Cost model: initial thoughts

Disk access costs depend on

- the current position of the disk arm and
- the angular position of the platters

Both are not known at query compilation time
Consequence:

- estimating the costs of a single disk access at query compilation time may result in large estimation error

Better: costs of many accesses
Nonetheless: First Simplistic Cost Model to give a feeling for disk drive access costs

Simplistic Cost Model

We introduce some disk drive parameters for out simplistic cost model:

- average latency time: average time for positioning (seek+rotational delay)
  - use average access time for a single request
  - Estimation error can (on the average) be as "low" as 35%
- sustained read/write rate:
  - after positioning, rate at which data can be delivered using sequential read

Model 2004

A hypothetical disk (inspired by disks available in 2004) then has the following parameters:

Model 2004		
Parameter	Value	Abbreviated Name
capacity	180 GB	D_{cap}
average latency time	5 ms	D_{lat}
sustained read rate	100 MB/s	D_{srr}
sustained write rate	100 MB/s	D_{swr}

The time a disk needs to read and transfer n bytes is then approximated by $D_{\text{lat}} + n/D_{\text{srr}}$.

Sequential vs. Random I/O

Database management system developers distinguish between

- *sequential* I/O and
- *random* I/O.

In our simplistic cost model:

- for sequential I/O, there is only one positioning at the beginning and then, we can assume that data is read with the sustained read rate.
- for random I/O, one positioning for every unit of transfer—typically a page of say 8 KB—is assumed.

Simplistic Cost Model

Read 100 MB

- Sequential read: 5 ms + 1 s
- Random read (8K pages): 65 s

Simplistic Cost Model (2)

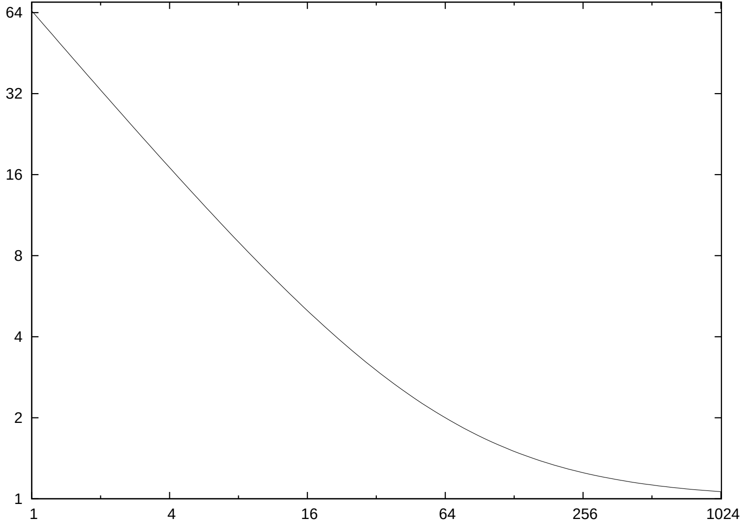
Problems:

- other applications
- other transactions
- other read operations in the same QEP

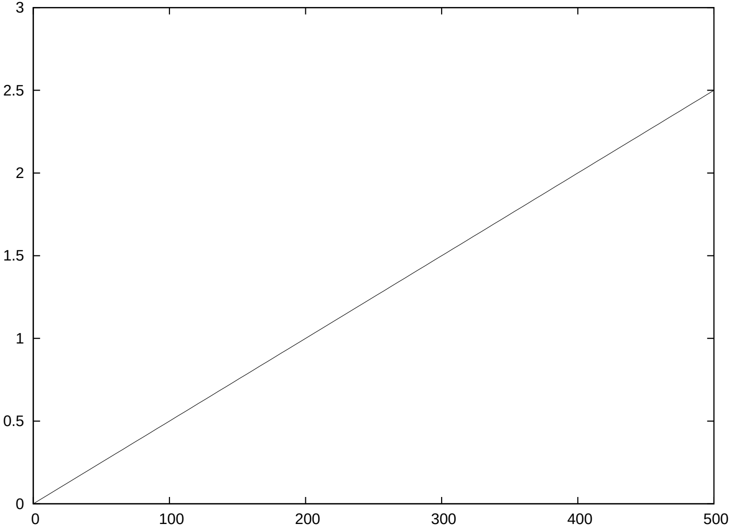
may request blocks from the same disk and move away the head(s) from the current position

