CompSci 516
Database Systems

Lecture 22
Query Optimization

Instructor: Sudeepa Roy

Where are we now?

Relational model, queries, db design
- Relational Model
- Normal Forms, FD
- Query in SQL / RA / RC
- Recursion

DBMS Internals and Query Processing
- Storage
- Index
- Join algo/Sorting
- Execution/ Optimization

Beyond Relational Model
- XML
- NOSQL **JSON/MongoDB**

Transactions
- Basics
- Concurrency Control
- Recovery

(Basic) Big Data Processing
- Map-Reduce/ Spark
- Parallel DBMS
- Distributed DBMS

Other Topics
- Data Mining
- Data Cube

Covered

Next

To be covered

Announcements (Tues, 03/29)

- HW3 due 4/5 (Tues) noon
  - Let us know if you need someone to work with
- More frequent check in for all teams by mentors
- Project report deadline 04/13

Reading Material

- [RG]
  - Query optimization: Chapter 15 (overview only)
- [GUW]
  - Chapter 16.2-16.7

- Original paper by Selinger et al. :
  - P. Selinger, M. Astrahan, D. Chamberlin, R. Lorie, and T. Price. *Access Path Selection in a Relational Database Management System*

    Proceedings of ACM SIGMOD, 1979. Pages 22-34
  - No need to understand the whole paper, but take a look at the example (link on the course webpage)

Acknowledgement:
- The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.
- Some of the following slides have been created by adapting slides by Profs. Shivnath Babu and Magda Balazinska

Query Blocks: Units of Optimization

- Query Block
  - No nesting
  - One SELECT, one FROM
  - At most one WHERE, GROUP BY, HAVING

```
SELECT  S.sname
FROM  Sailors S
WHERE  S.age IN
   (SELECT  MAX (S2.age)
     FROM  Sailors S2
     GROUP BY  S2.rating)
```

Outer block *Nested block*

- SQL query
- => parsed into a collection of query blocks
- => the blocks are optimized one block at a time

- Express single-block it as a relational algebra (RA) expression

Cost Estimation

- For each plan considered, must estimate cost:

- Must estimate cost of each operation in plan tree.
  - Depends on input cardinalities
  - We've discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)

- Must also estimate size of result for each operation in tree
  - gives input cardinality of next operators

- Also consider
  - whether the output is sorted
  - intermediate results written to disk

Relational Algebra Equivalences

- Allow us to choose different join orders and to `push' selections and projections ahead of joins.

- **Selections:** $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots \sigma_{cn}(R))$ *(Cascade)*

  $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$ *(Commute)*

- **Projections:** $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{an}(R)))$ *(Cascade)*

- **Joins:** $R \bowtie (S \bowtie T) \equiv (R \bowtie S) \bowtie T$ *(Associative)*

  $(R \bowtie S) \equiv (S \bowtie R)$ *(Commute)*

There are many more intuitive equivalences, see 15.3.4 for details if interested

Notation

- T(R) : Number of tuples in R
- B(R) : Number of blocks (pages) in R
- V(R, A) : Number of distinct values of attribute A in R

Query Optimization Problem

Pick the best plan from the space of physical plans

Cost-based Query Optimization

Pick the plan with least cost

Challenge:

- Do not want to execute more than one plans
- Need to estimate the cost without executing the plan!

"heuristic-based" optimizer (e.g. push selections down) have limited power and not used much

Cost-based Query Optimization

Pick the plan with least cost

Tasks:

1. Estimate the cost of individual operators
   done
2. Estimate the size of output of individual operators
   today
3. Combine costs of different operators in a plan
   today
4. Efficiently search the space of plans today

Task 1 and 2
Estimating cost and size of different operators

- Size = #tuples, NOT #pages
- Cost = #page I/O
    - need to consider whether the intermediate relation fits in memory, is written back to/read from disk (or on-the-fly goes to the next operator), etc.

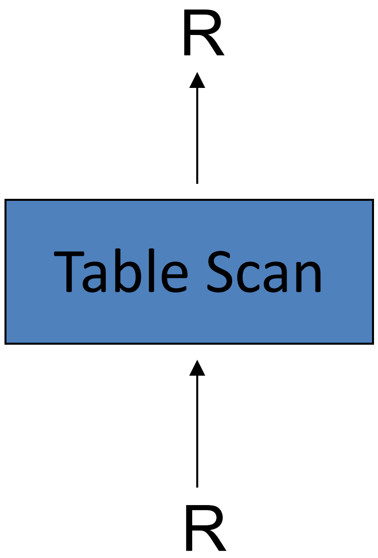
Desired Properties of Estimating Sizes of Intermediate Relations

Ideally,

- should give accurate estimates (as much as possible)
- should be easy to compute
- should be logically consistent
  - size estimate should be independent of how the relation is computed (e.g. which join algorithm/join order is used)

- But, no "universally agreed upon" ways to meet these goals

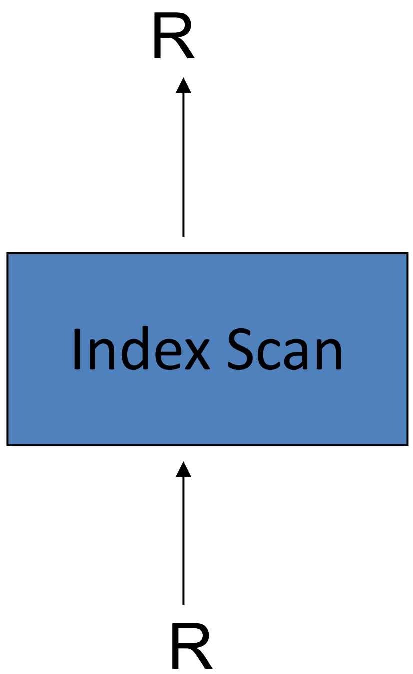
Cost of Table Scan



Cost: B(R)
Size: T(R)

