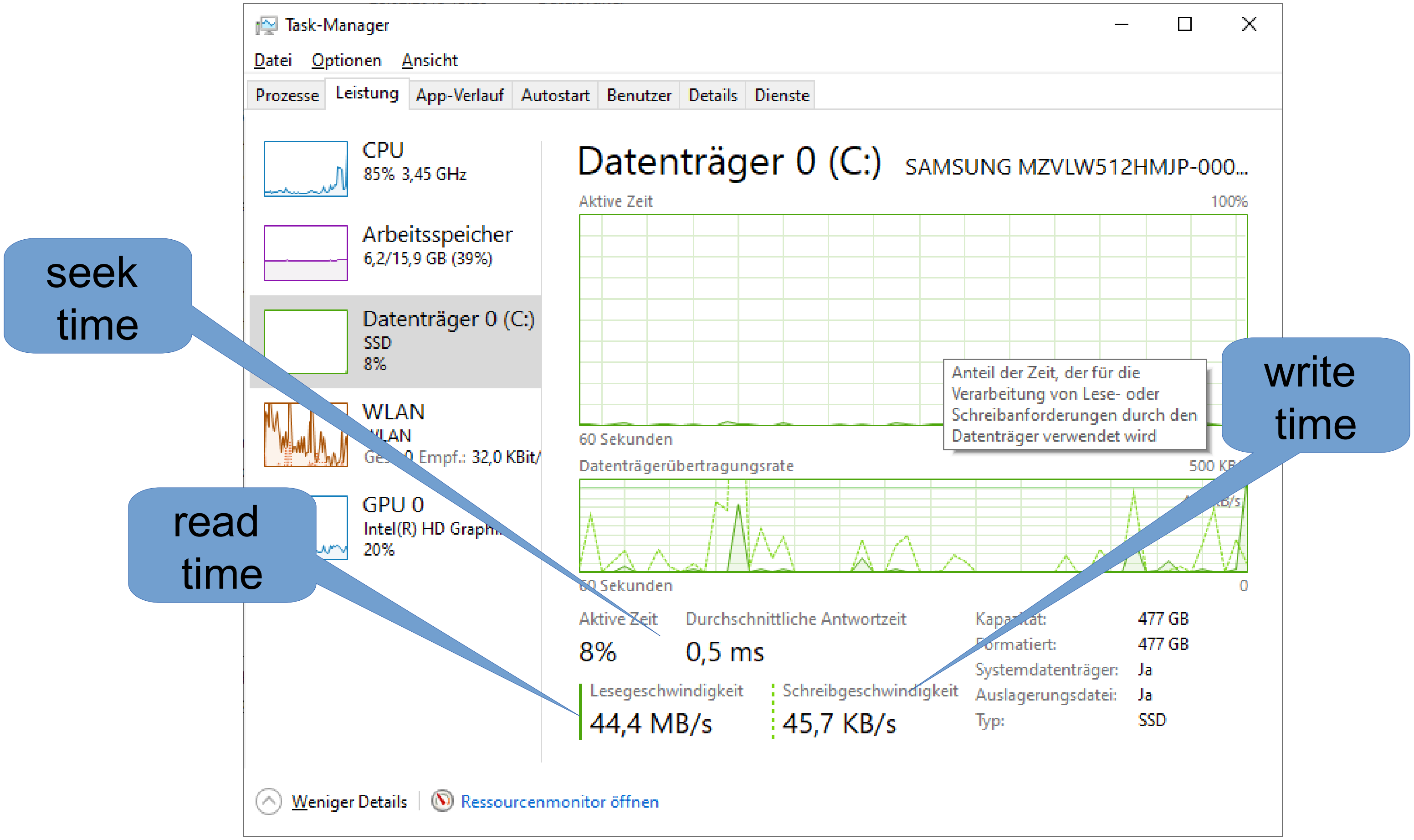
Measuring Query Cost

- We want to execute the query as “cheap” as possible
- But what is “cheap”?
  - Execution time
  - Memory consumption
  - Electrical power consumption
  - ...
- Most approaches seek to minimize the *execution time*

Measuring Query Cost

- Cost is generally measured as *total elapsed time* for answering query
- Many factors contribute to time cost
  - *disk accesses, CPU*, or even network *communication*
- Typically disk access is the predominant cost, and is also relatively easy to estimate
- Measured by taking into account
  - Number of seeks * average-seek-cost
  - Number of blocks read * average-block-read-cost
  - Number of blocks written * average-block-write-cost
- Cost to write a block is greater than cost to read a block
  - data is read back after being written to ensure that the write was successful

Measuring Hardware Performance



Task-Manager

Datei Optionen Ansicht

Prozesse | Leistung | App-Verlauf | Autostart | Benutzer | Details | Dienste

CPU
85% 3,45 GHz

Arbeitsspeicher
6,2/15,9 GB (39%)

Datenträger 0 (C:)
SSD
8%

WLAN
WLAN
Ge... 0 Empf.: 32,0 KBit/

GPU 0
Intel(R) HD Graph...
20%

Datenträger 0 (C:) SAMSUNG MZVLW512HMJP-000...

Aktive Zeit 100%

Anteil der Zeit, der für die Verarbeitung von Lese- oder Schreibanforderungen durch den Datenträger verwendet wird