Further: 100 MB sequential search poses problem to buffer manager

Time to Read 100 MB (x: number of 8 KB chunks)



Time to Read n Random Pages



Simplistic Cost Model (3)

100 MB can be stored on 12800 8 KB pages.

In our simplistic cost model, reading 200 pages randomly costs about the same as reading 100 MB sequentially.

That is, reading 1/64th of 100 MB randomly takes as long as reading the 100 MB sequentially.

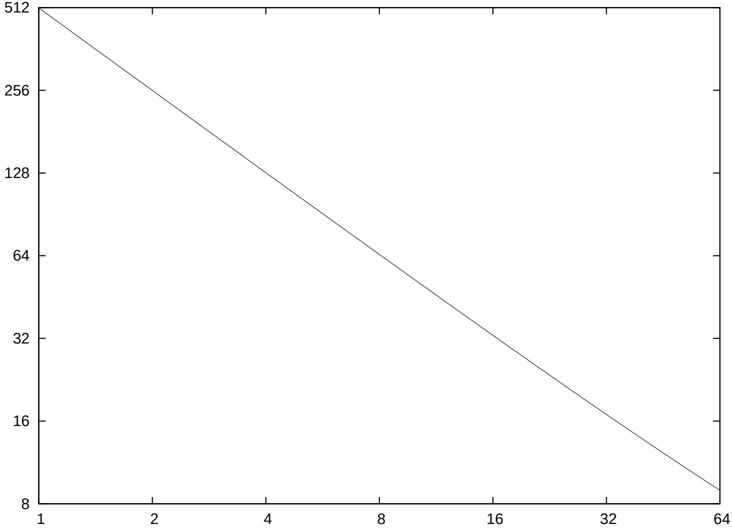
Simplistic Cost Model (4)

Let us denote by a the positioning time, s the sustained read rate, p the page size, and d some amount of consecutively stored bytes. Let us calculate the break even point

$$\begin{aligned} n * (a + p/s) &= a + d/s \\ n &= (a + d/s)/(a + p/s) \\ &= (as + d)/(as + p) \end{aligned}$$

a and s are disk parameters and, hence, fixed. For a fixed d, the break even point depends on the page size.
Next Figure: x-axis: is the page size p in multiples of 1 K; y-axis: $(d/p)/n$ for $d = 100$ MB.

Break Even Point (depending on page size)



Two Lessons Learned

- sequential read is much faster than random read
- the runtime system should secure sequential read

The latter point can be generalized:

- the runtime system of a database management system has, as far as query execution is concerned, two equally important tasks:
  - allow for efficient query evaluation plans and
  - allow for smooth, simple, and robust cost functions.

Measures to Achieve the Above

Typical measures on the database side are

- carefully chosen physical layout on disk
  (e.g. cylinder or track-aligned extents, clustering)
- disk scheduling, multi-page requests
- (asynchronous) prefetching,
- piggy-back scans,
- buffering (e.g. multiple buffers, replacement strategy) and last but not least
- efficient and robust algorithms for algebraic operators

Disk Drive: Parameters

D_{cyl}	total number of cylinders
D_{track}	total number of tracks
D_{sec}	total number of sectors
D_{tpc}	number of tracks per cylinder (= number of surfaces)

D_{cmd}	command interpretation time
D_{rot}	time for a full rotation
D_{rdsettle}	time for settle for read
D_{wrsettle}	time for settle for write
D_{hdswitch}	time for head switch

Disk Drive: Parameters (2)

