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Carnegie Mellon Univ.
Dept. of Computer Science
15-415/615 - DB Applications

Lecture #15: Query Optimization
(R&G ch. 15; Sys. R q-opt paper)

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Overview - detailed

- Why q-opt?
- Equivalence of expressions
- Cost estimation
- Plan generation
- Plan evaluation

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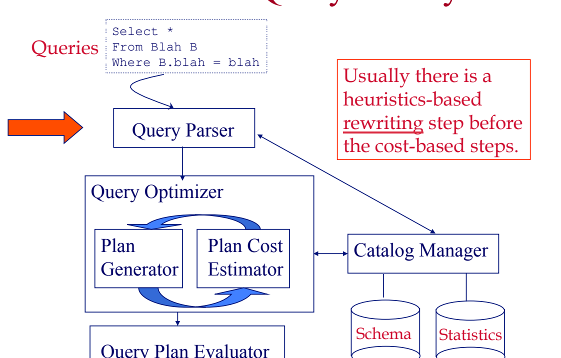
Cost-based Query Sub-System



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Why Q-opt?

- SQL: ~declarative
- good q-opt -> big difference
  - eg., seq. Scan vs
  - B-tree index, on P=1,000 pages

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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- generate alt. plans
- estimate cost; pick best

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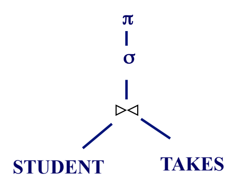
Q-opt - example

```
select name
from STUDENT, TAKES
where c-id='415' and
STUDENT.ssn=TAKES.ssn
```

→



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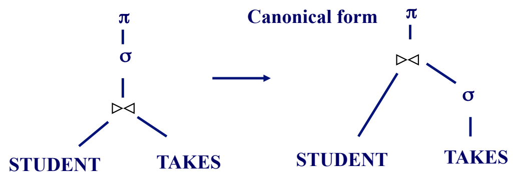
Q-opt - example



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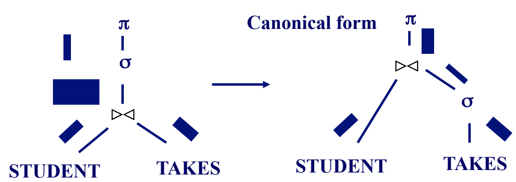
Q-opt - example



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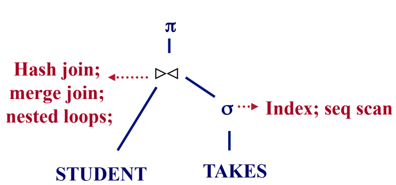
Q-opt - example



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Overview - detailed

- Why q-opt?
- **Equivalence of expressions**
- Cost estimation
- ...

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Equivalence of expressions

- A.k.a.: syntactic q-opt
- in short: perform selections and projections early
- More details: see transf. rules in text

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Equivalence of expressions

- Q: How to prove a transf. rule?

$$\sigma_P(R1 \bowtie R2) \stackrel{?}{=} \sigma_P(R1) \bowtie \sigma_P(R2)$$

- A: use RTC, to show that LHS = RHS, eg:

$$\sigma_P(R1 \cup R2) \stackrel{?}{=} \sigma_P(R1) \cup \sigma_P(R2)$$

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Equivalence of expressions

$$\sigma_P(R1 \cup R2) \overset{?}{=} \sigma_P(R1) \cup \sigma_P(R2)$$

$$t \in LHS \Leftrightarrow$$

$$t \in (R1 \cup R2) \wedge P(t) \Leftrightarrow$$

$$(t \in R1 \vee t \in R2) \wedge P(t) \Leftrightarrow$$

$$(t \in R1 \wedge P(t)) \vee (t \in R2) \wedge P(t)) \Leftrightarrow$$

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Equivalence of expressions

$$\sigma_P(R1 \cup R2) \overset{?}{=} \sigma_P(R1) \cup \sigma_P(R2)$$

...

$$(t \in R1 \wedge P(t)) \vee (t \in R2) \wedge P(t)) \Leftrightarrow$$

$$(t \in \sigma_P(R1)) \vee (t \in \sigma_P(R2)) \Leftrightarrow$$

$$t \in \sigma_P(R1) \cup \sigma_P(R2) \Leftrightarrow$$

$$t \in RHS$$

$$QED$$

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Equivalence of expressions

- Q: how to disprove a rule??

$$\pi_A(R1 - R2) \overset{?}{=} \pi_A(R1) - \pi_A(R2)$$

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Equivalence of expressions

- Q: how to disprove a rule??

$$\pi_A(R1 - R2) \stackrel{?}{=} \pi_A(R1) - \pi_A(R2)$$

R1	A	B
	Smith	pizza

R2	A	B
	Smith	steak

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Equivalence of expressions

- Selections
  - perform them early
  - break a complex predicate, and push

$$\sigma_{p1\wedge p2\wedge \ldots pn}(R) = \sigma_{p1}(\sigma_{p2}(\ldots\sigma_{pn}(R))\ldots)$$

  - simplify a complex predicate
    - ('X=Y and Y=3') -> 'X=3 and Y=3'

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Equivalence of expressions

- Projections
  - perform them early (but carefully…)
    - Smaller tuples
    - Fewer tuples (if duplicates are eliminated)
  - project out all attributes except the ones requested or required (e.g., joining attr.)