T (R) : Number of tuples in R
B (R) : Number of blocks in R

Cost of Index Scan



Cost: B(R) – if clustered
T(R) – if unclustered

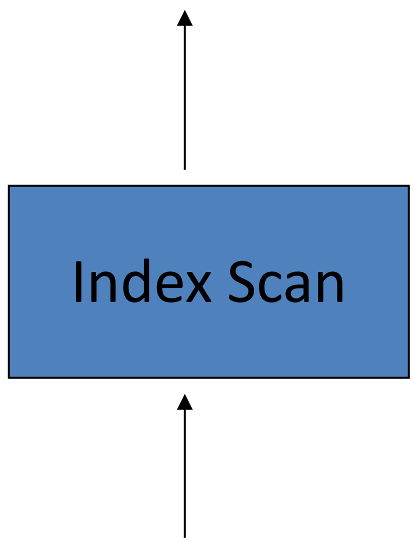
Size: T(R)

T (R) : Number of tuples in R
B (R) : Number of blocks in R

Note:
1. size is independent of the implementation of the scan/index
2. Index scan is bad if unclustered

Cost of Index Scan with Selection

$X = \sigma_{R.A > 50} R$



R

Cost: B(R) * f – if clustered
T(R) * f – if unclustered

Size: T(R) * f

T (R) : Number of tuples in R
B (R) : Number of blocks in R

Reduction factor
$f = (Max(R.A) - 50) / (Max(R.A) - Min(R.A))$
assumes uniform distribution

Cost of Index Scan with Selection (and multiple conditions)

$X = \sigma_{R.A > 50 \text{ and } R.B = C} R$

assume index on (A, B)

What is f1 if the first condition is 100 > R.1 > 50?

↑

Index Scan

↑

R

Cost: B(R) * f – if clustered
T(R) * f – if unclustered

Size: T(R) * f

Reduction factors

range selection

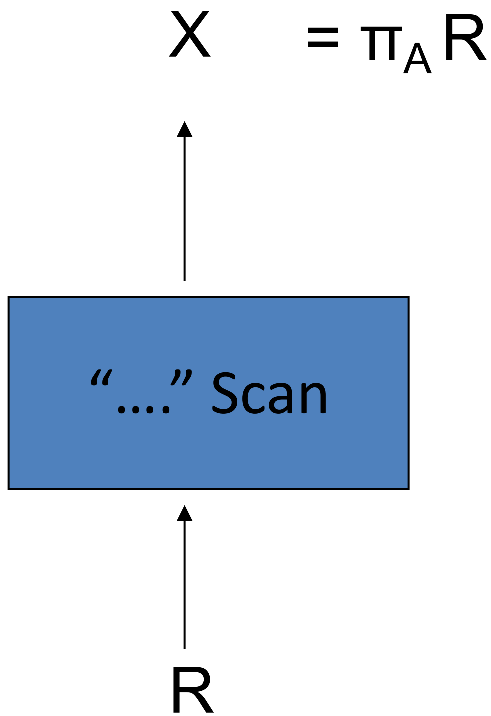
f1 = (Max(R.A) - 50) / (Max(R.A) - Min(R.A))

f2 = 1/ V(R, B) value selection

T (R) : Number of tuples in R
B (R) : Number of blocks in R
V(R, A) : Number of distinct values of attribute A in R

f = f1 * f2 (assumes independence and uniform distribution)

Cost of Projection



Cost: depends on the method of scanning R

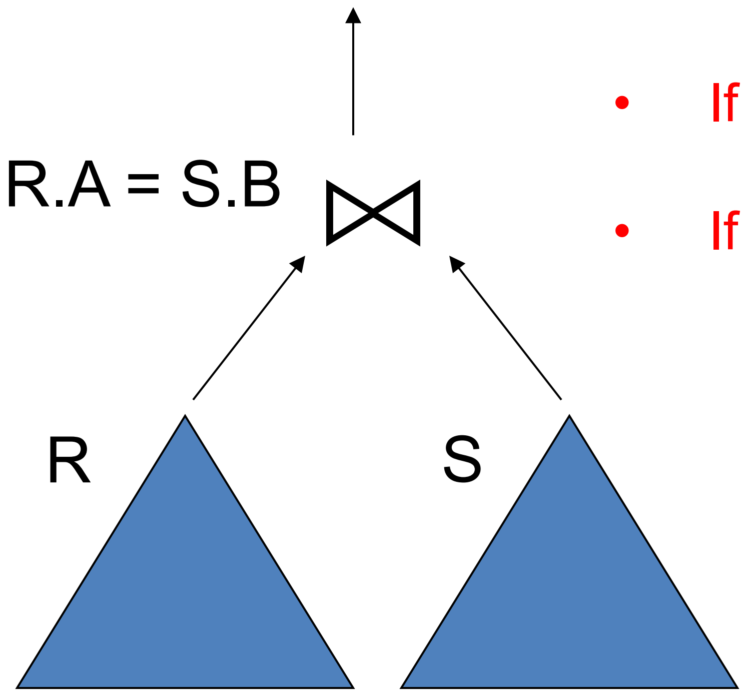
B(R) for table scan or clustered index scan