60 Sekunden

Datenträgerübertragungsrate 500 KB/s

60 Sekunden 0

Aktive Zeit	Durchschnittliche Antwortzeit
8%	0,5 ms

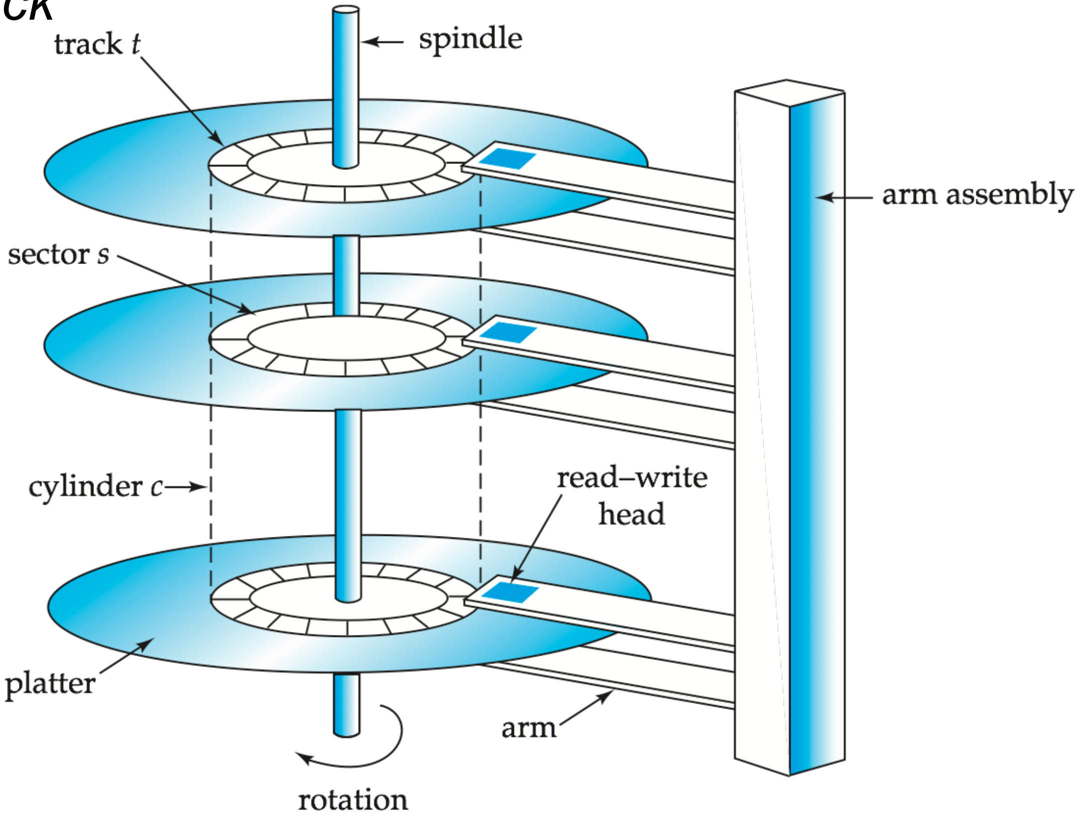
Lesegeschwindigkeit	Schreibgeschwindigkeit
44,4 MB/s	45,7 KB/s

Kapazität:	477 GB
Formatiert:	477 GB
Systemdatenträger:	Ja
Auslagerungsdatei:	Ja
Typ:	SSD

Weniger Details | Ressourcenmonitor öffnen

Recap: Data Access from Hard Disks

- Typically, not all the database can be kept in memory
- Databases are stored on hard disks
- Minimal unit of transfer: *block*
  - optimizing cost
    means
    minimizing block transfer



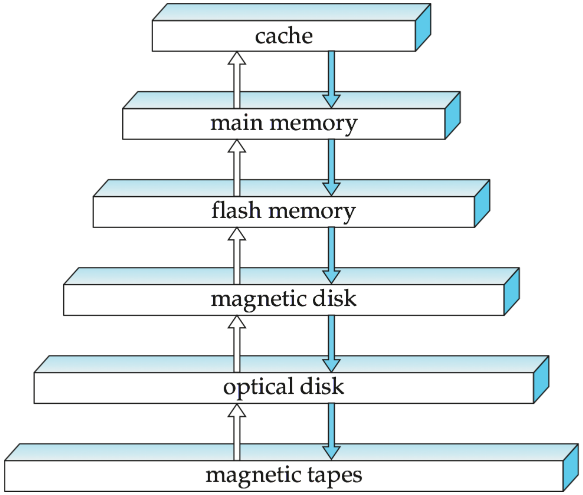
Measuring Query Cost

- For simplicity we just use the **number of block transfers** *from disk and the* **number of seeks** as the cost measures
  - t_T – time to transfer one block
  - t_S – time for one disk seek (i.e., finding a block on the disk)
  - Cost for b block transfers plus S seeks

    $b * t_T + S * t_S$
- We ignore CPU costs for simplicity
  - Real systems do take CPU cost into account
  - We do not include cost of writing output to disk

Measuring Query Cost

- Several algorithms can reduce disk IO by using extra buffer space
  - Amount of real memory available to buffer depends on other concurrent queries and OS processes, known only during execution
  - We often use worst case estimates, assuming only the minimum amount of memory needed for the operation is available
- Required data may be buffer resident already, avoiding disk I/O
  - But hard to take into account for cost estimation



Selection Operation

- **File scan**
- Algorithm **A1** (**linear search**).
  - Seek first block
  - Scan this and each consecutive file block and test all records to see whether they satisfy the selection condition
  - $cost = b_r * t_T + t_S$
  - b_r denotes number of blocks containing records from relation r

Assumption:
File is stored in
consecutive blocks

Selection Operation

- If selection is on a key attribute, can stop on finding the single record (if it exists)
  - *cost* $= (b_r/2) * t_T + t_S$
- Linear search can be applied regardless of
  - selection condition or
  - ordering of records in the file, or
  - availability of indices
- Note: binary search generally does not make sense since data is not stored in order
  - except when there is an index available
  - *cost* $= \log_2(b_r) * (t_T + t_S)$

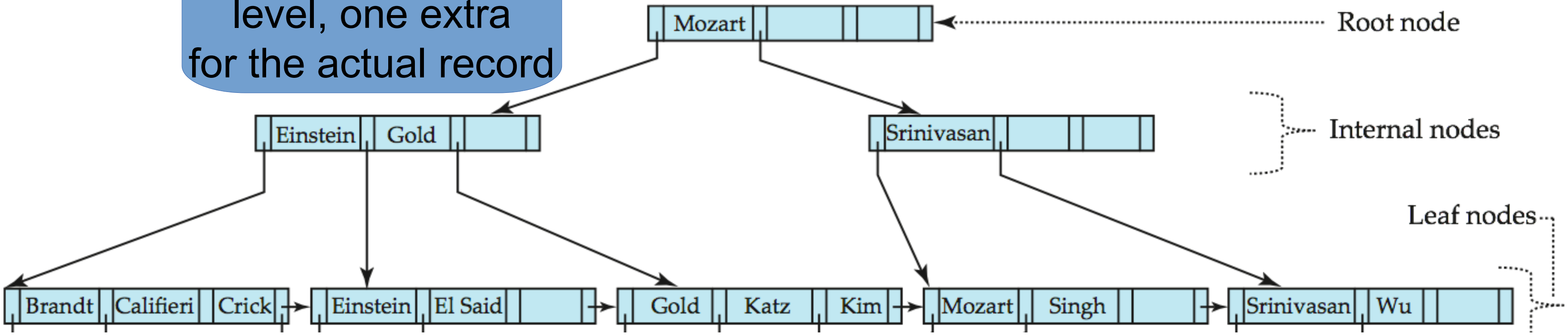
more seeks, less reads

Selections Using Indices

- Assuming a B+ tree of height h_i
- **Index scan** – search algorithms that use an index
  - selection condition must be on search-key of index
- **A2** (**primary index, equality on key**). Retrieve a single record that satisfies the corresponding equality condition
- *Cost* = $(h_i + 1) * (t_T + t_S)$

