Query processing and optimization

Definitions

- Query processing
  - translation of query into low-level activities
  - evaluation of query
  - data extraction
- Query optimization
  - selecting the most efficient query evaluation

Query Processing (1/2)

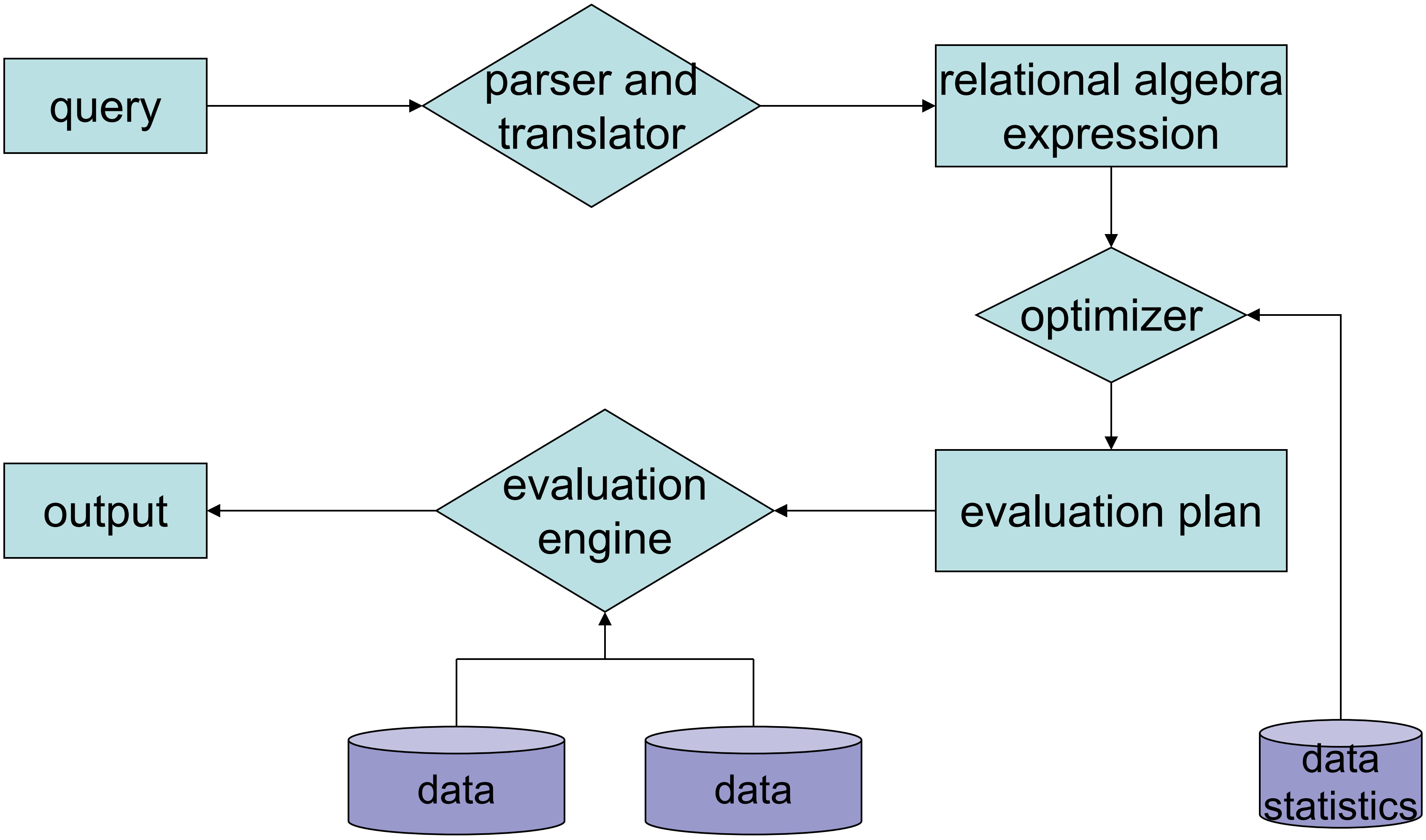
- SELECT * FROM student WHERE name=Paul
- Parse query and translate
  - check syntax, verify names, etc
  - translate into relational algebra (RDBMS)
  - create **evaluation plans**
- Find best plan (optimization)
- Execute plan

student	
cid	name
00112233	Paul
00112238	Rob
00112235	Matt

takes	
cid	courseid
00112233	312
00112233	395
00112235	312

course	
courseid	coursename
312	Advanced DBs
395	Machine Learning

Query Processing (2/2)



Relational Algebra (1/2)

- Query language
- Operations:
  - select: σ
  - project: π
  - union: $\cup$
  - difference: -
  - product: x
  - join: $\bowtie$
- Extended relational algebra operations:

Relational Algebra (2/2)