Size: T(R)

But tuples are smaller

If you have more information on the size of the smaller tuples, can estimate #I/O better

Size of Join



Quite tricky

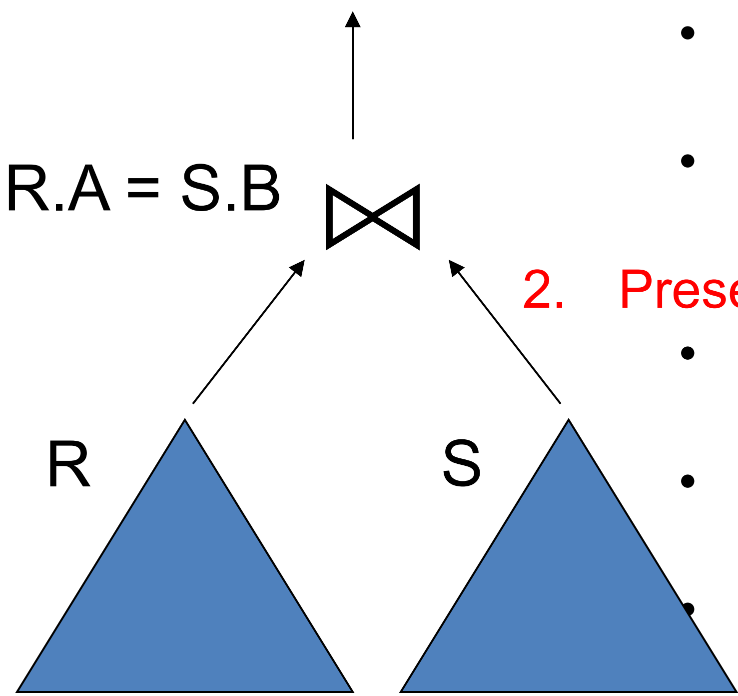
- If disjoint A and B values
  - then 0
- If A is key of R and B is foreign key of S
  - then T(S)
- If all tuples have the same value of R.A= S.B = x
  - then T(R) * T(S)

T (R) : Number of tuples in R
B (R) : Number of blocks in R
V(R, A) : Number of distinct values of attribute A in R

T (R) : Number of tuples in R
B (R) : Number of blocks in R
V(R, A) : Number of distinct values of attribute A in R

Optional slide

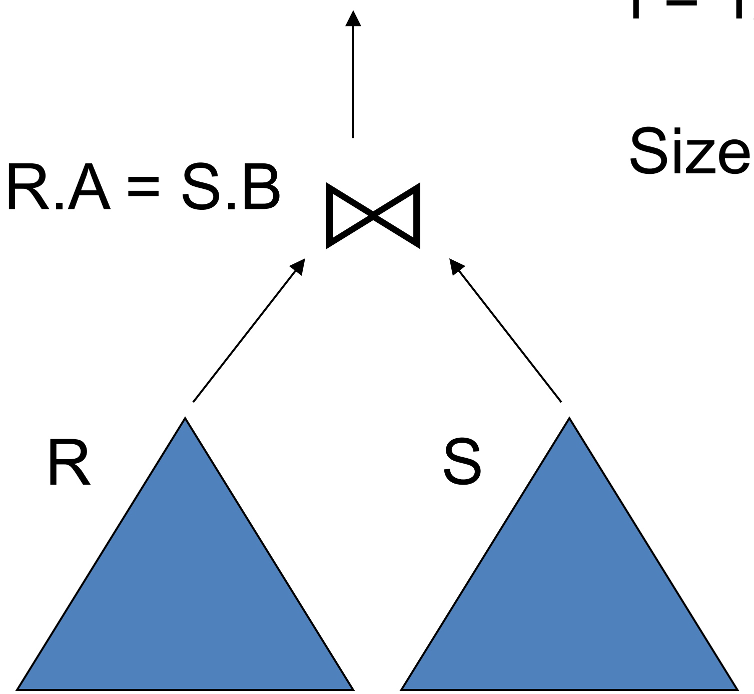
Size of Join



Two standard assumptions

1. Containment of value sets:
    - if V(R, A) <= V(S, B), then all A-values of R are included in B-values of S
    - e.g. satisfied when A is foreign key, B is key
2. Preservation of value sets:
    - For all "non-joining" attributes, the set of distinct values is preserved in join
    - $V(R \bowtie S, C) = V(R, C)$, where $C \neq A$ is an attribute in R
    - $V(R \bowtie S, D) = V(S, D)$, where $D \neq B$ is an attribute in S
    - Helps estimate distinct set size in $R \bowtie S \bowtie T$