Nodes *in* the tree are not stored consecutively

One per tree level, one extra for the actual record



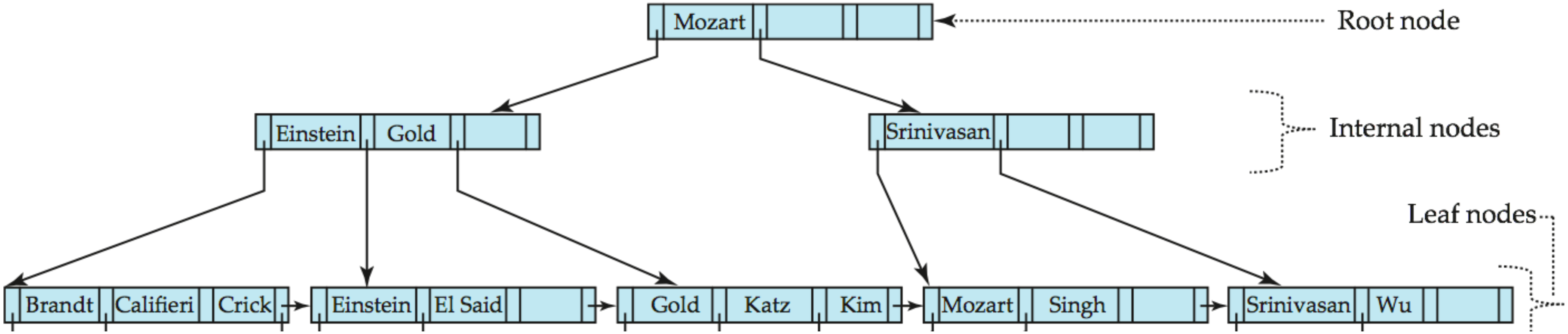
Selections Using Indices

- Assuming a B+ tree of height h_i
- **A3** (**primary index, equality on nonkey**) Retrieve multiple records.
  - Records will be on *consecutive* blocks
  - Let b = number of blocks containing matching records
  - $Cost = h_i * (t_T + t_S) + t_S + t_T * b$

Search in tree

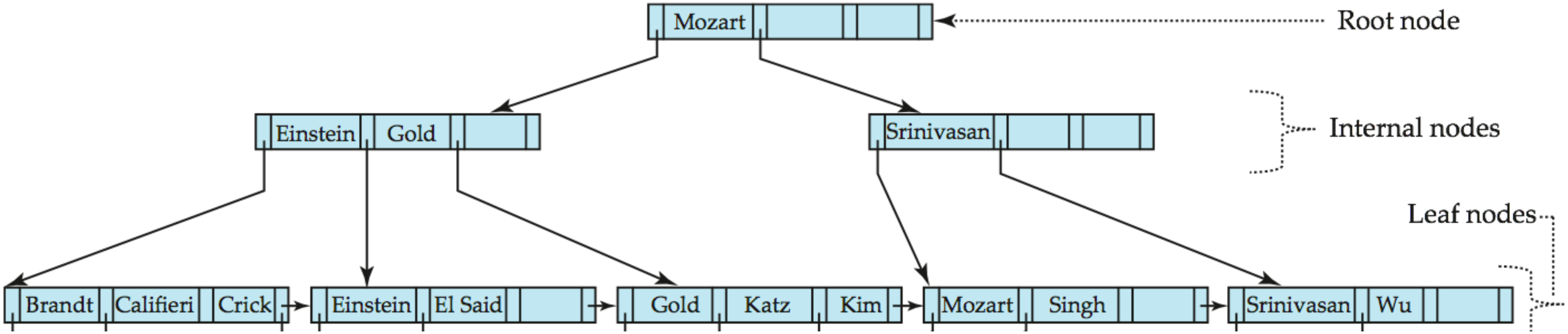
Retrieve first

Retrieve consecutive



Selection Using Secondary Index

- **A4** (**secondary index, equality on nonkey**).
- Retrieve a single record if the search-key is a candidate key
  - *Cost* = $(h_i + 1) * (t_T + t_S)$
- Retrieve multiple records if search-key is not a candidate key
  - each of *n* matching records may be on a different block
  - *Cost* = $(h_i + n) * (t_T + t_S)$
- Can be very expensive!



Selection: A1-A4 in Numbers

- Recap:
  - A1 (file scan): $b_r * t_T + t_S$
  - A3 (tree, primary index): $h_i * (t_T + t_S) + t_S + t_T * b$
  - A4 (tree, secondary index): $(h_i + n) * (t_T + t_S)$
- Let's assume:
  - 1,000 records, $b_r = 50$ (20 records per block), tree height $h_i = 3$, $n = b = 4$ matching records on different blocks
- A1: $50 * t_T + t_S$
- A3: $3 * (t_T + t_S) + t_S + t_T * 4 = \boxed{7 * t_T + 4 * t_S}$
- A4: $(3 + 4) * (t_T + t_S) = 7 * t_T + 7 * t_S$

Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \leq V}(r)$ or $\sigma_{A \geq V}(r)$ by using
  - a linear file scan,
  - or by using an index
- **A5** (**primary index, comparison**). (Relation is sorted on A)
  - For $\sigma_{A \geq V}(r)$ use index to find first tuple $\geq v$ and scan relation sequentially from there
  - For $\sigma_{A \leq V}(r)$ just scan relation sequentially till first tuple > *v;* do not use index
  - $Cost = h_i * (t_T + t_S) + t_S + t_T * b$
    - identical to A3 (index on nonkey)

Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \leq V}(r)$ or $\sigma_{A \geq V}(r)$ by using
  - a linear file scan,
  - or by using an index
- **A6** (secondary **index, comparison**). (Relation not sorted on A)
  - For $\sigma_{A \geq V}(r)$ use index to find first index entry ≥ *v* and scan index sequentially from there, to find pointers to records.
  - For $\sigma_{A \leq V}(r)$ just scan leaf pages of index finding pointers to records, till first entry > *v*
  - In either case, retrieving records that are pointed to
    - requires an I/O for each record
    - may be more expensive than linear file scan
  - $Cost = (h_i + n) * (t_T + t_S)$
    - identical to A4 (index on nonkey)

