# Week 08 Lectures

## Implementing Join

### Join



DBMSs are engines to *store*, *combine* and *filter* information.

*Join* (⋈) is the primary means of *combining* information.

*Join* is important and potentially expensive

Most common join condition: equijoin, e.g. `(R.pk = S.fk)`

Join varieties (natural, inner, outer, semi, anti) all behave similarly.

We consider three strategies for implementing join

- *nested loop* ... simple, widely applicable, inefficient without buffering
- *sort-merge* ... works best if tables are sorted on join attributes
- *hash-based* ... requires good hash function and sufficient buffering

### Join Example



Consider a university database with the schema:

```
create table Student(
   id     integer primary key,
   name   text,  ...
);
create table Enrolled(
   stude  integer references Student(id),
   subj   text references Subject(code),  ...
);
create table Subject(
   code   text primary key,
   title  text,  ...
);
```

#### ... Join Example



*List names of students in all subjects, arranged by subject.*

SQL query to provide this information:

```
select E.subj, S.name
from   Student S, Enrolled E
where  S.id = E.stude
order  by E.subj, S.name;
```

And its relational algebra equivalent:

*Sort[subj] ( Project[subj,name] ( Join[id=stude](Student,Enrolled) ) )*

To simplify formulae, we denote `Student` by *S* and `Enrolled` by *E*

## ... Join Example

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Some database statistics:

| Sym | Meaning | Value |
|---|---|---|
| $r_S$ | # student records | 20,000 |
| $r_E$ | # enrollment records | 80,000 |
| $c_S$ | `Student` records/page | 20 |
| $c_E$ | `Enrolled` records/page | 40 |
| $b_S$ | # data pages in `Student` | 1,000 |
| $b_E$ | # data pages in `Enrolled` | 2,000 |

Also, in cost analyses below, $N$ = number of memory buffers.

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## ... Join Example

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`Out` = *Student* ⋈ *Enrolled* relation statistics:

| Sym | Meaning | Value |
|---|---|---|
| $r_{Out}$ | # tuples in result | 80,000 |
| $C_{Out}$ | result records/page | 80 |
| $b_{Out}$ | # data pages in result | 1,000 |

Notes:

- $r_{Out}$ ... one result tuple for each `Enrolled` tuple
- $C_{Out}$ ... result tuples have only `subj` and `name`
- in analyses, ignore cost of writing result ... same in all methods

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# Nested Loop Join

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Basic strategy (R.a ⋈ S.b):

```
Result = {}
for each page i in R {
   pageR = getPage(R,i)
   for each page j in S {
      pageS = getPage(S,j)
      for each pair of tuples tR,tS
                       from pageR,pageS {
         if (tR.a == tS.b)
            Result = Result ∪ (tR:tS)
}  }  }
```

Needs input buffers for R and S, output buffer for "joined" tuples

Terminology: R is outer relation, S is inner relation

Cost = $b_R . b_S$ ... ouch!

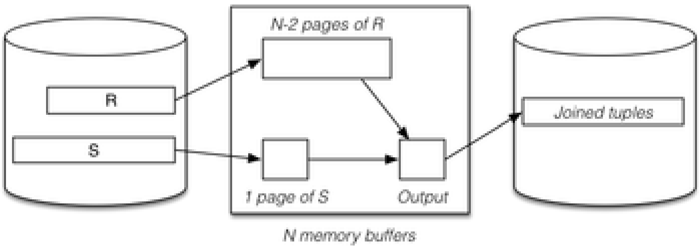
---

## Block Nested Loop Join



Method (for *N* memory buffers):

- read *N–2*–page chunk of *R* into memory buffers
- for each *S* page
  check join condition on all $(t_R, t_S)$ pairs in buffers
- repeat for all *N–2*–page chunks of *R*

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### ... Block Nested Loop Join



Best–case scenario: $b_R \leqslant N–2$

- read $b_R$ pages of relation *R* into buffers
- while whole *R* is buffered, read $b_S$ pages of *S*

Cost = $b_R + b_S$

Typical–case scenario: $b_R > N–2$

- read $ceil(b_R/(N–2))$ chunks of pages from *R*
- for each chunk, read $b_S$ pages of *S*