- SELECT * FROM student WHERE name=Paul
  - $\sigma_{name=Paul}(\text{student})$
- $\pi_{name}(\ \sigma_{cid<00112235}(\text{student})\ )$
- $\pi_{name}(\sigma_{coursename=Advanced\ DBs}((\text{student} \bowtie_{cid} \text{takes}) \bowtie_{courseid} \text{course})\ )$

student	
cid	name
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course	
courseid	coursename
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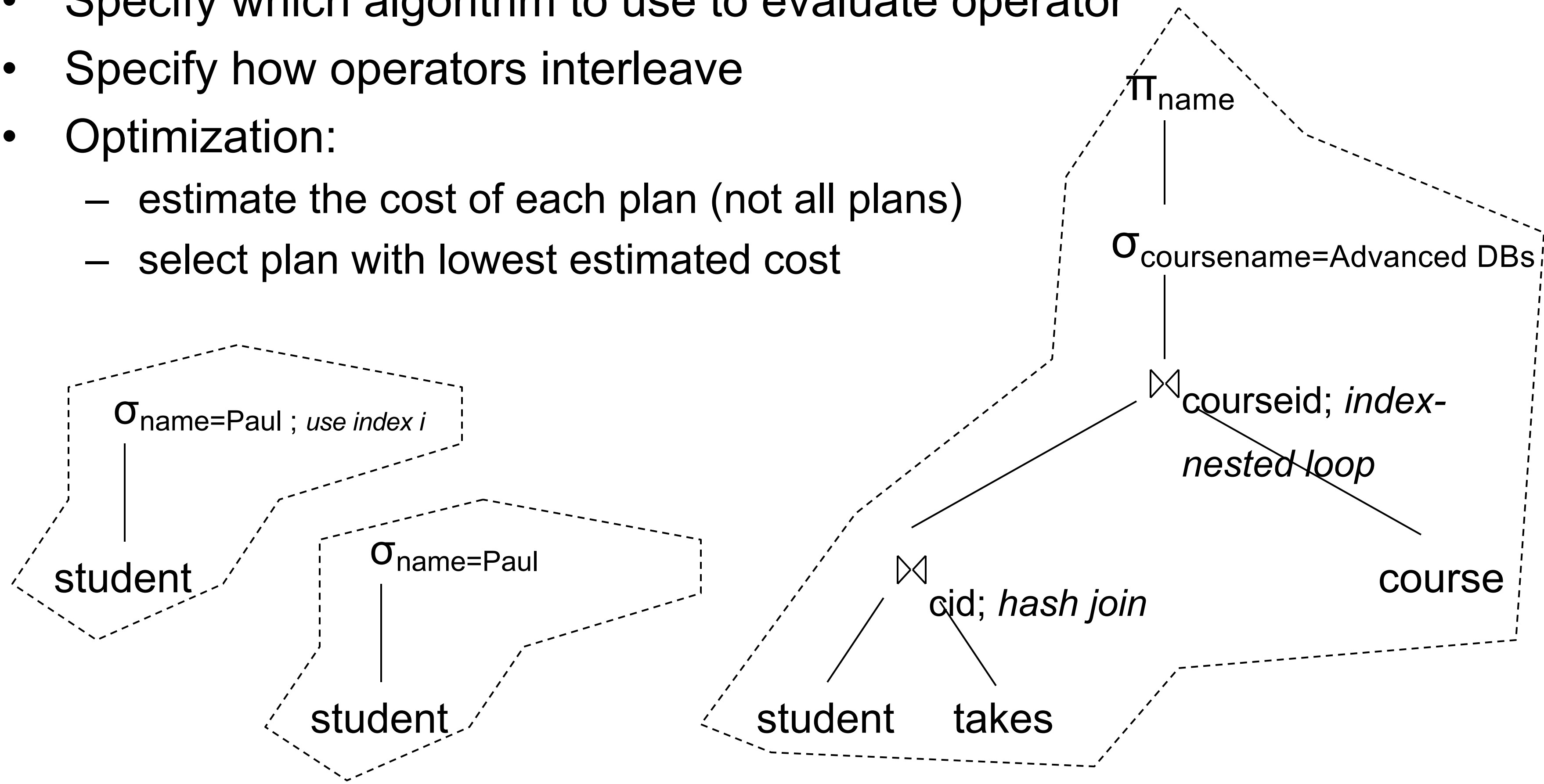
Why Optimize?

- Many alternative options to evaluate a query
  - $\pi_{name}(\sigma_{coursename=Advanced\ DBs}((student \bowtie_{cid} takes) \bowtie_{courseid} course))$
  - $\pi_{name}((student \bowtie_{cid} takes) \bowtie_{courseid} \sigma_{coursename=Advanced\ DBs}(course))$
- Several options to evaluate a single operation
  - $\sigma_{name=Paul}(student)$
    - scan file
    - use secondary index on student.name
- Multiple access paths
  - access path: how can records be accessed
    (using index; which index?; etc.)

Evaluation plans

- Specify which access path to follow
- Specify which algorithm to use to evaluate operator
- Specify how operators interleave
- Optimization:
  - estimate the cost of each plan (not all plans)
  - select plan with lowest estimated cost



Estimating Cost

- What needs to be considered:
  - Disk I/Os
    - sequential (reading neighbouring pages is faster)
    - random
  - CPU time
  - Network communication
- What are we going to consider:
  - Disk I/Os
    - page (data block) reads/writes
  - Ignoring cost of writing final output

Operations and Costs (1/2)

- Operations: σ, π, $\cup$, $\cap$, -, x, $\bowtie$
- Costs:
  - N_R: number of records in R (other notation: T_R or T(R) -> tuple)
  - L_R: size of record in R (length of record)
  - bf_R: blocking factor (other notation: F_R)
    - number of records in a page (datablock)
  - B_R: number of pages to store relation R
  - V(R, A): number of distinct values of attribute A in R
    other notation: I_A(R) (Image size)
  - SC(R,A): selection cardinality of A in R (number of matching rec.)
    - A key: SC(R, A)=1
    - A nonkey: SC(R, A)= T_R / V(R,A) (uniform distribution assumption)
  - HT_i: number of levels in index I (-> height of tree)
  - rounding up fractions and logarithms

Operations and Costs (2/2)