Size of Join



Reduction factor

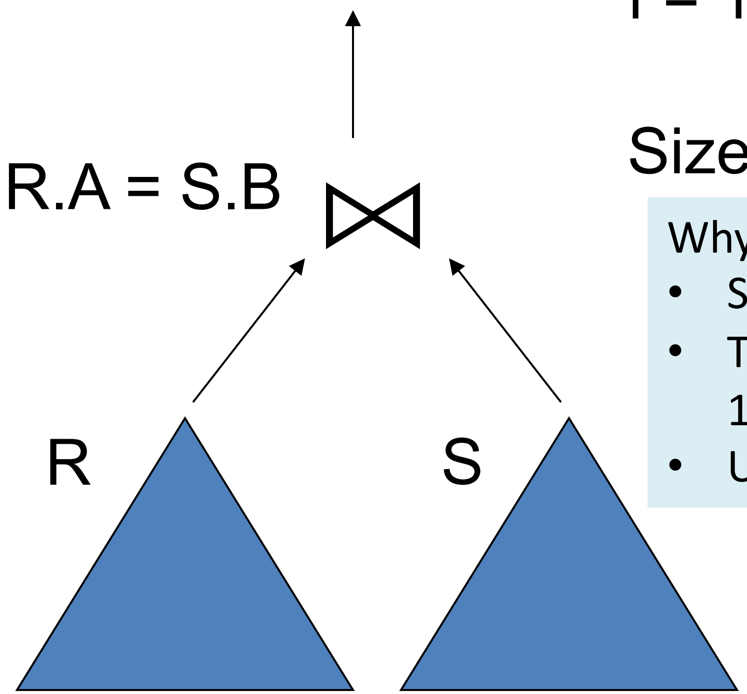
f = 1/max(V(R, A), V(S, B))

Size = T(R) * T(S) * f

T (R) : Number of tuples in R
B (R) : Number of blocks in R
V(R, A) : Number of distinct values of attribute A in R

Size of Join

Assumes index on both A and B
if one index: 1/V(…, …)
if no index: say 1/10



Reduction factor

$f = 1/\max(V(R, A), V(S, B))$

$Size = T(R) * T(S) * f$

Why max?

- Suppose V(R, A) <= V(S, B)
- The probability of a A-value joining with a B-value is 1/V(S.B) = reduction factor
- Under the two assumptions stated earlier + uniformity

T (R) : Number of tuples in R
B (R) : Number of blocks in R
V(R, A) : Number of distinct values of attribute A in R

Task 3: Combine cost of different operators in a plan

With Examples
"Given" the physical plan

- Size = #tuples, NOT #pages
- Cost = #page I/O
- but, need to consider whether the intermediate relation fits in memory, is written back to disk (or on-the-fly goes to the next operator) etc.

Example Query

Student (<u>sid</u>, name, age, address)
Book(<u>bid</u>, title, author)
Checkout(<u>sid, bid</u>, date)

Query:

```
SELECT S.name
FROM Student S, Book B, Checkout C
WHERE S.sid = C.sid
AND B.bid = C.bid
AND B.author = 'Olden Fames'
AND S.age > 12
AND S.age < 20
```

S(sid,name,age,addr)
B(bid,title,author)
C(sid,bid,date)

Assumptions

- Student: S, Book: B, Checkout: C

On disk initially

- Sid, bid foreign key in C referencing S and B resp.
- There are 10,000 Student records stored on 1,000 pages.
- There are 50,000 Book records stored on 5,000 pages.
- There are 300,000 Checkout records stored on 15,000 pages.
- There are 500 different authors.
- Student ages range from 7 to 24.

Warning: a few dense slides next ☺

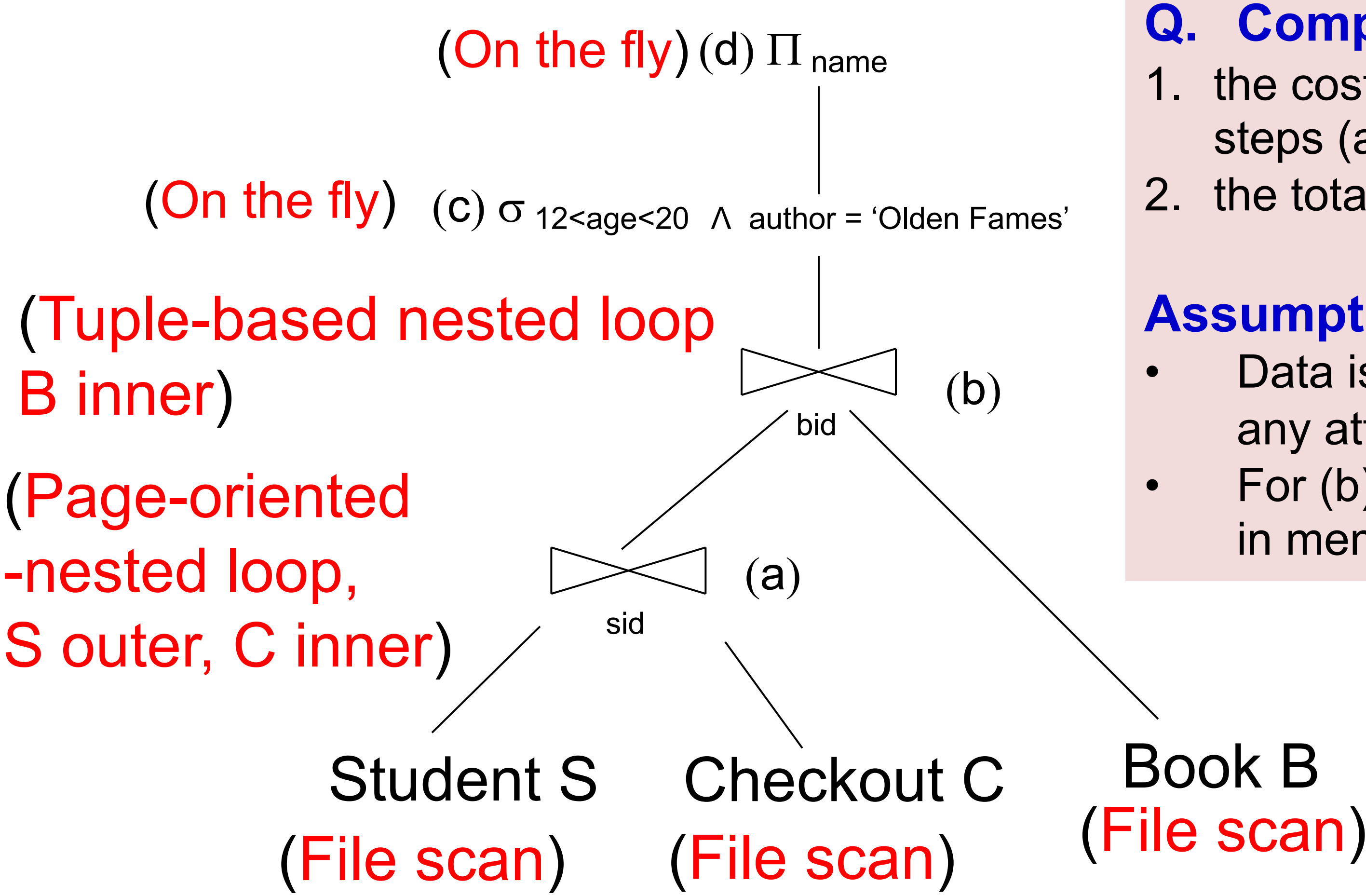
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author)
C(<u>sid</u>,<u>bid</u>,date)