Cost = $b_R + b_S \, . \, ceil(b_R/N–2)$

Note: always requires $r_R.r_S$ checks of the join condition

---

## Exercise 1: Nested Loop Join Cost



Compute the cost (# pages fetched) of $(S \bowtie E)$

| Sym | Meaning | Value |
|---|---|---|
| $r_S$ | # student records | 20,000 |
| $r_E$ | # enrollment records | 80,000 |
| $c_S$ | `Student` records/page | 20 |
| $c_E$ | `Enrolled` records/page | 40 |
| $b_S$ | # data pages in `Student` | 1,000 |
| $b_E$ | # data pages in `Enrolled` | 2,000 |

for *N = 22, 202, 2002* and different inner/outer combinations

---

If the query in the above example was:

```
select j.code, j.title, s.name
from   Student s
       join Enrolled e on (s.id=e.student)
       join Subject j on (e.subj=j.code)
```

how would this change the previous analysis?

What join combinations are there?

Assume 2000 subjects, with $c_J = 10$

How large would the intermediate tuples be? What assumptions?

Compute the cost (# pages fetched, # pages written) for $N = 202$

---

### ... Block Nested Loop Join



Why block nested loop join is actually useful in practice ...

Many queries have the form

```
select * from R,S where r.i=s.j and r.x=K
```

This would typically be evaluated as

```
Tmp = Sel[x=K](R)
Res = Join[i=j](Tmp, S)
```

If `Tmp` is small ⇒ may fit in memory (in small #buffers)

---

## Index Nested Loop Join



A problem with nested-loop join:

- needs repeated scans of *entire* inner relation *S*

If there is an index on *S*, we can avoid such repeated scanning.

Consider *Join[i=j](R,S)*:

```
for each tuple r in relation R {
    use index to select tuples
        from S where s.j = r.i
    for each selected tuple s from S {
        add (r,s) to result
}   }
```

---

### ... Index Nested Loop Join



This method requires:

- one scan of *R* relation ($b_R$)
  - only one buffer needed, since we use *R* tuple-at-a-time
- for each *tuple* in *R* ($r_R$), one index lookup on *S*
  - cost depends on type of index and number of results
  - best case is when each *R.i* matches few *S* tuples

Cost = $b_R + r_R.Sel_S$  ($Sel_S$ is the cost of performing a select on *S*).

Typical $Sel_S$ = 1–2 (hashing) .. $b_q$ (unclustered index)

Trade-off: $r_R.Sel_S$ vs $b_R.b_S$, where $b_R \ll r_R$ and $Sel_S \ll b_S$

## Exercise 2: Index Nested Loop Join Cost



Consider executing *Join[i=j](S,T)* with the following parameters:

- $r_S = 1000$, $b_S = 50$, $r_T = 3000$, $b_T = 600$
- *S.i* is primary key, and *T* has index on *T.j*
- *T* is sorted on *T.j*, each *S* tuple joins with 2 *T* tuples
- DBMS has *N = 12* buffers available for the join

Calculate the costs for evaluating the above join

- using block nested loop join
- using index nested loop join

$Cost_r$ = # pages read and $Cost_j$ = # join-condition checks

## Sort-Merge Join



Basic approach:

- sort both relations on join attribute (reminder: *Join [i=j] (R,S)*)
- scan together using *merge* to form result `(r,s)` tuples

Advantages:

- no need to deal with "entire" *S* relation for each *r* tuple
- deal with runs of matching *R* and *S* tuples

Disadvantages:

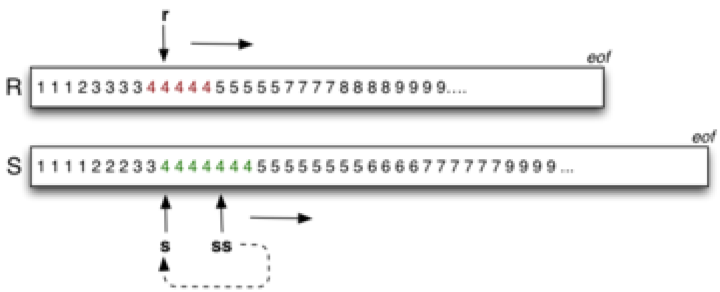
- cost of sorting both relations (already sorted on join key?)
- some rescanning required when long runs of *S* tuples