Implementation of Complex Selections

- **Conjunction:** $\sigma_{\theta 1} \wedge _{\theta 2} \wedge \ldots _{\theta n}(r)$
  - e.g., all students enrolled in the MMDS, in semester 4 or higher with GPA<2.0
- **A7** (**conjunctive selection using one index**).
  - Select a combination of θ_i and algorithms A2 through A6 that results in the least cost for $\sigma_{\theta i}(r)$
  - Test other conditions on tuple after fetching it into memory buffer
- **A8** (**conjunctive selection using composite index**).
  - Use appropriate composite (multiple-key) index if available
  - Use one of the algorithms A2-A4 with the least cost
  - Test other conditions on tuple after fetching it into memory buffer

Implementation of Complex Selections

- **A9** (**conjunctive selection by intersection of identifiers**)
  - Requires indices with record pointers
  - Use corresponding index for each condition, and take intersection of all the obtained sets of record pointers
    - all record pointers of students with program “MMDS”,
    - all record pointers of students with semester ≥ 4
    - all record pointers of students with GPA<2.0
  - Then fetch records from file
    - minimizes block transfers as far as possible
  - If some conditions do not have appropriate indices
    - apply remaining tests in memory

Implementation of Complex Selections

- **Disjunction:**$\sigma_{\theta 1} \vee {}_{\theta 2} \vee . . . {}_{\theta n} (r)$.
- **A10** (**disjunctive selection by union of identifiers**)
  - Use corresponding index for each condition
  - collect pointers for each condition
  - use union of all the obtained sets of record pointers
  - Then fetch records from file
- Applicable only if *all* conditions have available indices
  - Otherwise use linear scan

Implementation of Complex Selections

- **Negation:** $\sigma_{\neg\theta}(r)$
  - Use linear scan on file
- Sometimes:
  - negation can be reformulated:
    - ¬(salary>4000) → salary≤4000
- Special case:
  - if very few records satisfy $\neg\theta$, and an index is applicable to θ
  - find satisfying records using index and fetch from file

Intermediate Recap: Selection

- Selection performance depends on availability of indices
- Conjunctive queries ($\wedge$):
  - mixed strategies are possible:
    - create intermediate result set using indices
    - perform remaining tests on intermediate result set
- Disjunctive queries ($\vee$) and negation ($\neg$):
  - less easy
  - disjunction requires complete set of indices
  - negation is not easily solveable (unless it can be resolved upfront)

Sorting

- Recap initial example:

  SELECT name, building, salary
  FROM instructor, building
  WHERE instructor.dept_name = department.dept_name
  AND salary>75000
  ORDER BY name

- Assuming we have indices on dept_name and salary
  - how do we sort the results efficiently?

- Variant 1: build an index on the sorting attribute
  - and read from that index
  - hard to combine with other conditions
- Variant 2: sort in memory (e.g., QuickSort)
- Variant 3: use *external sort merge*

used if the results do not fit in memory

External Sort-Merge

- Two steps:
  1) Created partially sorted data chunks
  2) Merge the partially sorted chunks

- First step:
  - Let M be the memory capacity
  - **Create sorted runs**. Let *i* be 0 initially

    Repeatedly do the following till the end of the relation:

    (a) Read *M* blocks of relation into memory

    (b) Sort the in-memory blocks

    (c) Write sorted data to run R_i; increment *i*

    Let the final value of *i* be *N*

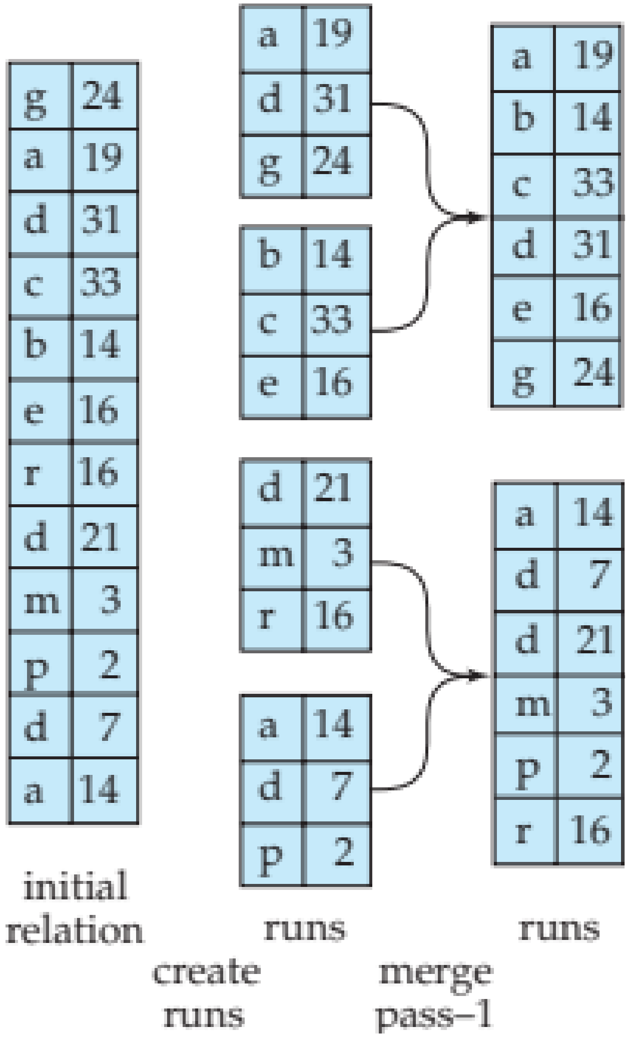
External Sort-Merge

- Second step: merge the runs
- **Merge the runs (N-way merge)**. We assume (for now) that $N < M$.
  - Use N blocks of memory to buffer input runs, and 1 block to buffer output. Read the first block of each run into its buffer page

```
repeat
    Select the first record (in sort order) among all buffer pages
    Write the record to the output buffer.
        If the output buffer is full write it to disk.
    Delete the record from its input buffer page.
    If the buffer page becomes empty then
        read the next block (if any) of the run into the buffer.
until all input buffer pages are empty
```

- If $N \geq M$, several merge *passes* are required
  - In each pass, contiguous groups of M - 1 runs are merged