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Equivalence of expressions

- Joins
  - Commutative , associative

$$R \bowtie S = S \bowtie R$$

$$(R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$$

  - Q: n-way join - how many diff. orderings?

Equivalence of expressions

- Joins - Q: n-way join - how many diff. orderings?
- A: Catalan number ~ 4^n
  - Exhaustive enumeration: too slow.

Q-opt steps

- bring query in internal form (eg., parse tree)
- … into ‘canonical form’ (syntactic q-opt)
- generate alt. plans
- **estimate cost**; pick best

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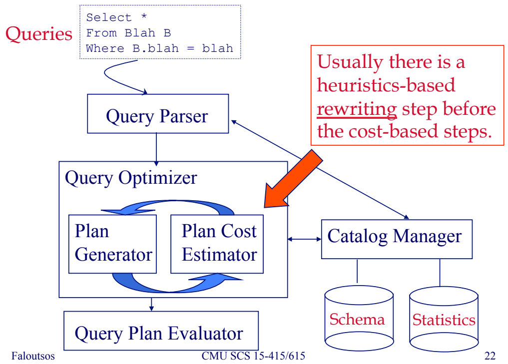
Cost-based Query Sub-System



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Cost estimation

- Eg., find ssn's of students with an 'A' in 415 (using seq. scanning)
- How long will a query take?
  - CPU (but: small cost; decreasing; tough to estimate)
  - Disk (mainly, # block transfers)
- How many tuples will qualify?
- (what statistics do we need to keep?)

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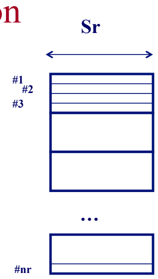
Cost estimation

- Statistics: for each relation 'r' we keep
  - nr : # tuples;
  - Sr : size of tuple in bytes



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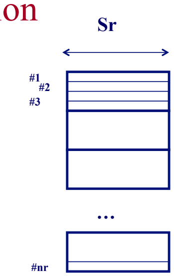
Cost estimation

- Statistics: for each relation 'r' we keep
  - …
  - V(A,r): number of distinct values of attr. 'A'
  - (histograms, too)



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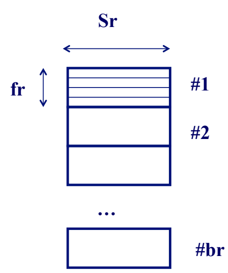
Derivable statistics

- blocking factor = max# records/block (=??)
- br: # blocks (=??)
- SC(A,r) = selection cardinality = avg# of records with A=given (=??)



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Derivable statistics

- blocking factor = max# records/block (= B/ Sr ; B: block size in bytes)
- br: # blocks (= nr / (blocking-factor))

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Derivable statistics

- SC(A,r) = selection cardinality = avg# of records with A=given (= nr / V(A,r)) (assumes uniformity...) – eg: 10,000 students, 10 colleges – how many students in SCS?

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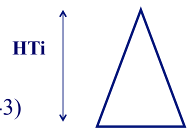
Additional quantities we need:

- For index ‘i’:
  - fi: average fanout (~50-100)
  - HTi: # levels of index ‘i’ (~2-3)
    - ~ log(#entries)/log(fi)
  - LBi: # blocks at leaf level



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Statistics

- Where do we store them?
- How often do we update them?

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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- generate alt. plans
- **estimate cost**; pick best

Selections

- we saw simple predicates (A=constant; eg., 'name=Smith')
- how about more complex predicates, like
  - 'salary > 10K'
  - 'age = 30 **and** job-code="analyst" '
- what is their selectivity?

Selections – complex predicates

- selectivity sel(P) of predicate P :

  == fraction of tuples that qualify

  sel(P) = SC(P) / nr

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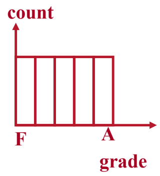
Selections – complex predicates

- eg., assume that V(grade, TAKES)=5 distinct values
- simple predicate P: A=constant
  - sel(A=constant) = 1/V(A,r)
  - eg., sel(grade=‘B’) = 1/5
- (what if V(A,r) is unknown??)



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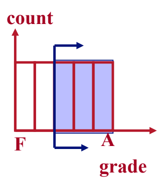
Selections – complex predicates

- range query: sel(grade >= ‘C’)
  - sel(A>a) = (Amax – a) / (Amax – Amin)



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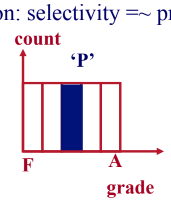
Selections - complex predicates

- negation: sel(grade != ‘C’)
  - sel(**not** P) = 1 – sel(P)
  - (Observation: selectivity =~ probability)



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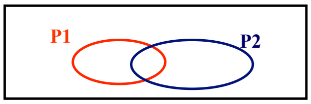
Selections – complex predicates

conjunction:

- sel(grade = ‘C’ and course = ‘415’)
- sel(P1 **and** P2) = sel(P1) * sel(P2)
- INDEPENDENCE ASSUMPTION