### ... Sort-Merge Join



Method requires several cursors to scan sorted relations:

- `r` = current record in *R* relation
- `s` = start of current run in *S* relation
- `ss` = current record in current run in *S* relation




### ... Sort-Merge Join



Algorithm using query iterators/scanners:

```
Query ri, si;  Tuple r,s;

ri = startScan("SortedR");
si = startScan("SortedS");
while ((r = nextTuple(ri)) != NULL
       && (s = nextTuple(si)) != NULL) {
    // align cursors to start of next common run
    while (r != NULL && r.i < s.j)
           r = nextTuple(ri);
    if (r == NULL) break;
    while (s != NULL && r.i > s.j)
           s = nextTuple(si);
    if (s == NULL) break;
    // must have (r.i == s.j) here
...
```

---

### ... Sort-Merge Join



```
...
    // remember start of current run in S
    TupleID startRun = scanCurrent(si)
    // scan common run, generating result tuples
    while (r != NULL && r.i == s.j) {
        while (s != NULL and s.j == r.i) {
            addTuple(outbuf, combine(r,s));
            if (isFull(outbuf)) {
                writePage(outf, outp++, outbuf);
                clearBuf(outbuf);
            }
            s = nextTuple(si);
        }
        r = nextTuple(ri);
        setScan(si, startRun);
    }
}
```

---

### ... Sort-Merge Join



Buffer requirements:

- for sort phase:
  - as many as possible (remembering that cost is $O(log_N)$ )
  - if insufficient buffers, sorting cost can dominate
- for merge phase:
  - one output buffer for result
  - one input buffer for relation *R*
  - (preferably) enough buffers for longest run in *S*

---

### ... Sort-Merge Join



Cost of sort-merge join.

Step 1: sort each relation (if not already sorted):

- Cost = $2.b_R\ (1 + log_{N-1}(b_R\ /N))\ +\ 2.b_S\ (1 + log_{N-1}(b_S\ /N))$
  (where $N$ = number of memory buffers)

Step 2: merge sorted relations:

- if every run of values in *S* fits completely in buffers,
  merge requires single scan, Cost = $b_R + b_S$

- if some runs in of values in *S* are larger than buffers,
  need to re-scan run for each corresponding value from *R*

---

## Sort-Merge Join on Example



Case 1: *Join[id=stude](Student,Enrolled)*

- relations are not sorted on *id#*
- memory buffers *N=32*; all runs are of length < *30*

$$
\begin{aligned}
\text{Cost} &= sort(S) + sort(E) + b_S + b_E \\
&= 2b_S(1+\log_{31}(b_S/32)) + 2b_E(1+\log_{31}(b_E/32)) + b_S + b_E \\
&= 2\times1000\times(1+2) + 2\times2000\times(1+2) + 1000 + 2000 \\
&= 6000 + 12000 + 1000 + 2000 \\
&= 21{,}000
\end{aligned}
$$

---

### ... Sort-Merge Join on Example



Case 2: *Join[id=stude](Student,Enrolled)*

- *Student* and *Enrolled* already sorted on *id#*
- memory buffers *N=4* (*S* input, 2 × *E* input, output)
- 5% of the "runs" in *E* span two pages
- there are no "runs" in *S*, since *id#* is a primary key

For the above, no re-scans of *E* runs are ever needed

*Cost* = *2,000 + 1,000* = *3,000* (regardless of which relation is outer)

---

## Exercise 3: Sort-merge Join Cost



Consider executing *Join[i=j](S,T)* with the following parameters:

- $r_S = 1000$, $b_S = 50$, $r_T = 3000$, $b_T = 150$
- *S.i* is primary key, and *T* has index on *T.j*
- *T* is sorted on *T.j*, each *S* tuple joins with 2 *T* tuples
- DBMS has *N = 42* buffers available for the join

Calculate the cost for evaluating the above join

- using sort-merge join
- compute #pages read/written
- compute #join-condition checks performed

---

## Hash Join



Basic idea:

- use hashing as a technique to partition relations
- to avoid having to consider all pairs of tuples

Requires sufficent memory buffers

- to hold substantial portions of partitions
- (preferably) to hold largest partition of outer relation

Other issues:

- works only for equijoin `R.i=S.j` (but this is a common case)
- susceptible to data skew (or poor hash function)

Variations: *simple*, *grace*, *hybrid*.