External Sort-Merge



initial relation

g	24
a	19
d	31
c	33
b	14
e	16
r	16
d	21
m	3
p	2
d	7
a	14

create runs

runs

a	19
d	31
g	24

b	14
c	33
e	16

d	21
m	3
r	16

a	14
d	7
p	2

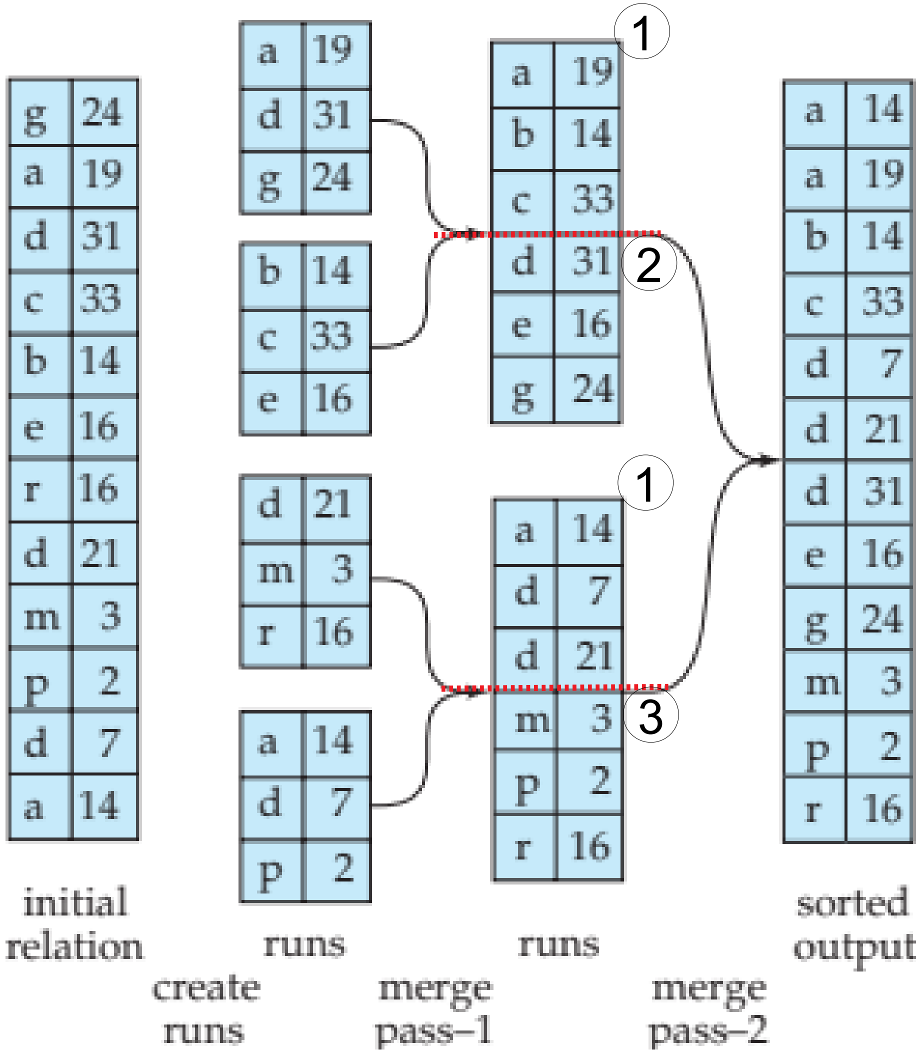
merge pass–1

runs

a	19
b	14
c	33
d	31
e	16
g	24

a	14
d	7
d	21
m	3
p	2
r	16

External Sort-Merge



External Sort-Merge

- At each merge step, only three blocks need to be kept in memory
  - the two (sorted) blocks which are currently merged
  - the current output block
  - after half way through sorting two blocks
    - the current output block is written to disk
    - a second output block is started

- Speed up:
  - the more blocks fit in memory at a same time, the larger the chunks can be
  - Ultimately, less passes are required
    - Number of passes is O(log M)

Join Operations

- Recap: Initial example:

```
SELECT name, building, salary
FROM instructor, building
WHERE instructor.dept_name = department.dept_name
AND salary>75000
ORDER BY name
```

- Several different algorithms to implement joins
- Choice based on cost estimate
- Examples use the following information
  - Number of records of *instructor*: 5,000 *department*: 10,000
  - Number of blocks of *instructor*: 100 *department*: 400

Nested Loop Join

- To compute the theta join $r \bowtie_{\theta} s$

```
for each tuple $t_r$ in $r$ do begin
  for each tuple $t_s$ in $s$ do begin
        test pair $(t_r, t_s)$ to see if they satisfy the join condition $\theta$
        if they do, add $t_r \cdot t_s$ to the result.
  end
end
```

- r is called the **outer relation** and s the **inner relation** of the join

- Requires no indices and can be used with any kind of join condition
- Expensive since it examines every pair of tuples in the two relations

Nested Loop Join

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is

  $n_r * b_s + b_r$ block transfers, plus

  $n_r + b_r$ seeks

- Assuming worst case memory availability cost estimate is
  - with *instructor* as outer relation:

    5000 ∗ 400 + 100 = 2,000,100 block transfers,

    5000 + 100 = 5,100 seeks
  - with *department* as the outer relation

    10000 ∗ 100 + 400 = 1,000,400 block transfers and 10,400 seeks

records/blocks
instructor: 5,000/100
department: 10,000/400

Nested Loop Join

- Best case: the smaller relation fits entirely in memory
  - use that as the inner relation
  - reduces cost to $b_r + b_s$ block transfers and two seeks
- If smaller relation (*instructor*) fits entirely in memory, the cost estimate will be 500 block transfers
  - 100 blocks reading the *instructor* relation into memory
  - 400 blocks of the *department* relation

records/blocks
instructor: 5,000/100
department: 10,000/400

Block Nested Loop Join

- Variant of nested-loop join in which every block of inner relation is paired with every block of outer relation
- Algorithm uses four nested loops

```
for each block $B_r$ of $r$ do
        for each block $B_s$ of $s$ do
            for each tuple $t_r$ in $B_r$ do
                for each tuple $t_s$ in $B_s$ do
                        Check if $(t_r, t_s)$ satisfy the join condition
                        if they do, add $t_r \cdot t_s$ to the result.
```

Block Nested Loop Join

- Worst case: only one block of each relation fits in memory
  - estimate: $b_r * b_s + b_r$ block transfers + 2 * b_r seeks
  - Each block in the inner relation *s* is read once for each *block* in the outer relation
- Best case: $b_r + b_s$ block transfers + 2 seeks
- Improvements to nested loop and block nested loop algorithms:
  - If equi-join attribute forms a key on inner relation, stop inner loop on first match
  - Scan inner loop forward and backward alternately, to make use of the blocks remaining in buffer (with LRU replacement)
  - Use index on inner relation if available (next slide)

Indexed Nested Loop Join

- Index lookups can replace file scans if
  - join is an equi-join or natural join and
  - an index is available on the inner relation’s join attribute
- For each tuple t_r in the outer relation *r,* use the index to look up tuples in *s* that satisfy the join condition with tuple t_r
- Worst case: buffer has space for only one page of *r*, and, for each tuple in *r*, we perform an index lookup on *s*
- If indices are available on join attributes of **both** *r* and *s*
  - use the relation with fewer tuples as the outer relation