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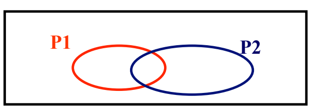
Selections – complex predicates

disjunction:

- sel(grade = ‘C’ or course = ‘415’)
- sel(P1 **or** P2) = sel(P1) + sel(P2) – sel(P1 **and** P2)
- = sel(P1) + sel(P2) – sel(P1)*sel(P2)
- INDEPENDENCE ASSUMPTION, again



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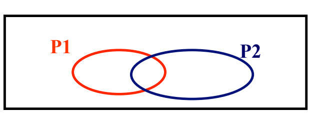
Selections – complex predicates

disjunction: in general

sel(P1 **or** P2 **or** … Pn) =
1 - (1- sel(P1)) * (1 - sel(P2)) * … (1 - sel(Pn))



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Selections – summary

- sel(A=constant) = 1/V(A,r)
- sel(A>a) = (Amax – a) / (Amax – Amin)
- sel(not P) = 1 – sel(P)
- sel(P1 **and** P2) = sel(P1) * sel(P2)
- sel(P1 **or** P2) = sel(P1) + sel(P2) – sel(P1)*sel(P2)
- sel(P1 **or** ... **or** Pn) = 1 - (1-sel(P1))*...*(1-sel(Pn))
- UNIFORMITY and INDEPENDENCE ASSUMPTIONS

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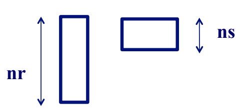
Result Size Estimation for Joins

- Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?
  - Hint: what if R_cols∩S_cols = ∅?
  - R_cols∩S_cols is a key for R (and a Foreign Key in S)?



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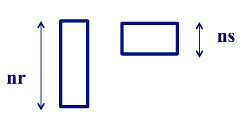
Result Size Estimation for Joins

- Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?
  - Hint: what if R_cols∩S_cols = ∅? **nr * ns**
  - R_cols∩S_cols is a key for R (and a Foreign Key in S)?



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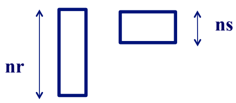
Result Size Estimation for Joins

- Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?
  - Hint: what if R_cols∩S_cols = ∅? **nr * ns**
  - R_cols∩S_cols is a key for R (and a Foreign Key in S)? **<=ns**



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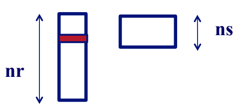
Result Size Estimation for Joins

- General case: R_cols∩S_cols = {A} (and A is key for neither)

Hint: for a given tuple of R,

how many tuples of S will it match?



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Result Size Estimation for Joins

- General case: R_cols∩S_cols = {A} (and A is key for neither)
  - match each R-tuple with S-tuples

    est_size <~ NTuples(R) * NTuples(S)/NKeys(A,**S**)

    <~ nr * ns / V(A,S)
  - symmetrically, for S:

    est_size <~ NTuples(R) * NTuples(S)/NKeys(A,**R**)

    <~ nr * ns / V(A,R)
  - Overall:

    est_size = NTuples(R)*NTuples(S)/MAX{NKeys(A,**S**), NKeys(A,**R**)}

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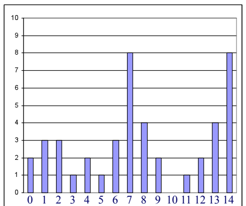
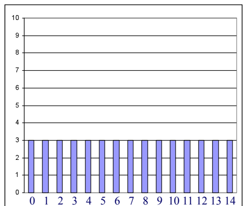
On the Uniform Distribution Assumption

- Assuming uniform distribution is rather crude

Distribution D



Uniform distribution approximating D



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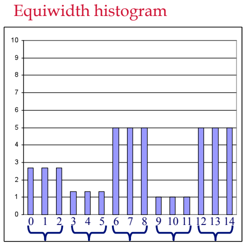
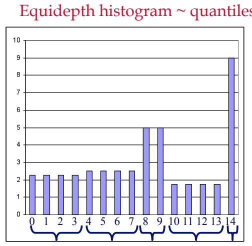
Histograms

- For better estimation, use a *histogram*

Equiwidth histogram



Equidepth histogram ~ quantiles



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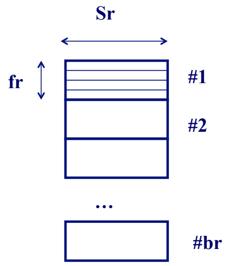
Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- **generate alt. plans**
  - **single relation**
  - multiple relations
- estimate cost; pick best

plan generation

- Selections – eg.,
  select *
  from TAKES
  where grade = 'A'
- Plans?