- relation *takes*
  - 7000 tuples
  - student cid 8 bytes
  - course id 4 bytes
  - 40 courses
  - 1000 students
  - page size 512 bytes
  - output size (in pages) of query:

    which students take the Advanced DBs course?
    - $T_{takes} = 7000$
    - V(courseid, takes) = 40
    - SC(courseid, takes)=ceil(T_{takes}/V(courseid, takes))=ceil(7000/40)=175
    - bf_{takes} = floor(512/12) = 42 B_{takes} = 7000/42 = 167 pages
    - bf_{output} = floor(512/8) = 64 B_{output} = 175/64 = 3 pages

Cost of Selection σ (1/2)

- Linear search
  - read all pages, find records that match (assuming equality search)
  - average cost:
    - nonkey (multiple occurences): B_R, key: $0.5*B_R$
- Binary search
  - on ordered field
  - average cost: $\left\lfloor \log_2 B_R \right\rfloor + m$
    - m additional pages to be read (first found then read the duplicates)
    - m = ceil($SC(A,R)/bf_R$) - 1
- Primary/Clustered Index (B+ tree)
  - average cost:
    - single record: $HT_i + 1$
    - multiple records: HT_i + ceil($SC(R,A)/bf_R$)

Cost of Selection σ (2/2)

- Secondary Index (B+ tree)
  - average cost:
    - key field: $HT_i + 1$
    - nonkey field
      - worst case $HT_i + SC(A,R)$
      - linear search more desirable if many matching records !!!

Complex selection σ_{expr}

- conjunctive selections: $\sigma_{\theta_1 \wedge \theta_2 .. \wedge \theta_n}$
  - perform simple selection using θ_i with the lowest evaluation cost
    - e.g. using an index corresponding to θ_i
    - apply remaining conditions θ on the resulting records
    - $\sigma_{cid > 00112233 \wedge courseid = 312}(takes)$
    - cost: the cost of the simple selection on selected θ
  - multiple indices
    - select indices that correspond to θ_is
    - scan indices and return RIDs (ROWID in Oracle)
    - answer: intersection of RIDs
    - cost: the sum of costs + record retrieval
- disjunctive selections: $\sigma_{\theta_1 \vee \theta_2 .. \vee \theta_n}$
  - multiple indices
    - union of RIDs
  - linear search

Projection and set operations

- SELECT DISTINCT cid FROM takes
  - π requires duplicate elimination
  - sorting
- set operations require duplicate elimination
  - $R \cap S$
  - $R \cup S$
  - sorting

Sorting

- efficient evaluation for many operations
- required by query:
  - SELECT cid, name FROM student ORDER BY name
- implementations
  - internal sorting (if records fit in memory)
  - external sorting

    (that’s why we need temporary space on disk)

External Sort-Merge Algorithm (1/3)

- Sort stage: create sorted *runs*

```
i=0;
repeat
    read M pages of relation R into memory (M: size of Memory)
    sort the M pages
    write them into file R_i
    increment i
until no more pages
N = i            // number of runs
```

External Sort-Merge Algorithm (2/3)