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

Physical Query Plan – 1



Q. Compute

1. the cost and cardinality in steps (a) to (d)
2. the total cost

Assumptions (given):

- Data is not sorted on any attributes
- For (b), outer relation fit in memory

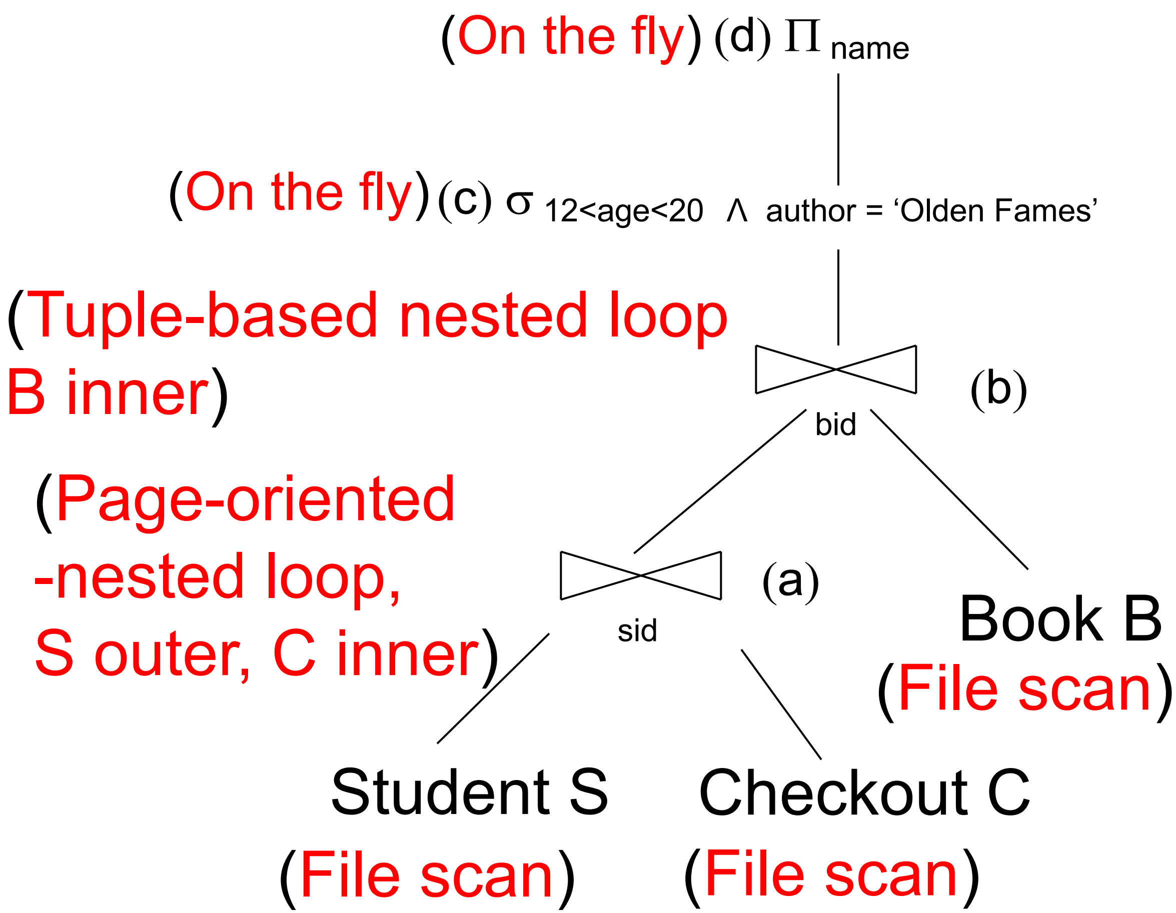
S(sid,name,age,addr)
B(bid,title,author)
C(sid,bid,date)

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(a)