---

## Simple Hash Join



Basic approach:

- hash part of outer relation *R* into memory buffers (build)
- scan inner relation *S*, using hash to search (probe)
  - if R.i=S.j, then h(R.i)=h(S.j) (hash to same buffer)
  - only need to check one memory buffer for each *S* tuple
- repeat until whole of *R* has been processed

No overflows allowed in in-memory hash table

- works best with uniform hash function
- can be adversely affected by data/hash skew

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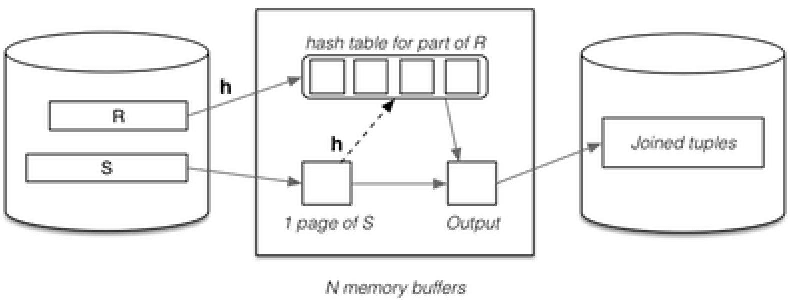
### ... Simple Hash Join



Data flow:

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### ... Simple Hash Join



Algorithm for simple hash join *Join[R.i=S.j](R,S)*:

```
for each tuple r in relation R {
   if (buffer[h(R.i)] is full) {
      for each tuple s in relation S {
         for each tuple rr in buffer[h(S.j)] {
            if ((rr,s) satisfies join condition) {
               add (rr,s) to result
      }  }  }
      clear all hash table buffers
   }
   insert r into buffer[h(R.i)]
}
```

Best case: # join tests ≤ $r_S.c_R$ (cf. nested-loop $r_S.r_R$)

### ... Simple Hash Join

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Cost for simple hash join ...

Best case: all tuples of R fit in the hash table

- Cost = $b_R + b_R$
- Same page reads as block nested loop, but less join tests

Good case: refill hash table *m* times (where $m \geq ceil(b_R / (N-2))$ )

- Cost = $b_R + m.b_R$
- More page reads that block nested loop, but less join tests

Worst case: everything hashes to same page

- Cost = $b_R + b_R.b_S$

## Exercise 4: Simple Hash Join Cost

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Consider executing *Join[i=j](R,S)* with the following parameters:

- $r_R = 1000$, $b_R = 50$, $r_S = 3000$, $b_S = 150$, $c_{Res} = 30$
- *R.i* is primary key, each *R* tuple joins with 2 *S* tuples
- DBMS has $N = 42$ buffers available for the join
- data + hash have uniform distribution

Calculate the cost for evaluating the above join

- using simple hash join
- compute #pages read/written
- compute #join-condition checks performed
- assume that hash table has $L=0.75$ for each partition

## Grace Hash Join

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Basic approach (for $R \bowtie S$ ):

- partition both relations on join attribute using hashing (*h1*)
- load each partition of *R* into N-buffer hash table (*h2*)
- scan through corresponding partition of *S* to form results
- repeat until all partitions exhausted

For best-case cost ($O(b_R + b_S)$ ):