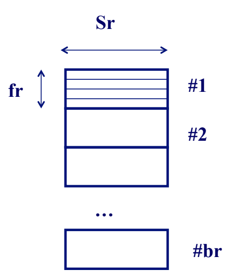
REMINDER

Cost estimation

	scan	eq	range	ins	del
Heap	B	B/2	B	2	Search+1
sorted	B	log_2B	<- +m	Search+B	Search+B
Clust.	1.5B	h	<- +m	Search+1	Search+1
u-tree	~B	1+h'	<- +m'	Search+2	Search+2
u-hash	~B	~2	B	Search+2	Search+2

plan generation

- Plans?
  - seq. scan
  - binary search
    - (if sorted & consecutive)
  - index search
    - if an index exists



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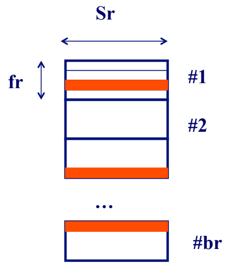
plan generation

seq. scan – cost?

- br (worst case)
- br/2 (average, if we search for primary key)



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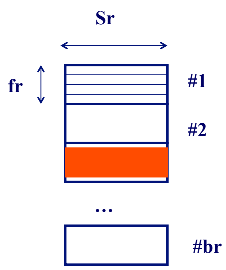
plan generation

binary search – cost?

if sorted and consecutive:

- ~log(br) +
- SC(A,r)/fr (=blocks spanned by qual. tuples)



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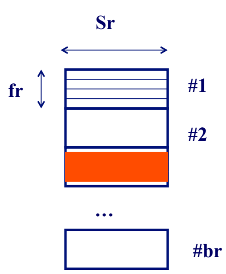
plan generation

estimation of selection cardinalities SC(A,r):

non-trivial – we saw it earlier



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plan generation

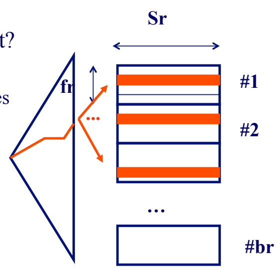
method#3: index – cost?

- levels of index +
- blocks w/ qual. tuples

case#1: primary key

case#2: sec. key – clustering index

case#3: sec. key – non-clust. index



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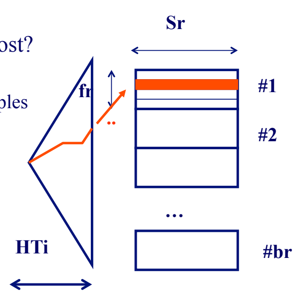
plan generation

method#3: index – cost?

- levels of index +
- blocks w/ qual. tuples

case#1: primary key – cost:

HTi + 1



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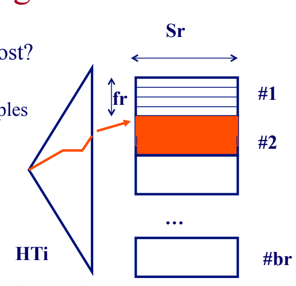
plan generation

method#3: index – cost?

- levels of index +
- blocks w/ qual. tuples

case#2: sec. key – clustering index

HTi + SC(A,r)/fr



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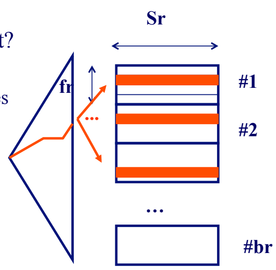
plan generation

method#3: index – cost?
- levels of index +
- blocks w/ qual. tuples



case#3: sec. key – non-clust. index

HTi + SC(A,r)

(actually, pessimistic...)

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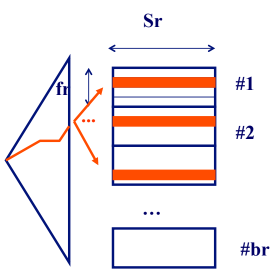
plan generation

method#3: index – cost?
- levels of index +
- blocks w/ qual. tuples



(actually, pessimistic...

better estimates:
Cardenas' formula)

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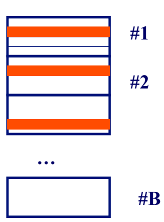
Not in exam

Cardena's formula

- q: # qual records
- Q: # qual. blocks
- N: # records total
- B: # blocks total
- Q=??



Alfonso Cardenas (IBM->UCLA)

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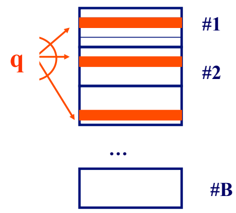
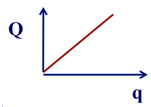
Not in exam

Cardena's formula

- Pessimistic:
  - Q = q





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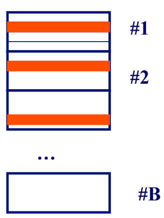
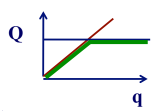
Not in exam

Cardena's formula

- Pessimistic:
  - Q = q
- More realistic
  - Q = q if q<=B
  - Q = B otherwise





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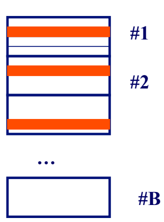
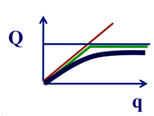
Not in exam

Cardena's formula

- Cardenas' formula

$$Q = B\,[1 - (1 - 1/B)^q\,]$$





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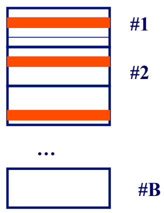
Not in exam

Cardena's formula

- Cardenas' formula

$$Q = B\,[1-(1-1/B)^q\,]$$

Prob (single shot, hits our favorite block)