Cost =
B(S) + B(S) * B(C)
= 1000 + 1000 * 15000
= 15,001,000

Cardinality =
T(C) = 300,000

- foreign key join, output pipelined to next join
- Can apply the "formula" as well

T(S) * T(C)/max (V(S, sid), V(C, sid))
= T(C)
since V(S, sid) > = V(C, sid)
and T(S) = V(S, sid)

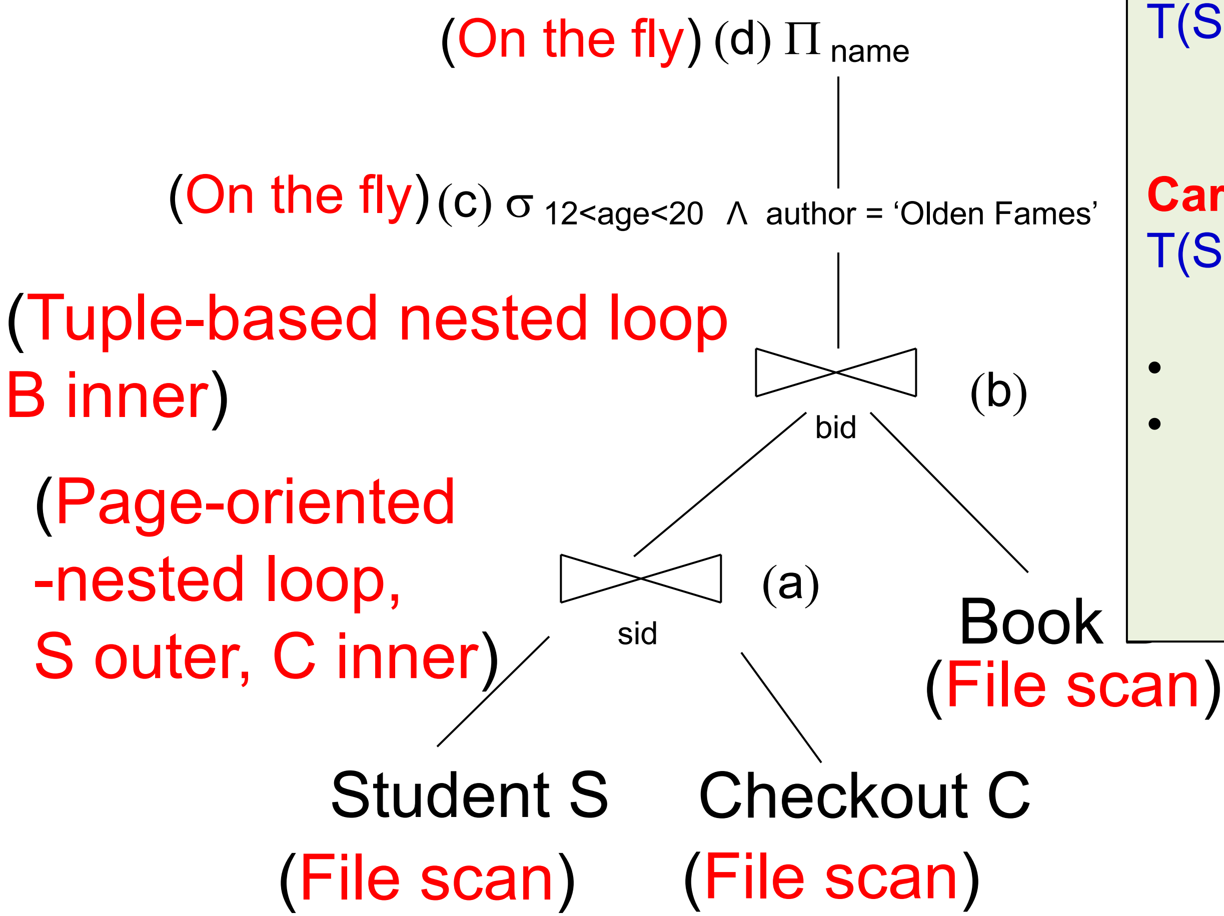
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author)
C(<u>sid,bid</u>,date)

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(b)



Cost =
$T(S \bowtie C) * B(B)$
$= 300{,}000 * 5{,}000 = 15 * 10^8$

Cardinality =
$T(S \bowtie C) = 300{,}000$

- foreign key join
- don't need scanning for outer relation
    - outer relation fits in memory