- need $\geq \sqrt{b_R}$ buffers to hold largest partition of outer relation

If $< \sqrt{b_R}$ buffers or poor hash distribution

- need to scan some partitions of *S* multiple times

### ... Grace Hash Join

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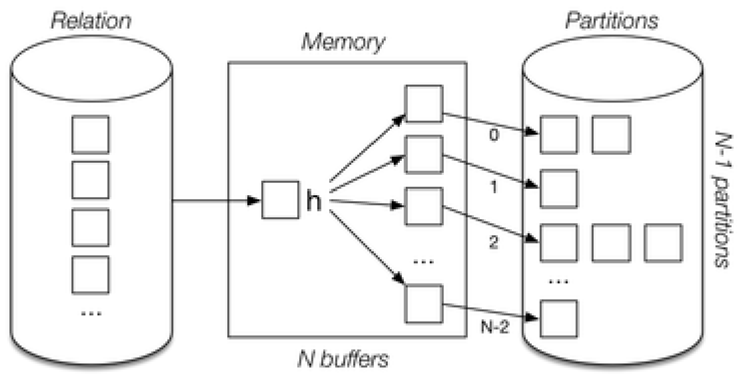
Partition phase (applied to both *R* and *S*):

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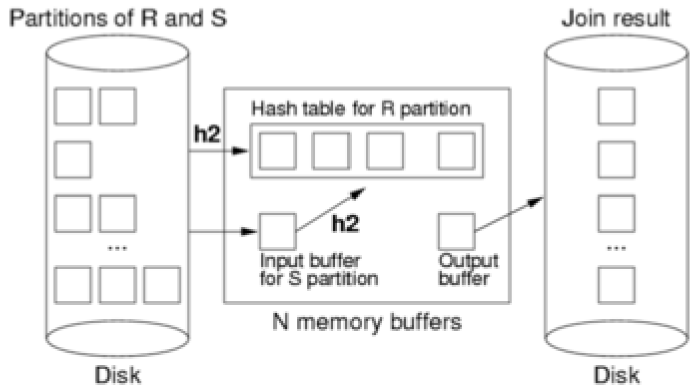
## ... Grace Hash Join



Probe/join phase:




The second hash function (`h2`) simply speeds up the matching process.
Without it, would need to scan entire *R* partition for each record in *S* partition.

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## ... Grace Hash Join



Cost of grace hash join:

- #pages in all partition files of $Rel \cong b_{Rel}$ (maybe slightly more)
- partition relation *R* ... Cost $= b_R.T_r + b_R.T_w = 2b_R$
- partition relation *S* ... Cost $= b_S.T_r + b_S.T_w = 2b_S$
- probe/join requires one scan of each (partitioned) relation
  Cost $= b_R + b_S$
- all hashing and comparison occurs in memory $\Rightarrow$ $\cong 0$ cost

Total Cost $= 2b_R + 2b_S + b_R + b_S = 3 (b_R + b_S)$

---

## Exercise 5: Grace Hash Join Cost



Consider executing *Join[i=j](R,S)* with the following parameters:

- $r_R = 1000$, $b_R = 50$, $r_S = 3000$, $b_S = 150$, $c_{Res} = 30$
- *R.i* is primary key, each *R* tuple joins with 2 *S* tuples
- DBMS has $N = 43$ buffers available for the join
- data + hash have reasonably uniform distribution

Calculate the cost for evaluating the above join

- using Grace hash join
- compute #pages read/written

- compute #join-condition checks performed
- assume that no $R$ partition is larger than 40 pages

---

## Exercise 6: Grace Hash Join Cost



Consider executing *Join[i=j](R,S)* with the following parameters:

- $r_R = 1000$, $b_R = 50$, $r_S = 3000$, $b_S = 150$, $c_{Res} = 30$
- *R.i* is primary key, each $R$ tuple joins with 2 $S$ tuples
- DBMS has $N = 42$ buffers available for the join
- data + hash have reasonably uniform distribution

Calculate the cost for evaluating the above join

- using Grace hash join
- compute #pages read/written
- compute #join-condition checks performed
- assume that one $R$ partition has 50 pages, others < 40 pages
- assume that the corresponding $S$ partition has 30 pages

---

## Hybrid Hash Join



A variant of grace join if we have $\sqrt{b_R} < N < b_R+2$

- create $k \ll N$ partitions, $m$ in memory, $k-m$ on disk
- buffers: 1 input, $k-m$ output, $p = N-(k-m)-1$ for in-memory partitions

When we come to scan and partition $S$ relation

- any tuple with hash in range $0..m-1$ can be resolved
- other tuples are written to one of $k$ partition files for $S$

Final phase is same as grace join, but with only $k$ partitions.