Cost of Nested Loop with and without Index

- Compute instructor $\bowtie$ *department,* with *department* as the outer relation
  - Let *department* have a primary B^+-tree index on the attribute *dept_name,* which contains 20 entries in each index node
  - Since *department* has 10,000 tuples, the height of the tree is 4
  - i.e.: five block transfers to find the actual data
- *instructor* has 5000 tuples
- Cost of block nested loops join
  - 400*100 + 100 = 40,100 block transfers + 2 * 100 = 200 seeks
  - assuming worst case memory

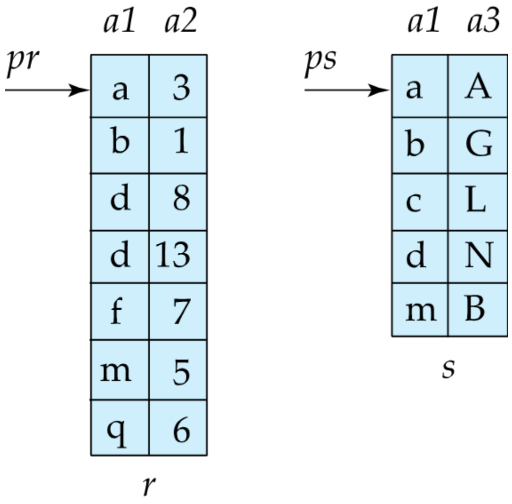
    (may be significantly less with more memory)
- Cost of indexed nested loops join
  - 100 + 5000 * 5 = 25,100 block transfers and seeks

records/blocks
instructor: 5,000/100
department: 10,000/400

Merge Join

- Sort both relations on their join attribute (if not already sorted on the join attributes):
  - move two pointers pr and ps
  - if pr=ps → add join result to result set

```
else
      if pr<ps
            advance pr
      else
            advance ps
```



a1	a2
a	3
b	1
d	8
d	13
f	7
m	5
q	6

r

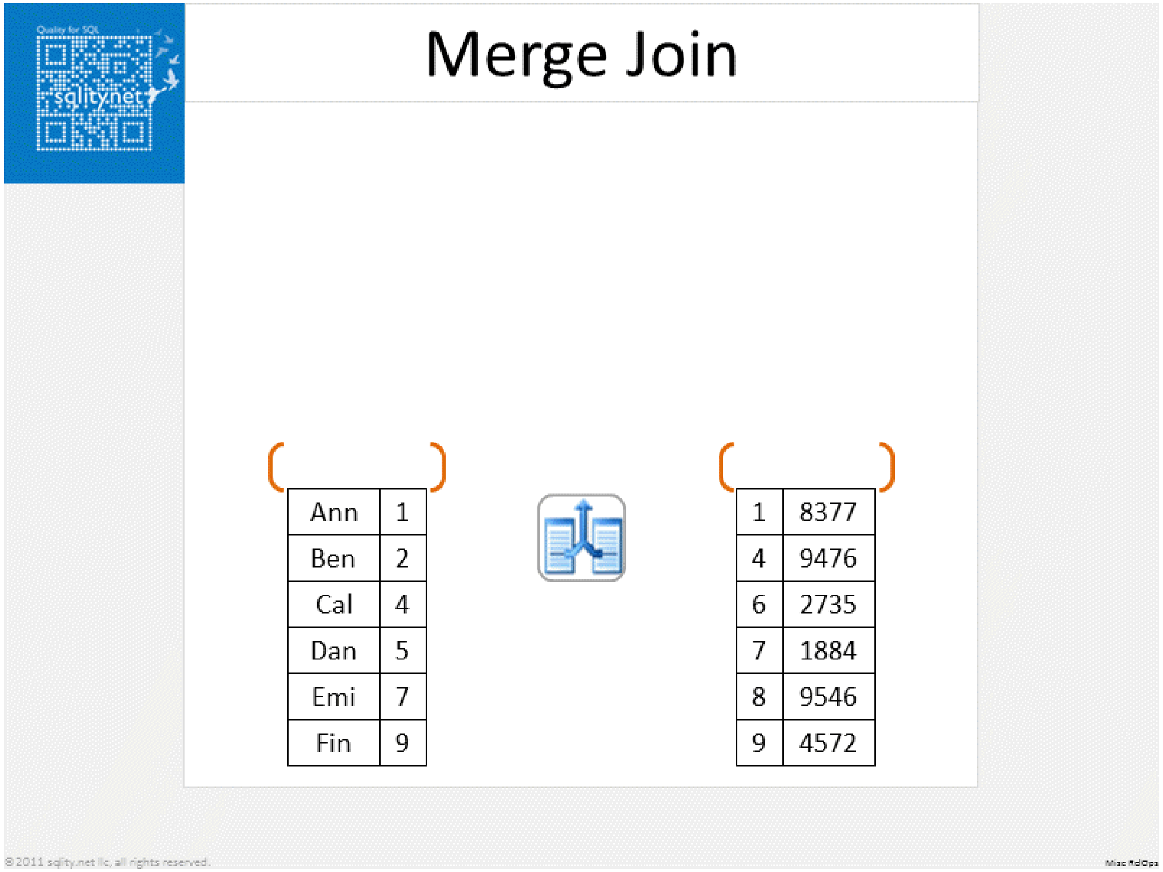
a1	a3
a	A
b	G
c	L
d	N
m	B

s

- Main difference is handling of duplicate values in join attribute:
  - every pair with same value on join attribute must be matched
- Detailed algorithm in books