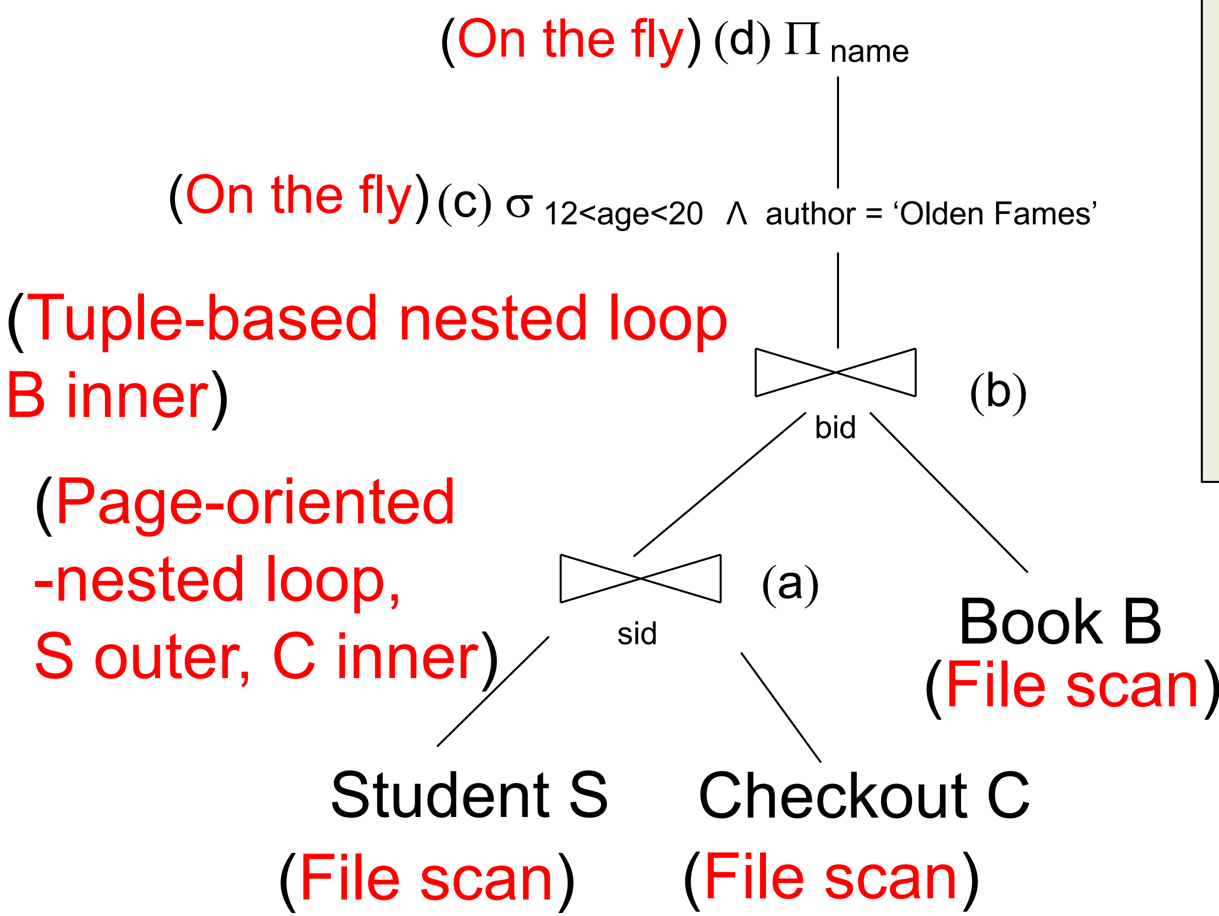
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author)
C(<u>sid,bid</u>,date)

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(c, d)



Cost =
0 (on the fly)

Cardinality =
300,000 * 1/500 * 7/18
= 234 (approx)
(assuming uniformity and independence)

S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author)
C(<u>sid,bid</u>,date)

T(S)=10,000
T(B)=50,000
T(C)=300,000

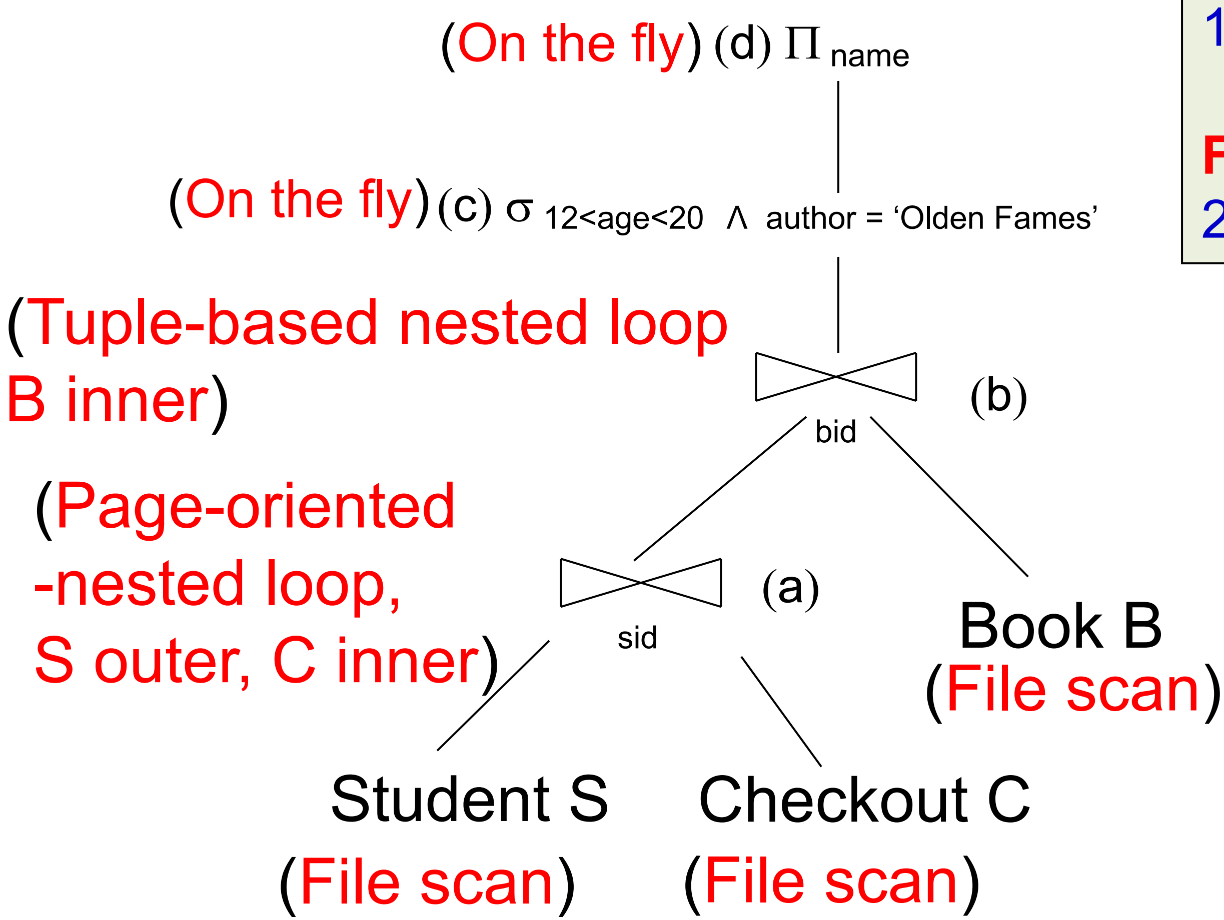
B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(Total)