D_{zone}	total number of zones
$D_{\text{zcyl}}(i)$	number of cylinders in zone i
$D_{\text{zspt}}(i)$	number of sectors per track in zone i
$D_{\text{zspc}}(i)$	number of sectors per cylinder in zone i $(= D_{\text{tpc}} D_{\text{zspt}}(i))$
$D_{\text{zscan}}(i)$	time to scan a sector in zone i $(= D_{\text{rot}}/Dzspti)$

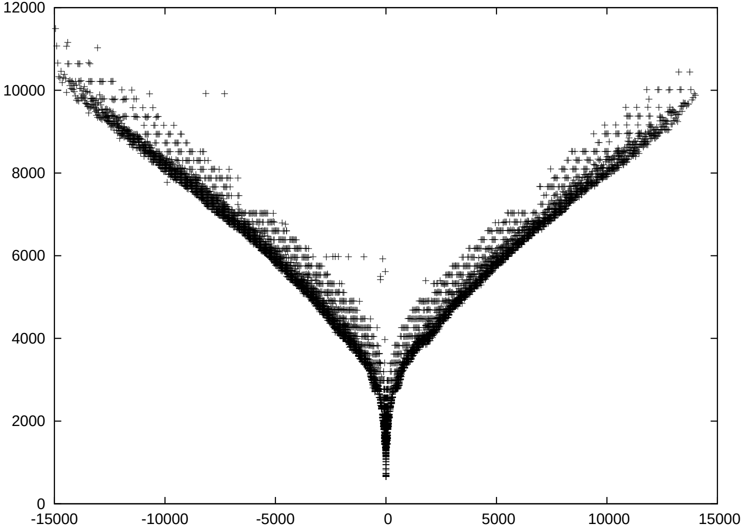
Disk Drive: Parameters (3)

D_{seekavg}	average seek costs
D_{clim}	parameter for seek cost function
D_{ca}	parameter for seek cost function
D_{cb}	parameter for seek cost function
D_{cc}	parameter for seek cost function
D_{cd}	parameter for seek cost function
$D_{\text{fseek}}(d)$	cost of a seek of d cylinders $D_{\text{fseek}}(d) = \begin{cases} D_{\text{ca}} + D_{\text{cb}}\sqrt{d} & \text{if } d \leq D_{\text{clim}} \\ D_{\text{cc}} + D_{\text{cd}}\,d & \text{if } d > D_{\text{clim}} \end{cases}$
$D_{\text{frot}}(s, i)$	rotation cost for s sectors of zone i $(= sD_{\text{zscan}}(i))$

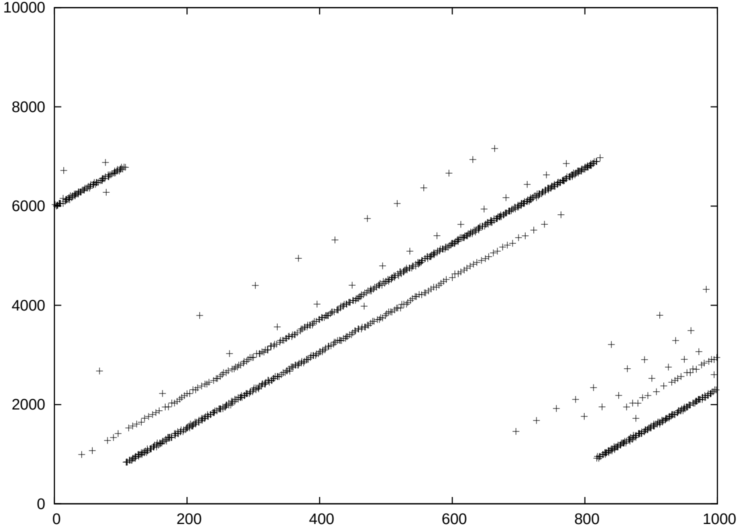
Extraction of Disk Drive Parameters

- documentation: often not sufficient
- mapping: interrogation via SCSI-Mapping command (disk drives lie)
- use benchmarking tools, e.g.:
  - Diskbench
  - Skippy (Microbenchmark)
  - Zoned