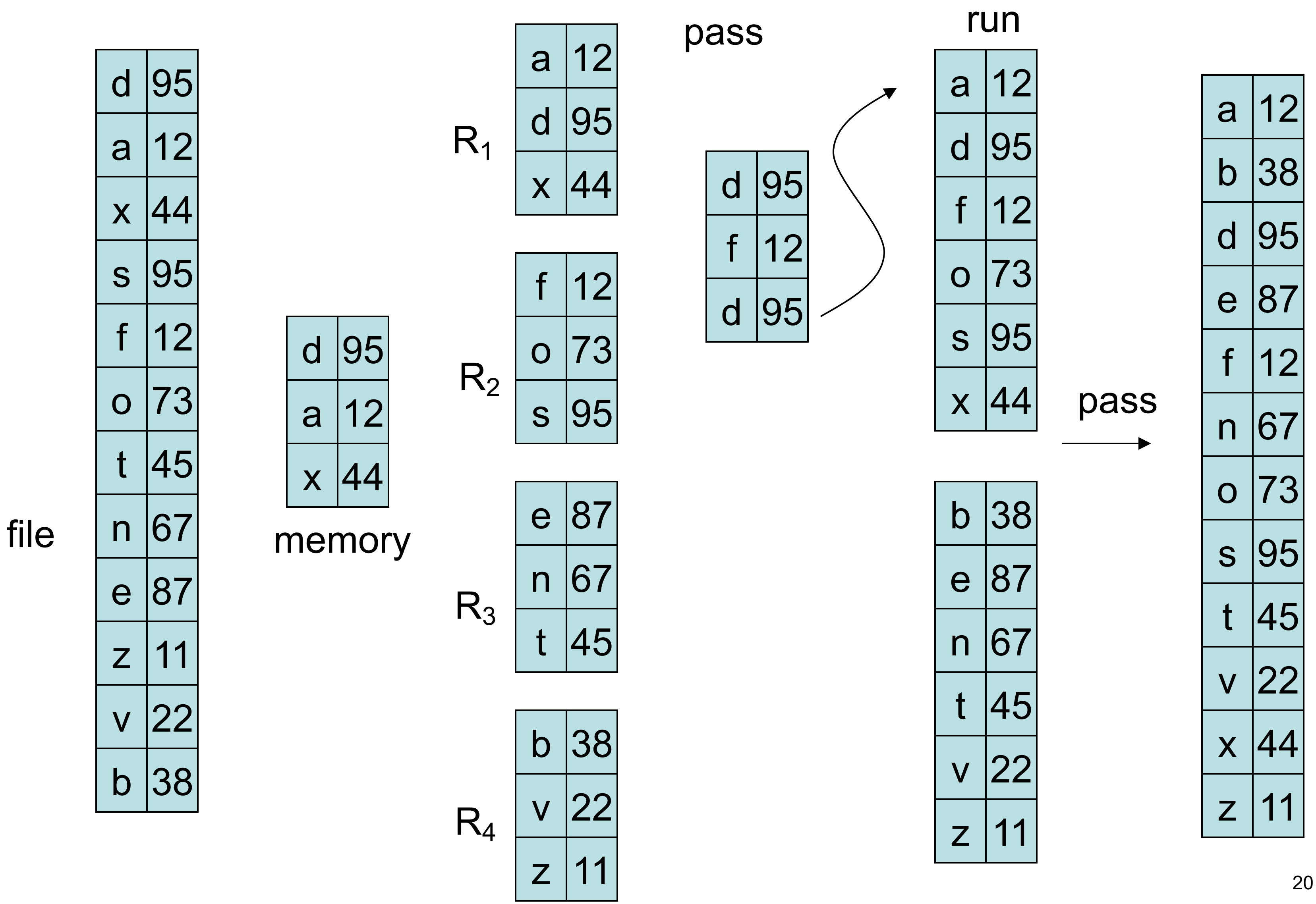
- Merge stage: merge sorted *runs*

//assuming N < M (N <= M-1 we need 1 output buffer)
allocate a page for each run file R_i // N pages allocated
read a page P_i of each R_i
repeat
    choose first record (in sort order) among N pages, say from page P_j
    write record to output and delete from page P_j
    if page is empty read next page P_j' from R_j
until all pages are empty

External Sort-Merge Algorithm (3/3)

- Merge stage: merge sorted *runs*
- What if N >= M ?
  - perform multiple *passes*
  - each *pass* merges M-1 runs until relation is processed
  - in next pass number of runs is reduced
  - final *pass* generated sorted output

Sort-Merge Example



Sort-Merge cost

- B_R the number of pages of R
- Sort stage: $2 * B_R$
  - read/write relation
- Merge stage:
  - initially $\left\lceil \frac{B_R}{M} \right\rceil$ runs to be merged
  - each *pass* M-1 runs sorted
  - thus, total number of passes: $\left\lceil \log_{M-1}\left(\frac{B_R}{M}\right) \right\rceil$
  - at each pass $2 * B_R$ pages are read/written
    - read/write relation ($B_R + B_R$)
    - apart from final write (B_R)
- Total cost:
  - $2 * B_R + 2 * B_R * \left\lceil \log_{M-1}\left(\frac{B_R}{M}\right) \right\rceil - B_R$ eg. B_R = 1000000, M=100

Projection

- $\pi_{A1,A2\ldots}$ (R)
- remove unwanted attributes
  - scan and drop attributes
- remove duplicate records
  - sort resulting records using all attributes as sort order
  - scan sorted result, eliminate duplicates (adjacent)
- cost
  - initial scan + sorting + final scan

Join

- $\pi_{name}(\sigma_{coursename=Advanced\ DBs}((student \bowtie_{cid} takes) \bowtie_{courseid} course))$
- implementations
  - nested loop join
  - block-nested loop join
  - indexed nested loop join
  - sort-merge join
  - hash join

Nested loop join (1/2)

- $R \bowtie S$

  for each tuple t_R of R
      for each t_S of S
          if (t_R t_S match) output $t_R.t_S$
      end
  end

- Works for any join condition
- S inner relation
- R outer relation

Nested loop join (2/2)

- Costs:
  - best case when smaller relation fits in memory
    - use it as inner relation
    - B_R+B_S
  - worst case when memory holds one page of each relation
    - S scanned for each tuple in R
    - $T_R * B_s + B_R$

Block nested loop join (1/2)

```
for each page X_R of R
    for each page X_S of S
        for each tuple t_R in X_R
            for each t_S in X_S
                if (t_R t_S match) output t_R.t_S
            end
        end
    end
end
```

Block nested loop join (2/2)

- Costs:
  - best case when smaller relation fits in memory
    - use it as inner relation
    - B_R+B_S
  - worst case when memory holds one page of each relation
    - S scanned for each page in R
    - $B_R * B_s + B_R$

Block nested loop join (an improvement)

Memory size: M

for each M – 1 page size chunk M_R of R

    for each page X_S of S

        for each tuple t_R in M_R

            for each t_S in X_S

                if (t_R t_S match) output $t_R.t_S$

            end

        end

    end

end

Block nested loop join (an improvement)

- Costs:
  - best case when smaller relation fits in memory
    - use it as inner relation
    - $B_R + B_S$
  - general case
    - S scanned for each M-1 size chunk in R
    - $(B_R / (M-1)) * B_s + B_R$

Indexed nested loop join

- $R \bowtie S$
- Index on inner relation (S)
- for each tuple in outer relation (R) *probe* index of inner relation
- Costs:
  - $B_R + T_R * c$
    - c the cost of index-based selection of inner relation

    $c \approx T(s)/V(s,A)$

    (if A is the join column and index is kept in memory)