Merge Join

- Example from http://sqlity.net/en/1480/a-join-a-day-the-sort-merge-join/



Merge Join

Ann	1
Ben	2
Cal	4
Dan	5
Emi	7
Fin	9

1	8377
4	9476
6	2735
7	1884
8	9546
9	4572

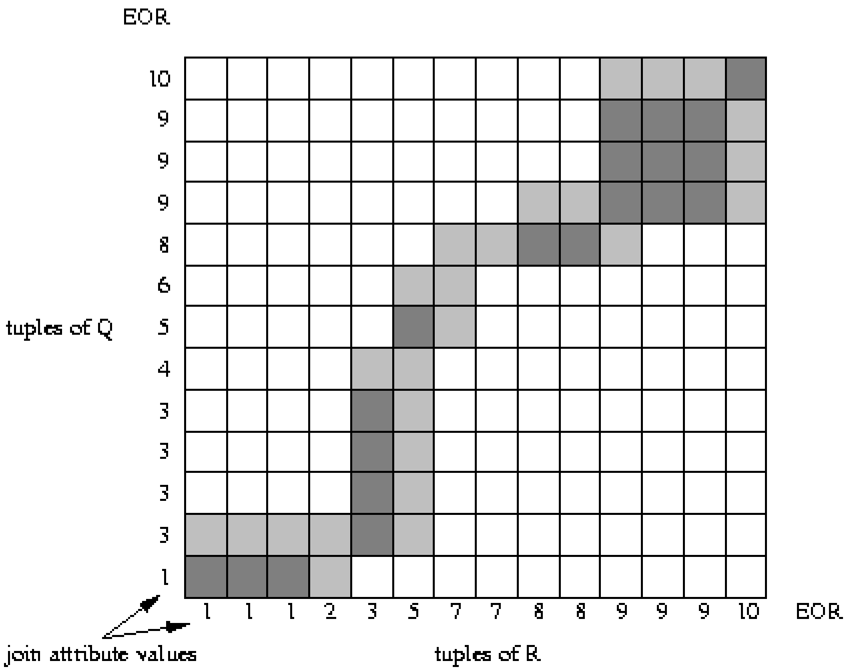
Merge Join

- Can be used only for equi-joins and natural joins
- Each block needs to be read only once (assuming all tuples for any given value of the join attributes fit in memory)
- Thus the cost of merge join is:
  - $b_r + b_s$ block transfers $+ \lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil$ seeks
  - plus the cost of sorting if relations are unsorted

b_b: no- of buffer blocks allocated to each relation

Merge Join

- Actual comparisons carried out by a merge join
  - roughly linear instead of quadratic

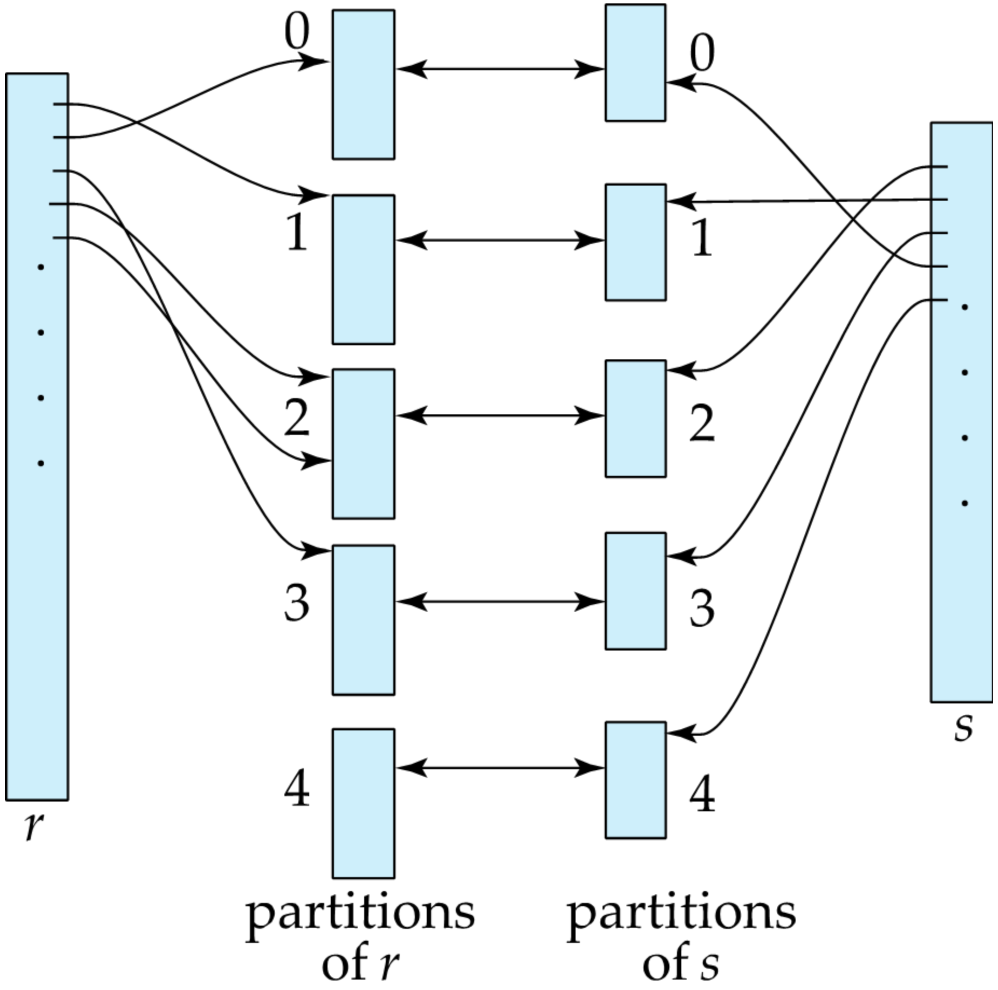


http://www.dcs.ed.ac.uk/home/tz/phd/thesis/node20.htm

Hash Join

- Applicable for equi-joins and natural joins
  - idea: partition relations to join using hashes
  - only compute joins based on the hash partitions
- A hash function *h* is used to partition tuples of *both* relations
- *h* maps *JoinAttrs* values to {0, 1, ..., *n*}, where *JoinAttrs* denotes the common attributes of *r* and *s* used in the natural join
  - $r_0, r_1, \ldots, r_n$ denote partitions of *r* tuples
    - Each tuple $t_r \in r$ is put in partition r_i where $i = h(t_r[JoinAttrs])$
  - $s_0, s_1 \ldots, s_n$ denotes partitions of *s* tuples
    - Each tuple $t_s \in s$ is put in partition s_i where $i = h(t_s[JoinAttrs])$

Hash Join



Hash Join

Computing Hash Join:

1. Partition the relation *s* using hashing function *h*
2. Partition *r* similarly
3. For each *i (1 ≤ i ≤ number of partitions):*

(a) Load s_i into memory and build an in-memory hash index on it using the join attribute (using a different hash function)

why different?