Seek Curve Measured with Diskbench



Skippy Benchmark Example



Interpretation of Skippy Results

- x-axis: distance (sectors)
- y-axis: time
- difference topmost/bottommost line: rotational latency
- difference two lowest ‘lines’: head switch time
- difference lowest ‘line’ topmost spots: cylinder switch time
- start lowest ‘line’: minimal time to media
- plus other parameters

Upper bound on Seek Time

Theorem (Qyang)

If the disk arm has to travel over a region of C cylinders, it is positioned on the first of the C cylinders, and has to stop at $s-1$ of them, then $sD_{fseek}(C/s)$ is an upper bound for the seek time.

Database Buffer

The database buffer

1. is a finite piece of memory,
2. typically supports a limited number of different page sizes (mostly one or two),
3. is often fragmented into several buffer pools,
4. each having a replacement strategy (typically enhanced by hints).

Given the page identifier, the buffer frame is found by a hashtable lookup.
Accesses to the hash table and the buffer frame need to be synchronized.
Before accessing a page in the buffer, it must be fixed.
These points account for the fact that the costs of accessing a page in the buffer are therefore greater than zero.

Buffer Accesses

Consider page acceses in a buffer with 2 pages:

page no	action
0	read page 0, place it in buffer
1	read page 1, place it in buffer
0	fix page 0 in buffer
2	swap out a page (e.g. 1), read 2, place it in buffer
0	fix page 0 in buffer
3	swap out a page, read 3, place it in buffer
...	

- replacement strategy is imporant
- unfixes omitted

Replacement Strategies

Some popular replacement strategies:

- random
- fifo
- lru
- Q2

lru is very popular

Replacement Strategies - random

- when a new page slot is needed, remove a random other page from the buffer
- easy to implements, needs no additional memory
- but does not take the access patterns into account
- primarily used as base line
- suitable for analytic results

Replacement Strategies - fifo

- first in - first out
- remove the page that was place in the buffer first
- easy to implement, needs no/few additional memory
- but does not adapt very well do access patterns
- increasing buffer size may hurt it

Fifo Anomaly:

- access pattern: 3 2 1 0 3 2 4 3 2 1 0 4
- buffer sizes: 3 vs. 4

Replacement Strategies - lru

- least recently used
- remove the page that has not been accessed for longest time
- requires a priority queue/linked list
- adapt to access patterns, popular pages stay in memory
- but slow to remove pages

very popular replacement strategy

Replacement Strategies - 2Q

- two queues
- a fifo queue and a lru queue
- place pages first in fifo, if they are accessed again place them in lru
- gets rid of pages that are accessed only once fast
- superior to lru, example of a "real" replacement strategy

Replacement Strategies - Effect on the Cost Model

- replacement affects the costs
- cost model needs predictions, though
- very hard to do in general

Typical approaches:

- ignore buffer effects
- assume random replacement
- make use of known access characteristics

Physical Database Organization

The database organizes the physical storage in multiple layers:

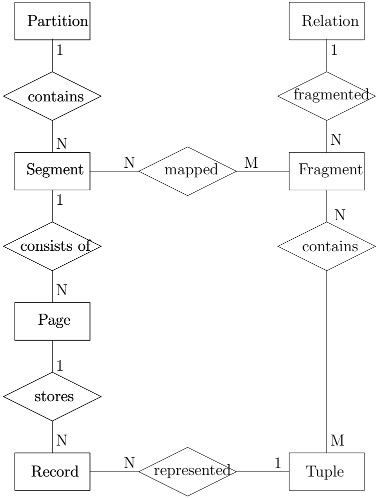
1. partition: sequence of pages (consecutive on disk)
2. extent: subsequence of a partition
3. segment (file): logical sequence of pages (implemented e.g. as set of extents)
4. record: sequence of bytes stored on a page