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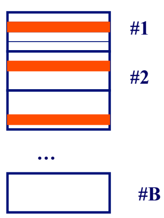
Not in exam

Cardena's formula

- Cardenas' formula

$$Q = B\,[1-(1-1/B)^q\,]$$

Prob(it avoids it)



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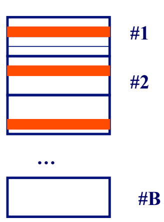
Not in exam

Cardena's formula

- Cardenas' formula

$$Q = B\,[1-(1-1/B)^q\,]$$

Prob(it avoids it, q times)



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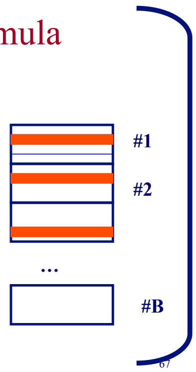
Not in exam

Cardena's formula

- Cardenas' formula

$$Q = B\,[1-(1-1/B)^q\,]$$



Prob(our favorite block is hit at least once, after q selections)

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Plans for single relation - summary

- no index: scan (dup-elim; sort)
- with index:
  - single index access path
  - multiple index access path
  - sorted index access path
  - index-only access path

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Overview - detailed

- Why q-opt?
- Equivalence of expressions
- Cost estimation
- Plan generation
- Plan evaluation

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Citation

- P. G. Selinger, M. M. Astrahan, D. D. Chamberlin, R. A. Lorie, and T. G. Price. *Access path selection in a relational database management system*. In SIGMOD Conference, pages 23--34, 1979.

Faloutsos CMU SCS 15-415/615 70

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Frequently cited database publications

http://www.informatik.uni-trier.de/~ley/db/about/top.html

#	Publication
608	Peter P. Chen: The Entity-Relationship Model - Toward a Unified View of Data. ACM Trans. Database Syst. 1(1): 9-36 (1976)
580	E. F. Codd: A Relational Model of Data for Large Shared Data Banks. Commun. ACM 13(6): 377-387(1970)
371	Patricia G. Selinger, Morton M. Astrahan, Donald D. Chamberlin, Raymond A. Lorie, Thomas G. Price: Access Path Selection in a Relational Database Management System. SIGMOD Conference 1979: 23-34
366	Jeffrey D. Ullman: Principles of Database and Knowledge Base Systems, Volume I. Computer Science Press 1988, ISBN 0-7167-8158-1
…	…

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Statistics for Optimization

- NCARD (T) - cardinality of relation T in tuples
- TCARD (T) - number of pages containing tuples from T
- P(T) = TCARD(T)/(# of non-empty pages in the segment)
  - If segments only held tuples from one relation there would be no need for P(T)
- ICARD(I) - number of distinct keys in index I
- NINDX(I) - number of pages in index I

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Predicate Selectivity Estimation

attr = value	**F = 1/ICARD(attr index)** – if index exists **F = 1/10** otherwise
attr1 = attr2	**F = 1/max(ICARD(I1),ICARD(I2))** or **F = 1/ICARD(Ii)** – if only index i exists, or **F = 1/10**
val1 < attr < val2	**F = (value2-value1)/(high key-low key)** **F = 1/4** otherwise
expr1 or expr2	**F = F(expr1)+F(expr2)–F(expr1)*F(expr2)**
expr1 and expr2	**F = F(expr1) * F(expr2)**
NOT expr	**F = 1 – F(expr)**

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Costs per Access Path Case

Unique index matching equal predicate	**1+1+W**
Clustered index I matching >=1 preds	**F(preds)*(NINDX(I)+TCARD)+W*RSICARD**
Non-clustered index I matching >=1 preds	**F(preds)*(NINDX(I)+NCARD)+W*RSICARD**
Segment scan	**TCARD/P + W*RSICARD**

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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into ‘canonical form’ (syntactic q-opt)
- generate alt. plans
  - single relation
  - **multiple relations**
    - Main idea
    - Dynamic programming – reminder
    - Example
- estimate cost; pick best

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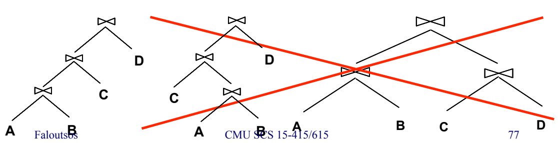
n-way joins

- r1 JOIN r2 JOIN ... JOIN rn
- typically, break problem into 2-way joins
  - choose between NL, sort merge, hash join, ...

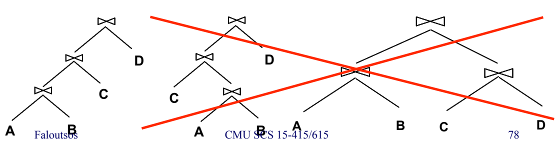
Queries Over Multiple Relations

- As number of joins increases, number of alternative plans grows rapidly → *need to restrict search space*
- Fundamental decision in System R: *only left-deep join trees* are considered. Advantages?



Queries Over Multiple Relations

- As number of joins increases, number of alternative plans grows rapidly → *need to restrict search space*
- Fundamental decision in System R: *only left-deep join trees* are considered. Advantages?
  - *fully pipelined* plans.
    - Intermediate results not written to temporary files.
    - Not all left-deep trees are fully pipelined (e.g., SM join).