  - relation with fewer records as outer relation

Sort-merge join

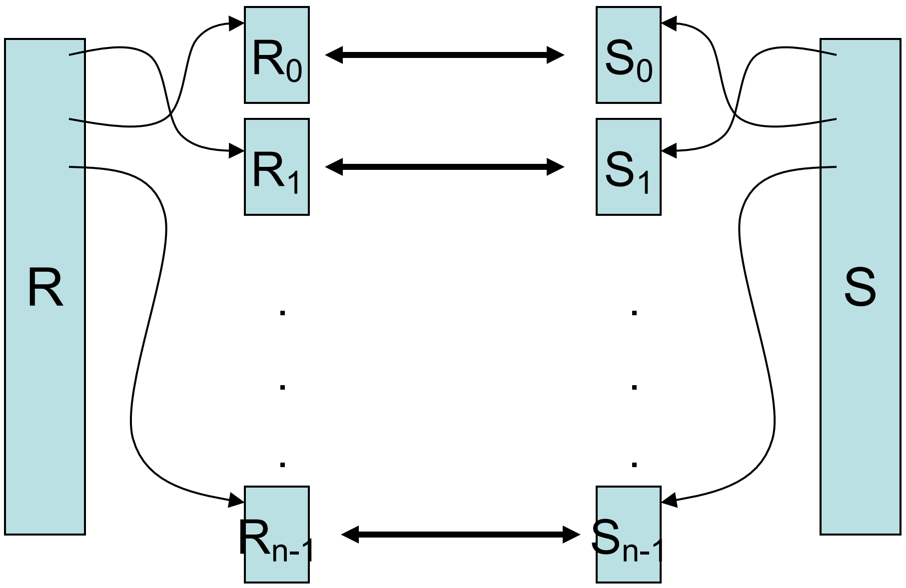
- $R \bowtie S$
- Relations sorted on the join attribute
- Merge sorted relations
  - pointers to first record in each relation
  - read in a group of records of S with the same values in the join attribute
  - read records of R and process
- Relations in sorted order to be read once
- Cost:
  - cost of sorting + B_S + B_R

d	D
e	E
x	X
v	V

e	67
e	87
n	11
v	22
z	38

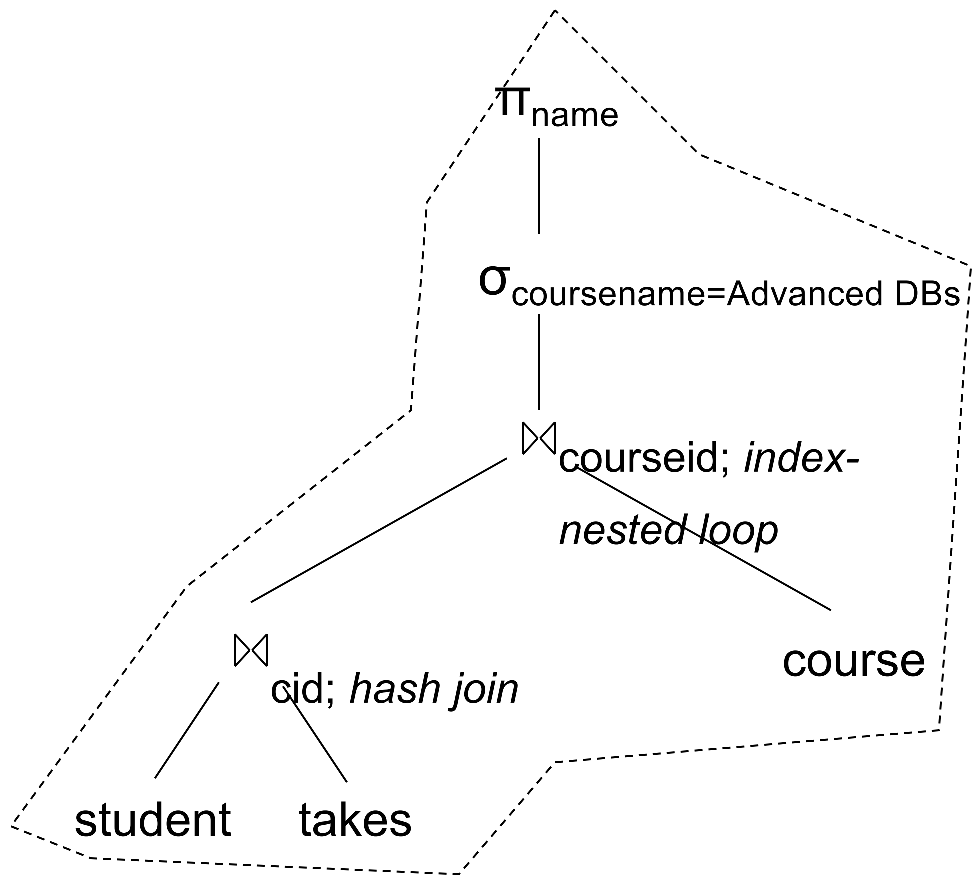
Hash join

- R ⋈ S
- use h_1 on joining attribute to map records to partitions that fit in memory
  - records of R are partitioned into $R_0 \ldots R_{n-1}$
  - records of S are partitioned into $S_0 \ldots S_{n-1}$
- join records in corresponding partitions
  - using a hash-based indexed block nested loop join
- Cost: $2*(B_R+B_S) + (B_R+B_S)$