Note:

- partition/extent/page/record are physical structures
- a segment is a logical structure

Physical Storage of Relations

Mapping of a relation's tuples onto records stored on pages in segments:



Access to Database Items

- database item: something stored in DB
- database item can be set (bag, sequence) of items
- access to a database item then produces stream of smaller database items
- the operation that does so is called *scan*

Scan Example

Using a relation scan `rscan`, the query

select *
from Student

can be answered by `rscan(Student)`
(segments? extents?): Assumption:

- segment scans and each relation stored in one segment
- segment and relation name identical

Then `fscan(Student)` and `Student` denote scans of all tuples in a relation

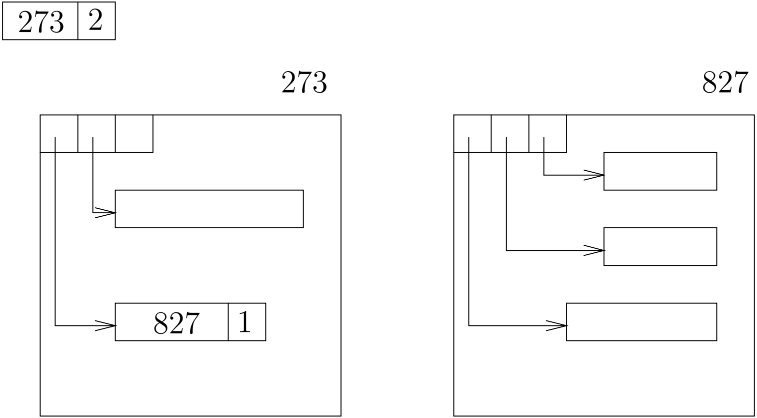
Model of a Segment

- for our cost model, we need a model of segments.
- we assume an extent-based segment implementation.
- every segment then is a sequence of extents.
- every extent can be described by a pair (F_j, L_j) containing its first and last cylinder.
  (For simplicity, we assume that extents span whole cylinders.)
- an extent may cross a zone boundary.
- hence: split extents to align them with zone boundaries.
- segment can be described by a sequence of triples (F_i, L_i, z_i) ordered on F_i where z_i is the zone number in which the extent lies.

Model of a Segment

S_{ext}	number of extents in the segment
$S_{\text{cfirst}}(i)$	first cylinder in extent i (F_i)
$S_{\text{clast}}(i)$	last cylinder in extent i (L_i)
$S_{\text{zone}}(i)$	zone of extent i (z_i)
$S_{\text{cpe}}(i)$	number of cylinders in extent i ($= S_{\text{clast}}(i) - S_{\text{cfirst}}(i) + 1$)
S_{sec}	total number of sectors in the segment ($= \sum_{i=1}^{S_{\text{ext}}} S_{\text{cpe}}(i) D_{\text{zspc}}(S_{\text{zone}}(i))$)

Slotted Page



- page is organized into areas (slots)
- slots point to data chunks
- slots may point to other pages

Tuple Identifier (TID)