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Queries over Multiple Relations

- Enumerate the orderings (= left deep tree)
- enumerate the plans for each operator
- enumerate the access paths for each table

Dynamic programming, to save cost estimations

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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- generate alt. plans
  - single relation
  - multiple relations
    - Main idea
    - **Dynamic programming – reminder**
    - Example
- estimate cost; pick best

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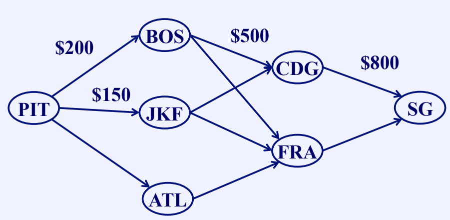
(Reminder: Dynamic Programming)



Cheapest flight PIT -> SG ?

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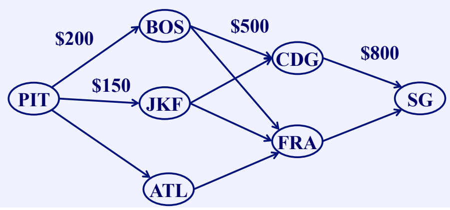
(Reminder: Dynamic Programming)



Assumption: NO package deals: cost CDG->SG is always $800, no matter how reached CDG

82

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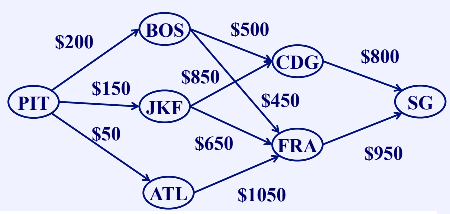
(Reminder: Dynamic Programming)



Solution: compute partial optimal, left-to-right:

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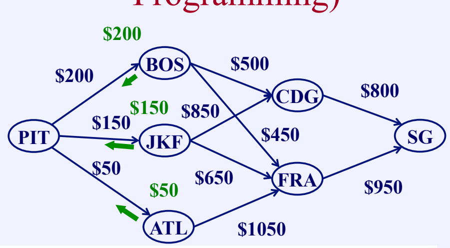
CMU SCS

(Reminder: Dynamic Programming)

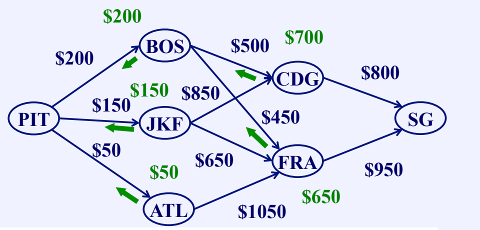


Solution: compute partial optimal, left-to-right:

Faloutsos CMU SCS 15-415/615 84

CMU SCS

(Reminder: Dynamic Programming)



Solution: compute partial optimal, left-to-right:

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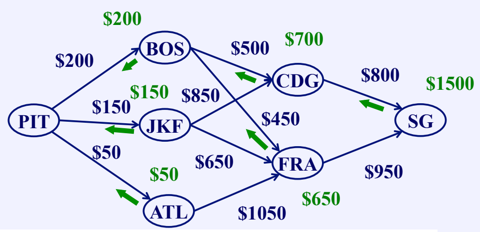
CMU SCS

(Reminder: Dynamic Programming)



Solution: compute partial optimal, left-to-right:

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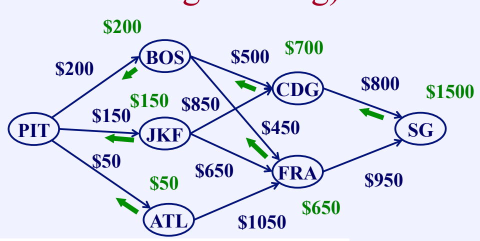
CMU SCS

(Reminder: Dynamic Programming)



So, best price is $1,500 – which legs?

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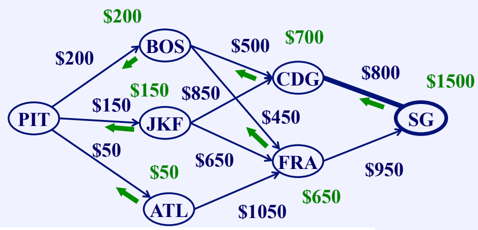
CMU SCS

(Reminder: Dynamic Programming)



So, best price is $1,500 – which legs?

A: follow the winning edges, backwards

88

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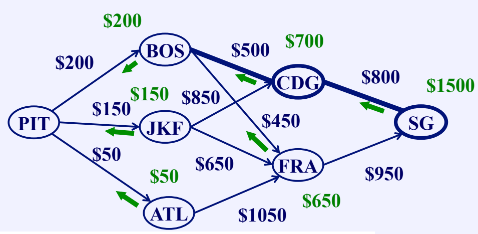
(Reminder: Dynamic Programming)



So, best price is $1,500 – which legs?