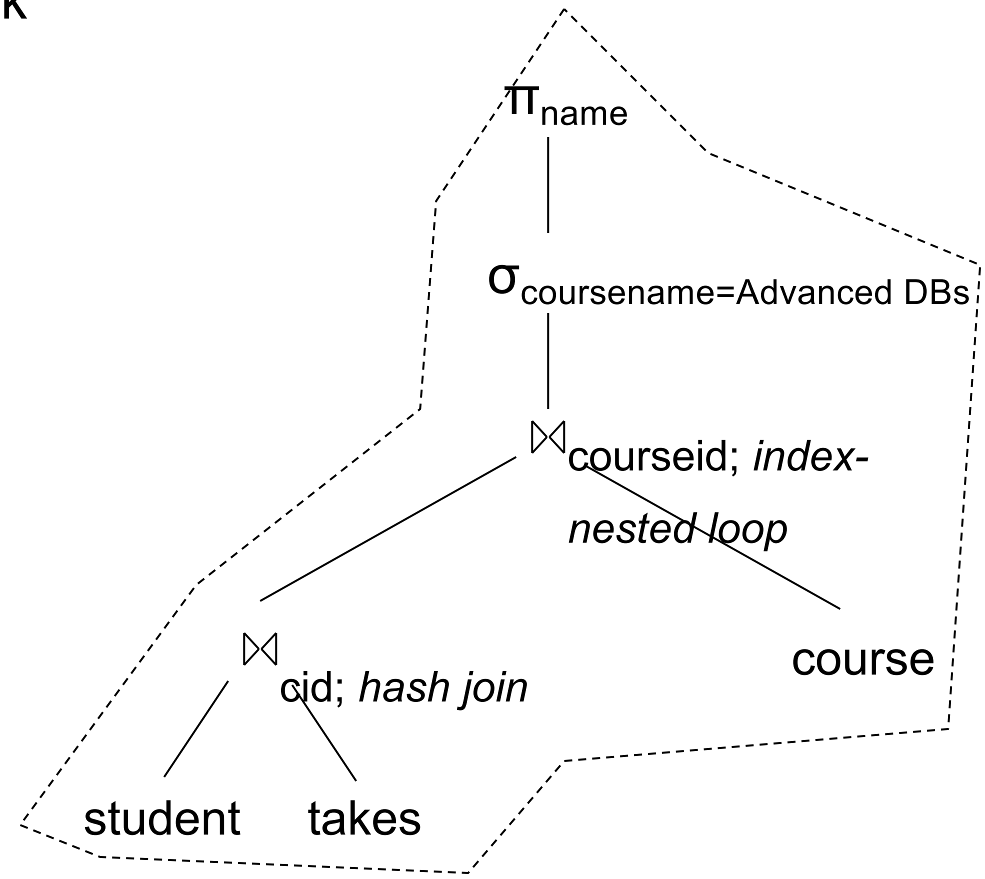
Evaluation

- evaluate multiple operations in a plan
- materialization
- pipelining



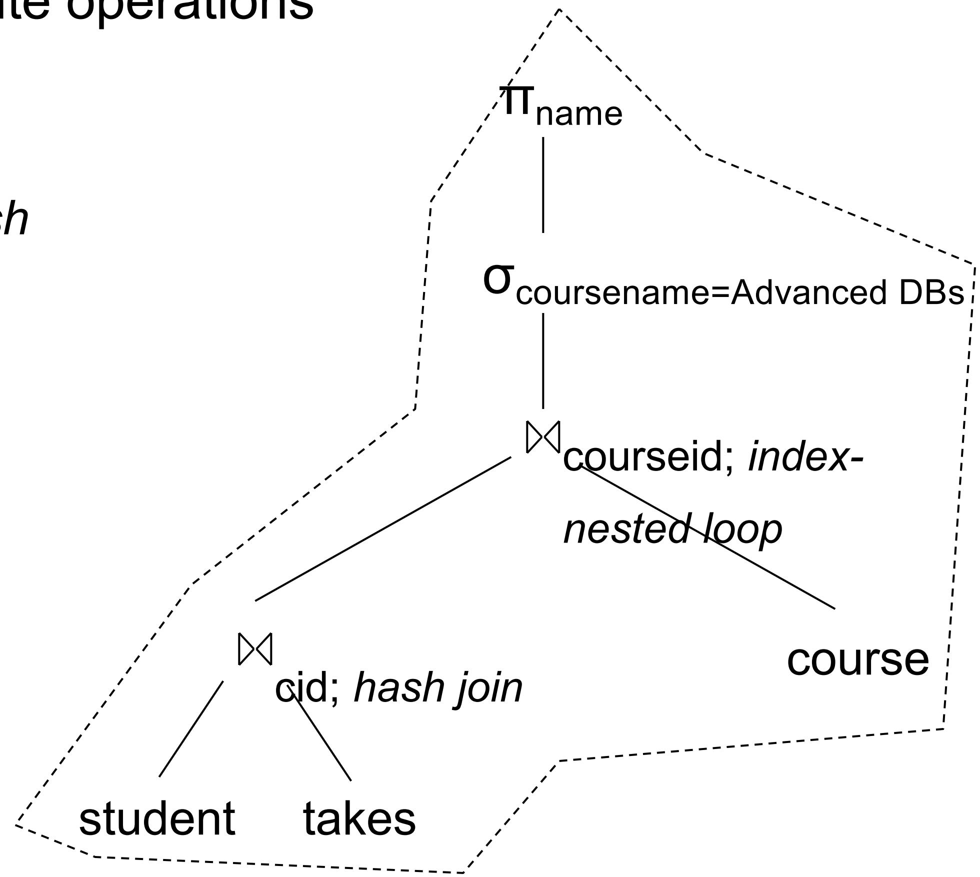
Materialization

- create and read temporary relations
- create implies writing to disk
  - more page writes