Comparison:

- grace hash join creates $N-1$ partitions on disk
- hybrid hash join creates $m$ (memory) + $k$ (disk) partitions

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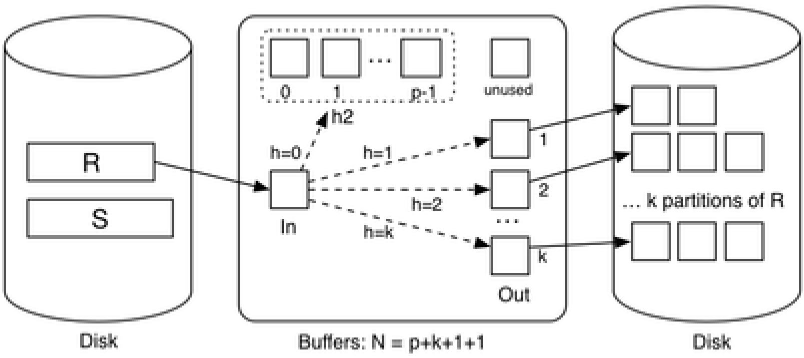
### ... Hybrid Hash Join



First phase of hybrid hash join with $m=1$ (partitioning $R$):

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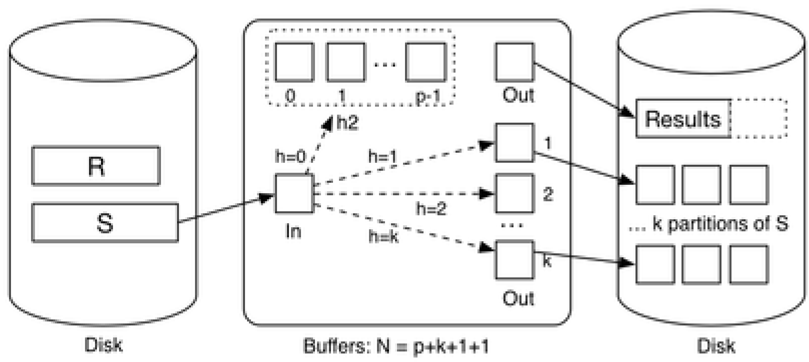
### ... Hybrid Hash Join

Next phase of hybrid hash join with *m=1* (partitioning *S*):

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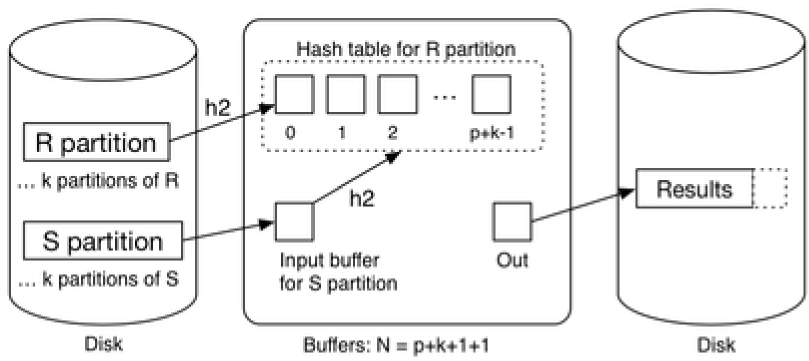
## ... Hybrid Hash Join



Final phase of hybrid hash join with *m=1* (finishing join):

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## ... Hybrid Hash Join



Some observations:

- with *k* partitions, each partition has expected size $b_R/k$
- holding *m* partitions in memory needs $\lceil mb_R/k \rceil$ buffers
- trade-off between in-memory partition space and #partitions

Best-cost scenario:

- $m = 1, \quad k \cong \lceil b_R/N \rceil$ (satisfying above constraint)

Other notes:

- if $N = b_R+2$, using block nested loop join is simpler
- cost depends on *N* (but less than grace hash join)

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# Exercise 7: Hybrid Hash Join Cost



Consider executing *Join[i=j](R,S)* with the following parameters:

- $r_R = 1000, \quad b_R = 50, \quad r_S = 3000, \quad b_S = 150, \quad c_{Res} = 30$
- *R.i* is primary key, each *R* tuple joins with 2 *S* tuples
- DBMS has $N = 42$ buffers available for the join
- data + hash have reasonably uniform distribution

Calculate the cost for evaluating the above join

- using hybrid hash join with *m=1, p=40*
- compute #pages read/written
- compute #join-condition checks performed
- assume that no *R* partition is larger than 40 pages

---

## Join Summary



No single join algorithm is superior in some overall sense.