A: follow the winning edges, backwards

89

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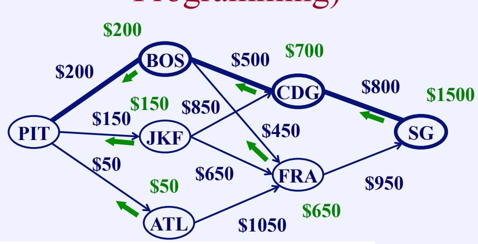
(Reminder: Dynamic Programming)



So, best price is $1,500 – which legs?

A: follow the winning edges, backwards

90

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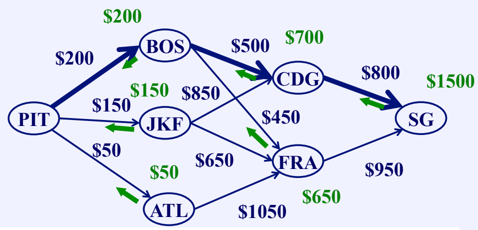
(Reminder: Dynamic Programming)



Q: what are the states, costs and arrows, in q-opt?

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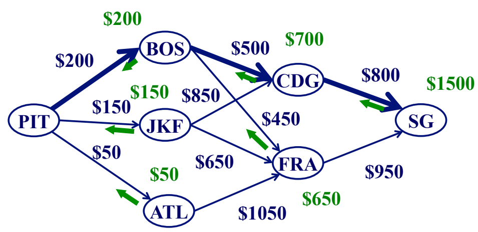
(Reminder: Dynamic Programming)



Q: what are the states (and costs and arrows), in q-opt?

A: set of intermediate result tables

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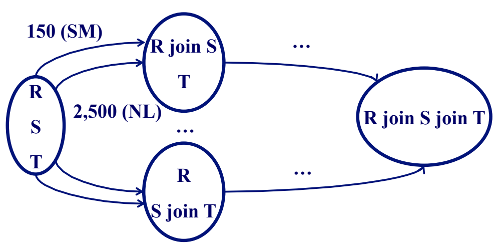
Q-opt and Dyn. Programming

- E.g., compute R join S join T



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Q-opt and Dyn. Programming

- Details: how to record the fact that, say R is sorted on R.a? or that the user requires sorted output?
- A:
- E.g., consider the query

```
select *
from R, S, T
where R.a = S.a and S.b = T.b
order by R.a
```

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Q-opt and Dyn. Programming

- Details: how to record the fact that, say R is sorted on R.a? or that the user requires sorted output?
- A: record orderings, in the state
- E.g., consider the query

```
select *
from R, S, T
where R.a = S.a and S.b = T.b
order by R.a
```

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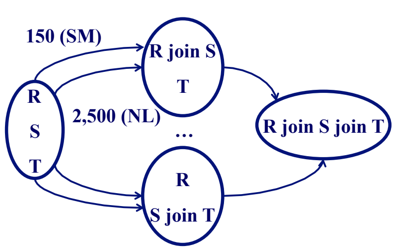
Q-opt and Dyn. Programming

- E.g., compute R join S join T order by R.a



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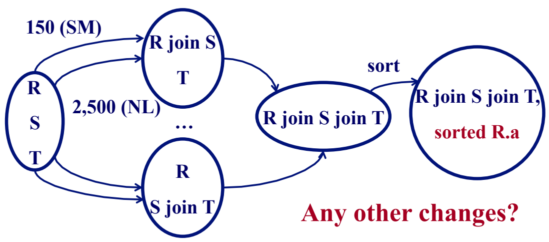
Q-opt and Dyn. Programming

- E.g., compute R join S join T order by R.a



Any other changes?

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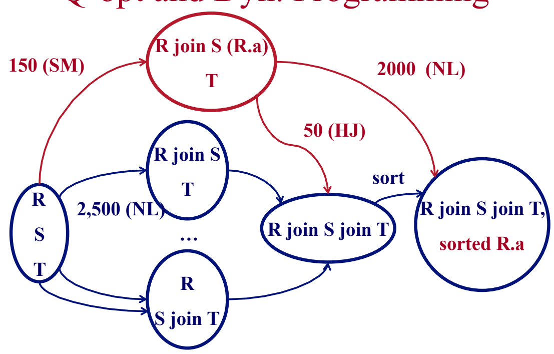
Q-opt and Dyn. Programming



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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- generate alt. plans
  - single relation
  - multiple relations
    - Main idea
    - Dynamic programming – reminder
    - **Example**
- estimate cost; pick best