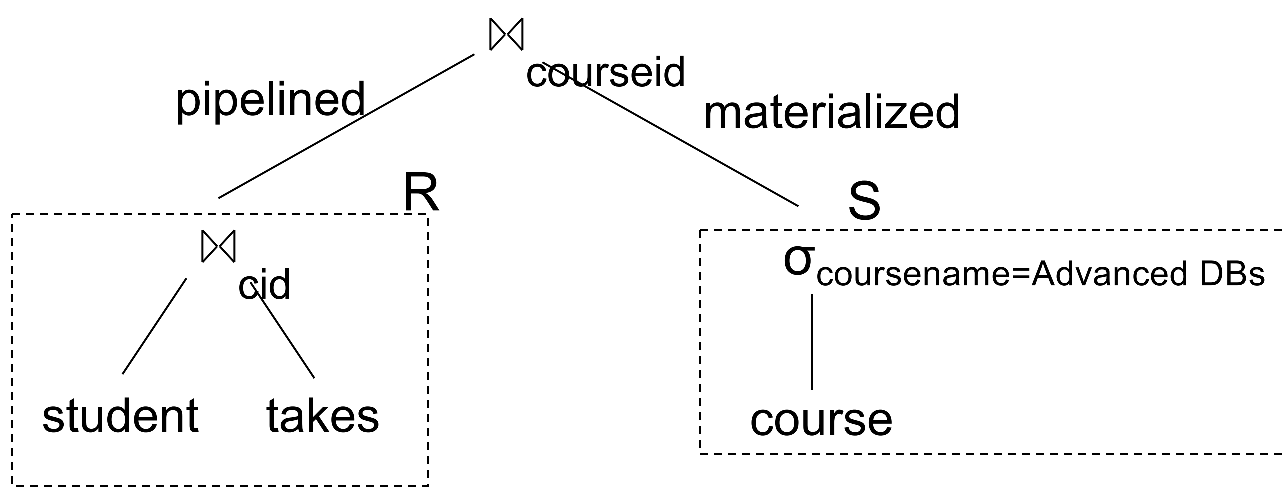
Pipelining (1/2)

- creating a pipeline of operations
- reduces number of read-write operations
- implementations
  - demand-driven - data *pull*
  - producer-driven - data *push*



Pipelining (2/2)

- can pipelining always be used?
- any algorithm?
- cost of $R \bowtie S$
  - materialization and hash join: $B_R + 3(B_R+B_S)$
  - pipelining and indexed nested loop join: $T_R * HT_i$



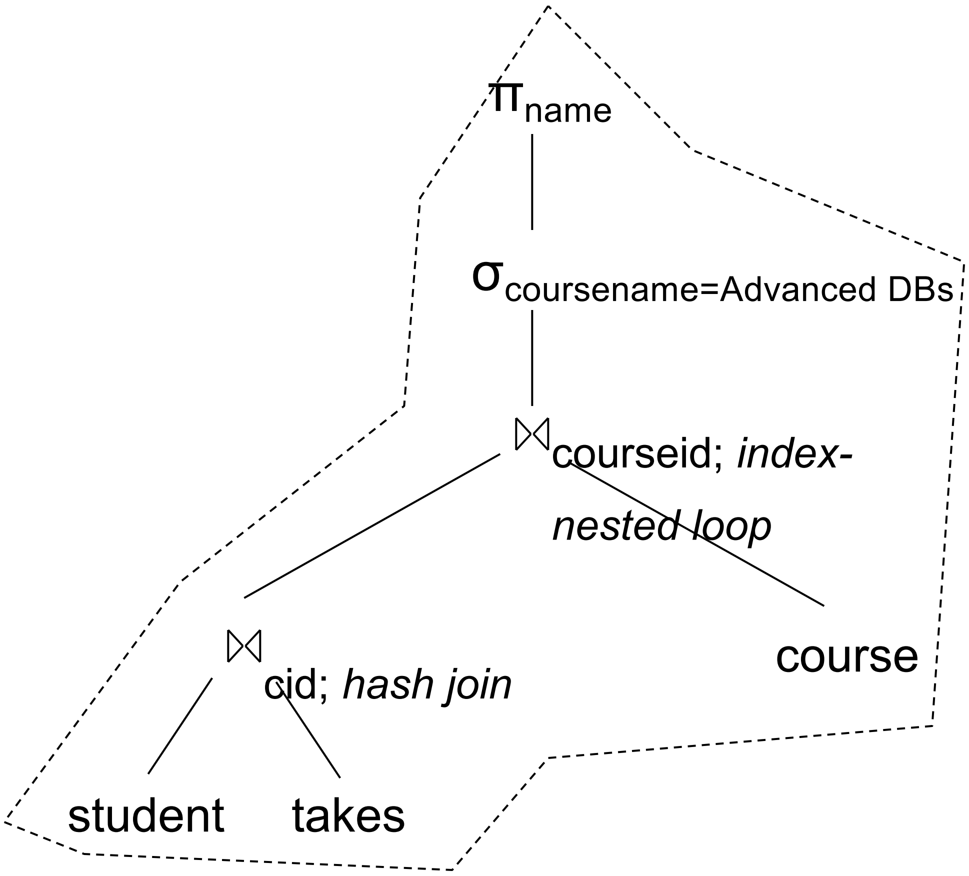
Choosing evaluation plans

- cost based optimization
- enumeration of plans
  - $R \bowtie S \bowtie T$, 12 possible orders (3! * 2)

  $(R \bowtie S) \bowtie T$, $R \bowtie (S \bowtie T)$
- cost estimation of each plan
- overall cost
  - cannot optimize operation independently

Cost estimation

- operation (σ, π, ⋈ …)
- implementation
- size of inputs
- size of outputs
- sorting