(b) Read the tuples in r_i from the disk one by one. For each tuple t_r locate each matching tuple t_s in s_i using the in-memory hash index

Relation *s* is called the **build input** and *r* is called the **probe input**

Hash Join

- Complexity
  - Building the hash: reading each block in each relation, and writing the partition back to disk: $2(b_r + b_s)$
  - Computing the join: reading each partition
- Partitions can also be underfull blocks
  - i.e., there might be n_h extra partitions for each relation
  - each of those needs to be written and read
- Thus, the total number of block transfers is
  - $3(b_r + b_s) + 4n_h$
- Number of seeks
  - need to seek original and partitioned blocks, respecting underfull blocks
  - i.e. $2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil)$

for simplicity, overflow partitions are not considered here

Joins with Complex Conditions

- Join with a conjunctive condition:

  $r \bowtie_{\theta 1 \wedge \theta\ 2 \wedge \ldots\ \wedge \theta\ n}\ s$

  - Either use nested loops/block nested loops, or
  - Compute the result of one of the simpler joins $r \bowtie_{\theta i} s$
  - final result comprises those tuples in the intermediate result that satisfy the remaining conditions

    $$\theta_1 \wedge \ldots \wedge \theta_{i-1} \wedge \theta_{i+1} \wedge \ldots \wedge \theta_n$$

- Join with a disjunctive condition

  $r \bowtie_{\theta 1 \vee \theta 2 \vee \ldots \vee \theta n} s$

  - Either use nested loops/block nested loops, or
  - Compute as the union of the records in individual joins $r \bowtie_{\theta i} s$:

    $$(r \bowtie_{\theta 1} s) \cup (r \bowtie_{\theta 2} s) \cup \ldots \cup (r \bowtie_{\theta n} s)$$

Duplicate Elimination & Projection

- In relational algebra, there are no duplicates by definition
  - i.e., each projection yields a unique result
- In SQL queries, they can be explicitly discarded
  - SELECT DISTINCT …
- Duplicates can be eliminated either via sorting or hashing
  - After sorting, duplicates are adjacent,
    and can be easily removed passing over the data
    - with sort merge, duplicate elimination can be done early
  - With hashing, they are sorted into the same bucket,
    and can be detected locally
- Projection
  - perform projection on each tuple
  - then run duplicate removal

Aggregation

- **Aggregation** can be implemented similarly to duplicate elimination
- Sorting or hashing
  - bring tuples in the same group together
  - then apply aggregate functions on each group
- Optimization:
  - combine tuples in the same group during run generation and intermediate merges
  - compute partial aggregate values
    - count, min, max, sum: keep aggregate values on tuples found so far in the group
    - avg: keep sum and count, and divide sum by count at the end

Outer Joins

- **Outer join** can be computed either as
  - a join followed by addition of null-padded non-participating tuples
  - by modifying the join algorithms
- Modifying merge join to compute r ⟕ s
  - In r ⟕ s, non participating tuples are those in $r - \Pi_R(r \bowtie s)$
  - During merging, for every tuple t_r from r that do not match any tuple in s, output t_r padded with nulls
    - Right outer join and full outer join can be computed similarly
- Modifying hash join to compute r ⟕ s
  - If r is probe relation, output non-matching r tuples padded with nulls
  - If r is build relation, keep track of which r tuples matched s tuples
    - at the end of s_i, output non-matched r tuples padded with nulls

Evaluation of Expressions

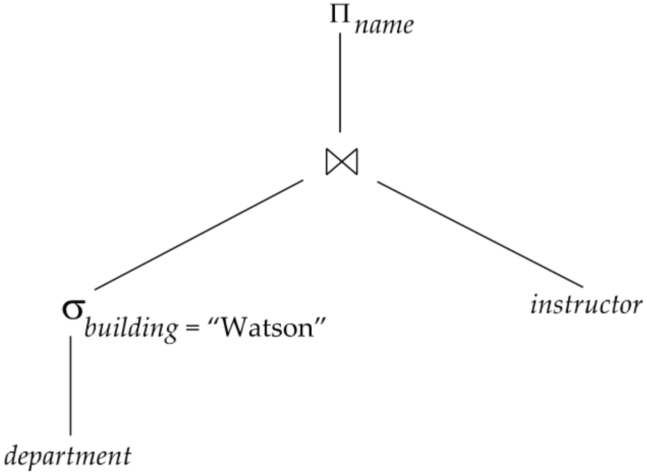
- So far: we have seen algorithms for individual operations
- Alternatives for evaluating an entire expression tree
  - **Materialization**: generate results of an expression whose inputs are relations or are already computed, **materialize** (store) it on disk. Repeat.
  - **Pipelining**: pass on tuples to parent operations even as an operation is being executed
- We study above alternatives in more detail

Materialization

- **Materialized evaluation:** evaluate one operation at a time, starting at the lowest level. Use intermediate results materialized into temporary relations to evaluate next-level operations
- E.g., in figure below, compute and store

$$\sigma_{building="\text{Watson}"}(department)$$

then compute and store its join with *instructor,* and finally compute the projection on *name.*



Cost of Materialization

- Materialized evaluation is always applicable
  - If it does not fit in memory:
    high cost of writing results to disk and reading them back
    - Our cost formulas for operations ignore cost of writing results to disk, so
    - Overall cost = Sum of costs of individual operations +
      cost of writing intermediate results to disk
- **Double buffering**: use two output buffers for each operation, when one is full write it to disk while the other is getting filled
  - Allows overlap of disk writes with computation and reduces execution time

Pipelining

- **Pipelined evaluation:** evaluate several operations simultaneously, passing the results of one operation on to the next
  - E.g., in previous expression tree, do not store result of
    $$\sigma_{building=\text{"Watson"}}(department)$$
  - instead, pass tuples directly to the join
  - do not store result of join, pass tuples directly to projection
- Much cheaper than materialization: no need to store a temporary relation to disk
  - Pipelining may not always be possible – e.g., sort, hash-join
  - For pipelining to be effective, use evaluation algorithms that generate output tuples even as tuples are received for inputs to the operation
- Pipelines can be executed in two ways: **demand driven** and **producer driven**

Pipelining

- In **demand driven** or **lazy** evaluation
  - system repeatedly requests next tuple from top level operation
  - Each operation requests next tuple from children operations as required, in order to output its next tuple
  - In between calls, operation has to maintain "**state**" so it knows what to return next
- In **producer-driven** or **eager** pipelining
  - Operators produce tuples eagerly and pass them up to their parents
  - Buffer maintained between operators, child puts tuples in buffer, parent removes tuples from buffer
  - if buffer is full, child waits till there is space in the buffer, and then generates more tuples
  - System schedules operations that have space in output buffer and can process more input tuples
- Alternative names: **pull** and **push** models of pipelining

Summary

- How are queries executed?
  - Each query is a sequence of operations
  - Sequence: materialization vs. pipelining
- Implementation of different operations
  - Selection
  - Joins
  - Sorting
  - Projection
  - …
- Estimation of query cost
  - block seeks and block transfers
  - gives way to query optimization (next lecture)

Questions?