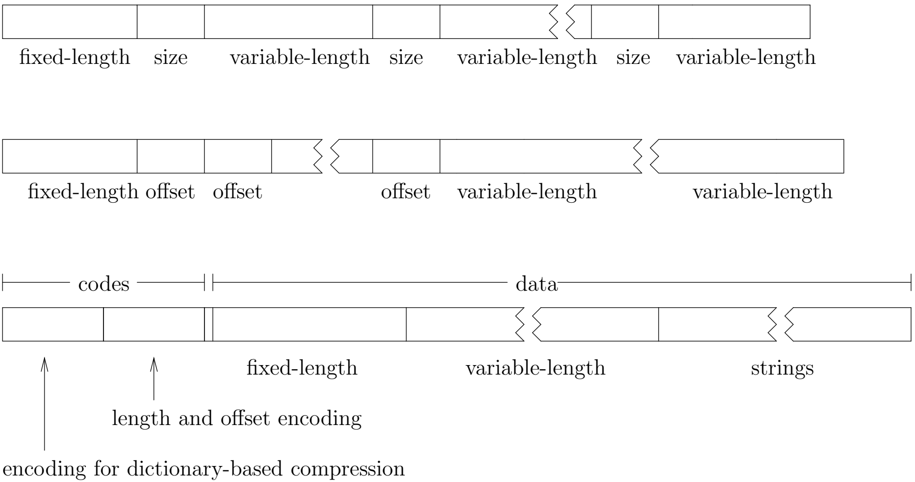
TID is conjunction of

- page identifier (e.g. partition/segment no, page no)
- slot number

TID sometimes called Row Identifier (RID)

Record Layout

Different layouts possible:



Record Layout (2)

Record layout is a compromise:

- space consumption vs. CPU
- data model specific properties: e.g. generalization
- versioning / easy schema migration
- record layout typically not trivial
- accessing an attribute value has non-zero cost

Physical Algebra

- building blocks for query execution
- implements the algorithms for query execution
- very generic, reusable components
- describes the general execution approach
- annotated with predicates etc. for query specific parts

Iterator Concept

The general interface of each operator is:

- open
- next
- close

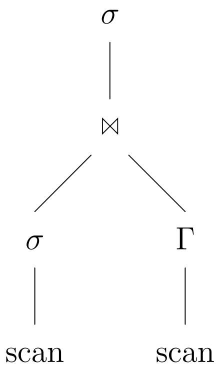
All physical algebraic operators are implemented as iterators.

- produce a stream of data items (tuples)

Implementations vary slightly for performance tuning (concept the same):

- `first`/`next` instead of `next`
- blocks of tuples instead of single tuples

Iterator Example



Note: all details (subscripts, implementations etc.) are omitted here

Pipelining

Pipelining is fundamental for the physical algebra:

- physical operators are iterators over the data
- they produce a stream of single tuples
- tuple stream if passed through other operators
- pipelining operators just pass the data through, they only filter or augment
- data is not copied or materialized
- very efficient processing

pipeline breakers disrupt this pipeline and materialize data:

- very expensive, can cause superfluous work
- sometimes cannot be avoided, though

Simple Scan

- a `rscan` operation is rarely supported.
- instead: scans on segments (files).
- since a (data) segment is sometimes called *file*, the correct plan for the above query is often denoted by `fscan(Student)`.

Several assumptions must hold:

- the `Student` relation is not fragmented, it is stored in a single segment,
- the name of this segment is the same as the relation name, and
- no tuples from other relations are stored in this segment.

Until otherwise stated, we assume that these assumptions hold.
Instead of `fscan(Student)`, we could then simply use `Student` to denote leaf nodes in a query execution plan.

Attributes/Variables and their Binding

select *
from Student

can be expressed as $Student[s]$ instead of $Student$.
Result type: set of tuples with a single attribute s.
s is assumed to bind a pointer

- to the physical record in the buffer holding the current tuple *or*
- a pointer to the slot pointing to the record holding the current tuple

Building Block

- scan
- a leaf of a query execution plan

Leaf can be complex.
But: Plan generator does not try to reorder within building blocks
Nonetheless:

- building block organized around a single database item

If more than a single database item is involved: *access path*

Scan and Attribute Access

Strictly speaking, the plan

$$\sigma_{age>30}(Student[s])$$

is incorrect (age is not bound!)
We have a choice:

- implicit attribute access
- make attribute accesses explicit

Scan and Attribute Access (2)

Explicit attribute access:

$$\sigma_{s.age>30}(Student[s])$$

Advantage: makes attribute access costs explicit

Scan and Attribute Access (3)

Consider:

$$\sigma_{s.age>30 \wedge s.age<40}(Student[s])$$

Problem: accesses age twice

Scan and Attribute Access (4)