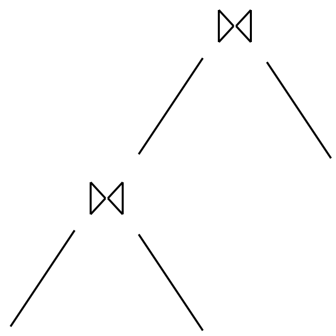


Expression Equivalence

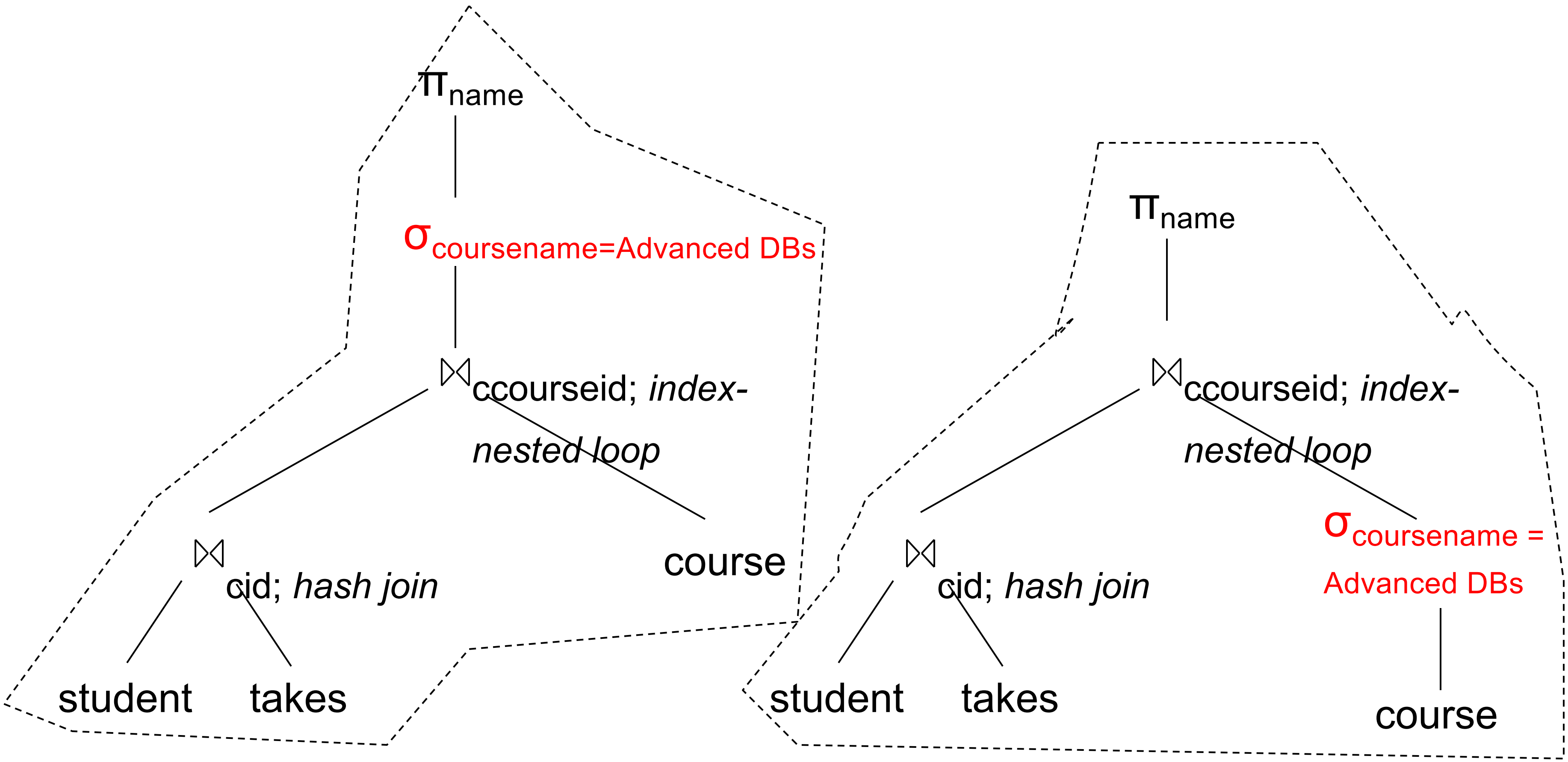
- conjunctive selection decomposition
  - $\sigma_{\theta_1 \wedge \theta_2}(R) = \sigma_{\theta_1}(\sigma_{\theta_2}(R))$
- commutativity of selection
  - $\sigma_{\theta_1}(\sigma_{\theta_2}(R)) = \sigma_{\theta_2}(\sigma_{\theta_1}(R))$
- combining selection with join and product
  - $\sigma_{\theta 1}(R \times S) = \ldots \quad R \bowtie_{\theta 1} S = \ldots$
- commutativity of joins
  - $R \bowtie_{\theta 1} S = S \bowtie_{\theta 1} R$
- distribution of selection over join
  - $\sigma_{\theta 1 \wedge \theta 2}(R \bowtie S) = \sigma_{\theta 1}(R) \bowtie \sigma_{\theta 2}(S)$
- distribution of projection over join
  - $\pi_{A1,A2}(R \bowtie S) = \pi_{A1}(R) \bowtie \pi_{A2}(S)$
- associativity of joins: $R \bowtie (S \bowtie T) = (R \bowtie S) \bowtie T$

Cost Optimizer (1/2)

- transforms expressions
  - equivalent expressions
  - heuristics, *rules of thumb*
    - perform selections early
    - perform projections early
    - replace products followed by selection σ (R x S) with joins R⋈S
    - start with joins, selections with smallest result
      - create **left-deep join trees**



Cost Optimizer (2/2)



Summary

- Estimating the cost of a single operation
- Estimating the cost of a query plan
- Optimization
  - choose the most efficient plan