Which algorithm is best for a given query depends on:

- sizes of relations being joined,   size of buffer pool
- any indexing on relations,   whether relations are sorted
- which attributes and operations are used in the query
- number of tuples in *S* matching each tuple in *R*
- distribution of data values (uniform, skew, ...)

Choosing the "best" join algorithm is critical because the cost difference between best and worst case can be very large.

E.g.   *Join[id=stude](Student,Enrolled)*:   3,000 ... 2,000,000

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## Join in PostgreSQL



Join implementations are under: **`src/backend/executor`**

PostgreSQL suports three kinds of join:

- nested loop join (**`nodeNestloop.c`**)
- sort-merge join   (**`nodeMergejoin.c`**)
- hash join   (**`nodeHashjoin.c`**)   (hybrid hash join)

Query optimiser chooses appropriate join, by considering

- physical characteristics of tables being joined
- estimated selectivity (likely number of result tuples)

---

## Exercise 8: Outer Join?



Above discussion was all in terms of theta inner-join.

How would the algorithms above adapt to outer join?

Consider the following ...

```
select *
from   R left outer join S on (R.i = S.j)

select *
from   R right outer join S on (R.i = S.j)

select *
from   R full outer join S on (R.i = S.j)
```

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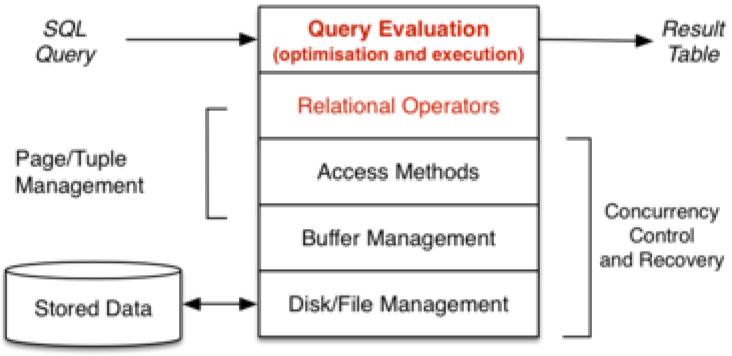
# Query Evaluation

## Query Evaluation






### ... Query Evaluation



A *query* in SQL:

- states *what* kind of answers are required (declarative)
- does not say *how* they should be computed (procedural)

A *query evaluator/processor* :

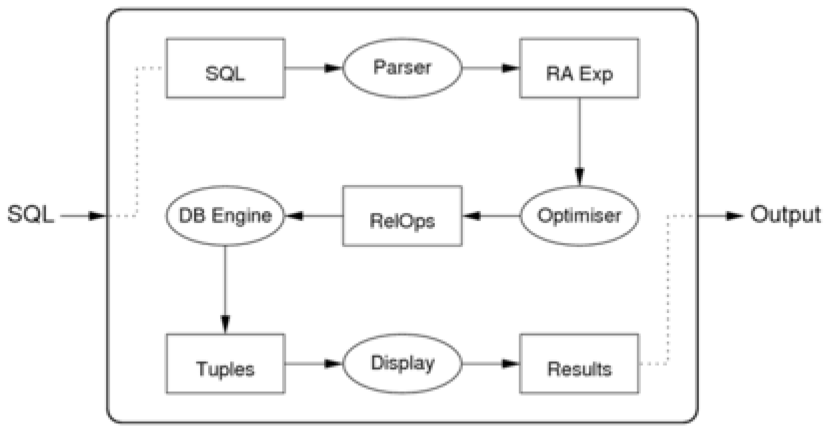
- takes declarative description of query (in SQL)
- parses query to internal representation (relational algebra)
- determines plan for answering query (expressed as DBMS ops)
- executes method via DBMS engine (to produce result tuples)

Some DBMSs can save query plans for later re-use.