Map operator:

$$\chi_{a_1:e_1,\ldots,a_n:e_n}(e) := \{t \circ [a_1 : c_1, \ldots, a_n : c_n] | t \in e, c_i = e_i(t) \; \forall \; (1 \leq i \leq n)\}$$

Loading Attributes

The above problem can now be solved by

$$\sigma_{age>30 \wedge age<40}(\chi_{age:s.age}(Student[s])).$$

In general, it is beneficial to load attributes as late as possible. The latest point at which all attributes must be read from the page is typically just before a pipeline breaker.

Loading Attributes (2)

select name
from Student
where age > 30

The plan

$$\Pi_n(\chi_{n:s.name}(\sigma_{a>30}(\chi_{a:s.age}(Student[s]))))$$

is better than

$$\Pi_n(\sigma a > 30(\chi_{n:s.name,a:s.age}(Student[s])))$$

Loading Attributes (3)

Alternative to this selective successive attribute access:

- scan has list of attributes to be projected (accessed, copied)
- predicate is applied before processing the projection list

Loading Attributes (4)

predicate evaluable on disk representation is called *SARGable* (search argument)

- boolean expression in simple predicates of the form $A\theta c$

If a predicate can be used for an index lookup: index SARGable
Other predicates: residual predicates

Loading Attributes (5)

$R[v; p]$ equivalent to $\sigma_p(R[v])$ but cheaper to evaluate

Remark

- if p is conjunct, order by $(f_i - 1)/c_i$

Example:

$$Student[s; age > 30, name\ like\ `\%m\%']$$

Loading Attributes and Pipeline Breakers

- attribute access not only for scans
- likewise all operators that materialize to disk
- most pipeline breakers
- projection and selection should always be integrated into pipeline breakers
- not that important for pipelining operators
- attribute access must happen before breaking the pipeline

Exception:

- RID join/semijoin techniques

Physical Operator - Selection

- consumes a tuple stream
- checks predicate on each tuple
- produces matching tuples

Characteristics:

- pipelining operator
- consumes no memory, causes no IO

Physical Operator - Nested Loop Join

- consumes two tuple streams
- for each tuple from one stream (trad: the left) consumes the whole other stream
- checks predicate on each pair
- produces matching tuples

Characteristics:

- pipelining operator
- consumes no memory, causes no IO (at least not directly)

Physical Operator - Blockwise Nested Loop Join

- consumes two tuple streams
- reads one stream (left) blockwise into memory, consumes the whole other stream for each block
- checks predicate on each pair of tuples
- produces matching tuples

Characteristics:

- pipeline breaker on the left stream
- consumes memory for the blocks, causes no IO (unusual for a pipeline breaker)

Variants (with hashing etc.) behave basically the same

Physical Operator - Sort Merge Join

We only consider the case that the input is already sorted (see *Sort*) and $1 : n$ or $1 : 1$.

- consumes two tuple streams
- skips uniformly through both streams
- checks predicate on each pair (implicitly)
- produces matching tuples

Characteristics:

- pipelining operator
- consumes no memory, causes no IO

Physical Operator - Grace Hash Join

- consumes two tuple streams
- reads one stream and splits it into partitions on disk
- the same of the other stream
- joins the partitions, produces matching tuples

Characteristics:

- full pipeline breaker
- consumes memory for one partition, writes/reads whole data at least one

IO behavior can be predicted relatively easily

Physical Operator - Hybrid Hash Join

- consumes two tuple streams
- reads one stream and splits it into partitions on disk. Tries to keep some partitions in memory
- reads the other stream, also splits it into partitions on disk, but already joins with partitions still in memory
- joins partitions on disk, produces matching tuples

Characteristics:

- (typically) full pipeline breaker. Might keep the pipeline for the second stream
- consumes memory for partitioning (size variable), might write/reads whole data