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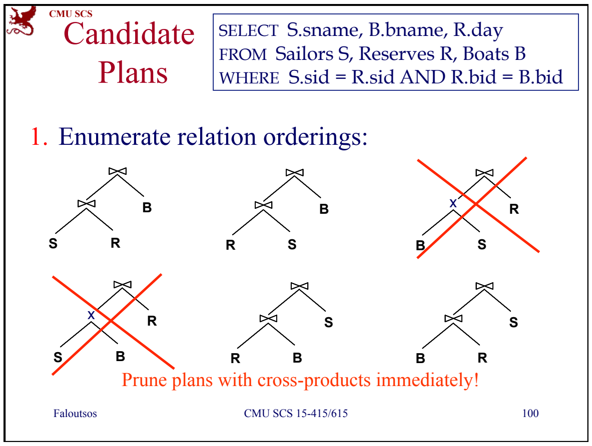
CMU SCS
Candidate Plans
SELECT S.sname, B.bname, R.day
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
1. Enumerate relation orderings:
Prune plans with cross-products immediately!
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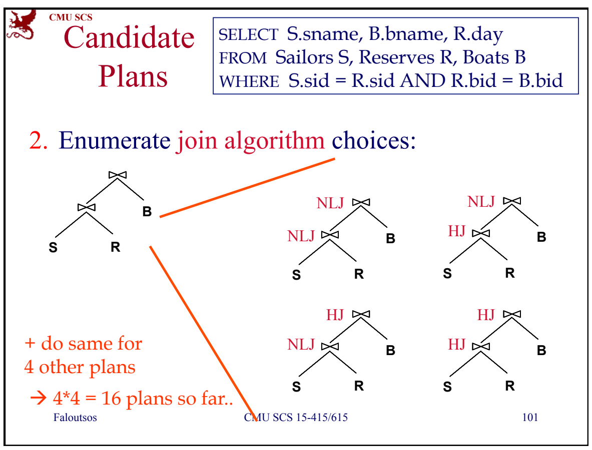
CMU SCS 15-415/615
100


CMU SCS
Candidate Plans
SELECT S.sname, B.bname, R.day
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
2. Enumerate join algorithm choices:
+ do same for
4 other plans
→ 4*4 = 16 plans so far..
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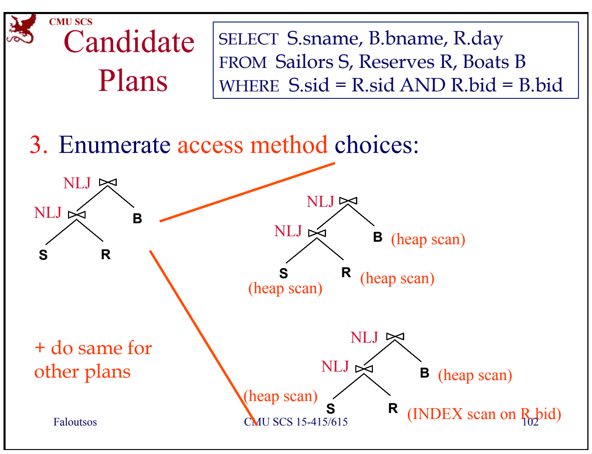
CMU SCS
Candidate Plans
SELECT S.sname, B.bname, R.day
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
3. Enumerate access method choices:
(heap scan)
(heap scan)
(heap scan)
+ do same for
other plans
(heap scan)
(heap scan)
(INDEX scan on R.bid)
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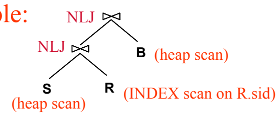
Now estimate the cost of each plan

Example:



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Q-opt steps

- bring query in internal form (eg., parse tree)
- … into 'canonical form' (syntactic q-opt)
- generate alt. plans
  - single relation
  - multiple relations
  - **nested subqueries**
- estimate cost; pick best

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Q-opt steps

- Everything so far: about a single query block

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Query Rewriting

- Re-write nested queries
- to: de-correlate and/or flatten them

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Example: Decorrelating a Query

```
SELECT S.sid
FROM Sailors S
WHERE EXISTS
  (SELECT *
   FROM Reserves R
   WHERE R.bid=103
   AND R.sid=S.sid)
```

Equivalent uncorrelated query:

```
SELECT S.sid
FROM Sailors S
WHERE S.sid IN
  (SELECT R.sid
   FROM Reserves R
   WHERE R.bid=103)
```

- Advantage: nested block only needs to be executed once (rather than once per S tuple)

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Example: "Flattening" a Query

```
SELECT S.sid
FROM Sailors S
WHERE S.sid IN
  (SELECT R.sid
   FROM Reserves R
   WHERE R.bid=103)
```

Equivalent non-nested query:

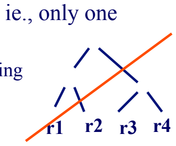
```
SELECT S.sid
FROM Sailors S, Reserves R
WHERE S.sid=R.sid
  AND R.bid=103
```

- Advantage: can use a join algorithm + optimizer can select among join algorithms & reorder freely

Structure of query optimizers:

System R:

- break query in query blocks
- simple queries (ie., no joins): look at stats
- n-way joins: left-deep join trees; ie., only one intermediate result at a time
  - pros: smaller search space; pipelining
  - cons: may miss optimal
- 2-way joins: NL and sort-merge



Structure of query optimizers:

More heuristics by Oracle, Sybase and Starburst (-> DB2)

In general: q-opt is very important for large databases.

(‘**explain select** <sql-statement>’ gives plan)

Q-opt steps

- bring query in internal form (eg., parse tree)
- … into ‘canonical form’ (syntactic q-opt)
- generate alt. plans
- estimate cost; pick best

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Conclusions

- Ideas to remember:
  - syntactic q-opt – do selections early
  - selectivity estimations (uniformity, indep.; histograms; join selectivity)
  - hash join (nested loops; sort-merge)
  - left-deep joins
  - dynamic programming

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