### ... Query Evaluation



Internals of the query evaluation "black-box":




### ... Query Evaluation



DBMSs provide several "flavours" of each RA operation.

For example:

- several "versions" of selection ($\sigma$) are available
- each version is effective for a particular kind of selection, e.g

```
select * from R where id = 100  -- hashing
select * from S                 -- Btree index
where age > 18 and age < 35
select * from T                 -- MALH file
where a = 1 and b = 'a' and c = 1.4
```

Similarly, $\pi$ and $\bowtie$ have versions to match specific query types.

---

### ... Query Evaluation



We call these specialised version of RA operations *RelOps*.

One major task of the query processor:

- given a RA expression to be evaluated
- find a combination of RelOps to do this efficiently

Requires the query translator/optimiser to consider

- information about relations (e.g. sizes, primary keys, ...)
- information about operations (e.g. selection reduces size)

RelOps are realised at execution time

- as a collection of inter-communicating *nodes*
- communicating either via pipelines or temporary relations

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## Terminology Variations



Relational algebra expression of SQL query

- intermediate query representation
- logical query plan

Execution plan as collection of RelOps

- query evaluation plan
- query execution plan
- physical query plan

Representation of RA operators and expressions

- $\sigma$ = *Select* = *Sel*,     $\pi$ = *Project* = *Proj*
- *R* $\bowtie$ *S* = *R Join S* = *Join(R,S)*,     $\land$ = *&*,     $\lor$ = *|*

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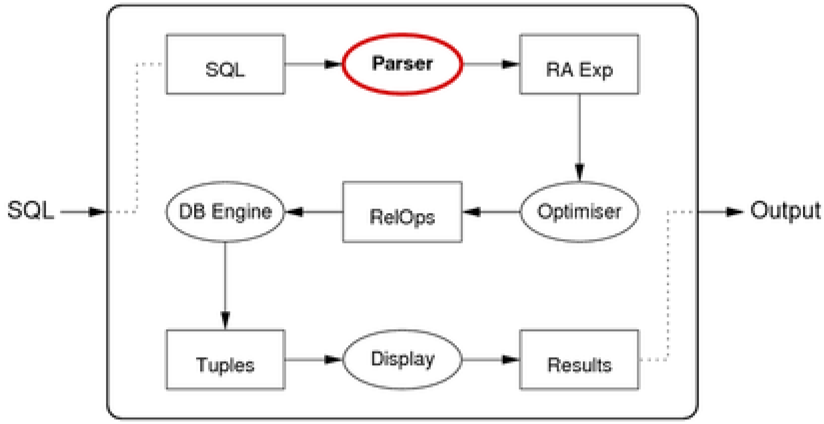
## Query Translation



Query translation:   SQL statement text → RA expression




## Query Translation



Translation step: SQL text → RA expression

Example:

```
SQL: select name from Students where id=7654321;
-- is translated to
RA:  Proj[name](Sel[id=7654321]Students)
```

Processes: lexer/parser, mapping rules, rewriting rules.

Mapping from SQL to RA may include some optimisations, e.g.

```
select * from Students where id = 54321 and age > 50;
-- is translated to
Sel[age>50](Sel[id=54321]Students)
-- rather than ... because of index on id
Sel[id=54321&age>50](Students)
```

## Parsing SQL



Parsing task is similar to that for programming languages.

Language elements:

- keywords: `create`, `select`, `from`, `where`, ...
- identifiers: `Students`, `name`, `id`, `CourseCode`, ...
- operators: `+`, `-`, `=`, `<`, `>`, `AND`, `OR`, `NOT`, `IN`, ...
- constants: `'abc'`, `123`, `3.1`, `'01-jan-1970'`, ...

PostgreSQL parser ...

- implemented via lex/yacc (**`src/backend/parser`**)
- maps all identifiers to lower-case (A-Z → a-z)
- needs to handle user-extendable operator set
- makes extensive use of catalog (**`src/backend/catalog`**)