Behavior difficult to predict, might cause no IO, might write everything

Physical Operator - Sort

- consumes one input stream
- creates sorted runs, spools runs to disk, merges the runs
- produces sorted output stream

Characteristics:

- pipeline breaker
- consumes memory for one run, reads/write data log n times

Exact behavior depends on implementation, e.g. HeapSort might produce one run, while QuickSort produces fixed number of runs

Physical Operator - Sort Based Group By

We assume that the input is already sorted

- consumes one input stream
- aggregates the input directly
- produces an output tuple whenever the group by attribute changes

Characteristics:

- pipeline breaker (nearly pipelining, though)
- consumes memory for one tuple, causes no IO

Sometimes interleaved with sort (early aggregation)

Physical Operator - Hash Bases Group By

- consumes one input stream
- reads the stream, splits into partitions, writes partitions to disk (if needed)
- aggregates partitions, produces output tuples

Characteristics:

- pipeline breaker
- consumes memory for buffering (variable), might read/write the whole data
- two possibilities, similar to Grace Hash vs. Hybrid Hash

Variants with early aggregation etc.

Physical Operators - Others

Only mainstream operators included, some are missing:

- projection usually implicit
- duplicate elimination is a special kind of aggregation
- dependent join (nested loop, can be done somewhat differently)
- outer join/semi join/anti join etc. roughly similar to normal joins
- specialized operators for query languages: staircase join, twig join etc.
- their characteristics have to be known to the query optimizer

Temporal Relations

The query optimizer might introduce temporal relations:

- a "relations" just for the query
- allows for reusing intermediate results
- related: temporary views
- more efficient nested loop join
- materializes a subquery

Creating a temporary relation is an expensive operation therefore

- should be decided by the query optimizer
- but often done as rewrite
- typically breaks optimization in parts

Temporal Relations (2)

select e.name, d.name
from Emp e, Dept d
where e.age > 30 **and** e.age < 40 **and** e.dno = d.dno

can be evaluated by

$$Dept[d] \bowtie^{nl}_{e.dno=d.dno} \sigma_{e.age>30 \wedge e.age<40}(Emp[d]).$$

Better:

$$Dept[d] \bowtie^{nl}_{e.dno=d.dno} temp(\sigma_{e.age>30 \wedge e.age<40}(Emp[d])).$$

Or:

1. $R_{tmp} = \sigma_{e.age>30 \wedge e.age<40}(Emp[d]);$
2. $Dept[d] \bowtie^{nl}_{e.dno=d.dno} R_{tmp}[e]$

Table Functions

A *table function* is a function that returns a relation.
Example query:

select *
from TABLE(Primes(1,100)) as p

Translation:

$$Primes(1, 100)[p]$$

Looks the same as regular scan, but is of course computed differently.

Table Functions (2)

Special birthdays of Anton:

select *
from Friends f,
TABLE(Primes(
CURRENT_YEAR, EXTRACT(YEAR FROM f.birthday) + 100)) as p
where f.name = 'Anton'

Note: The result of the table function depends on our friend Anton.
Translation: uses d-join

Table Functions (3)

Definition d-join:

$$R \rtimes\!\!\ltimes S = \{r \circ s | r \in R, s \in S(t)\}.$$

Translation of the above query:

$$\chi_{\text{b}:XTRY(f.birthday)+100}(\sigma_{f.name=''Anton''}(Friends[f])) \rtimes\!\!\ltimes Primes(c, b)[p]$$

where we assume that some global entity c holds the value of CURRENT_YEAR.

Table Functions (4)

The same for all friends:

select *
from Friends f,
TABLE(Primes(
CURRENT_YEAR, EXTRACT(YEAR FROM f.birthday) + 100)) as p

Better:

select *
from Friends f,
TABLE(Primes(
CURRENT_YEAR, (**select** max(birthday) **from** Friends) + 100)) as p
where p.prime $\geq$ f.birthday

At the algebraic level: this optimization requires some knowledge