Total cost =
1,515,001,000

Final cardinality =
234 (approx)



S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author)
C(<u>sid,bid</u>,date)

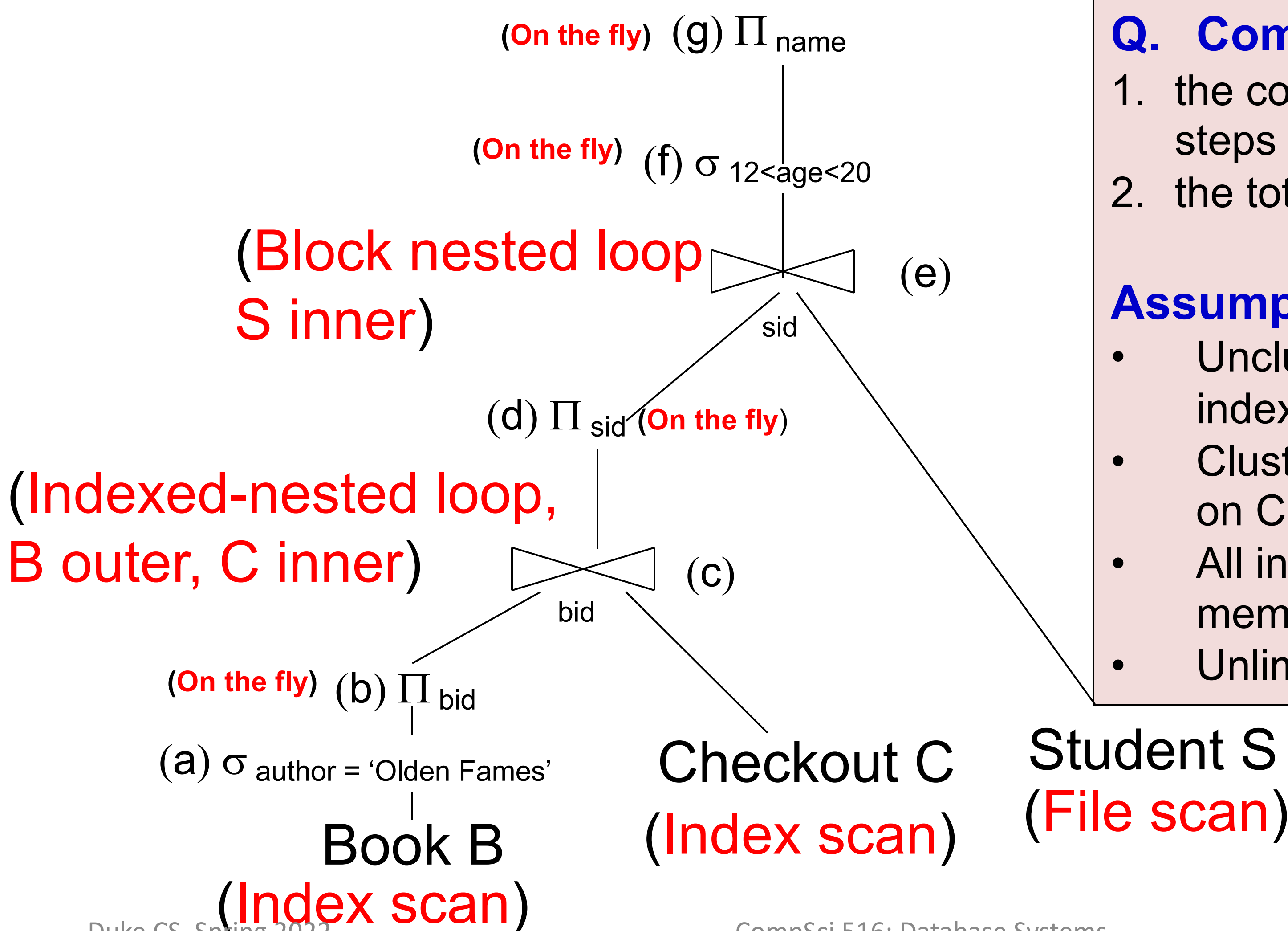
T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

V(B,author) = 500
7 <= age <= 24

Physical Query Plan – 2



Q. Compute

1. the cost and cardinality in steps (a) to (g)
2. the total cost

Assumptions (given):

- Unclustered B+tree index on B.author
- Clustered B+tree index on C.bid
- All index pages are in memory
- Unlimited memory

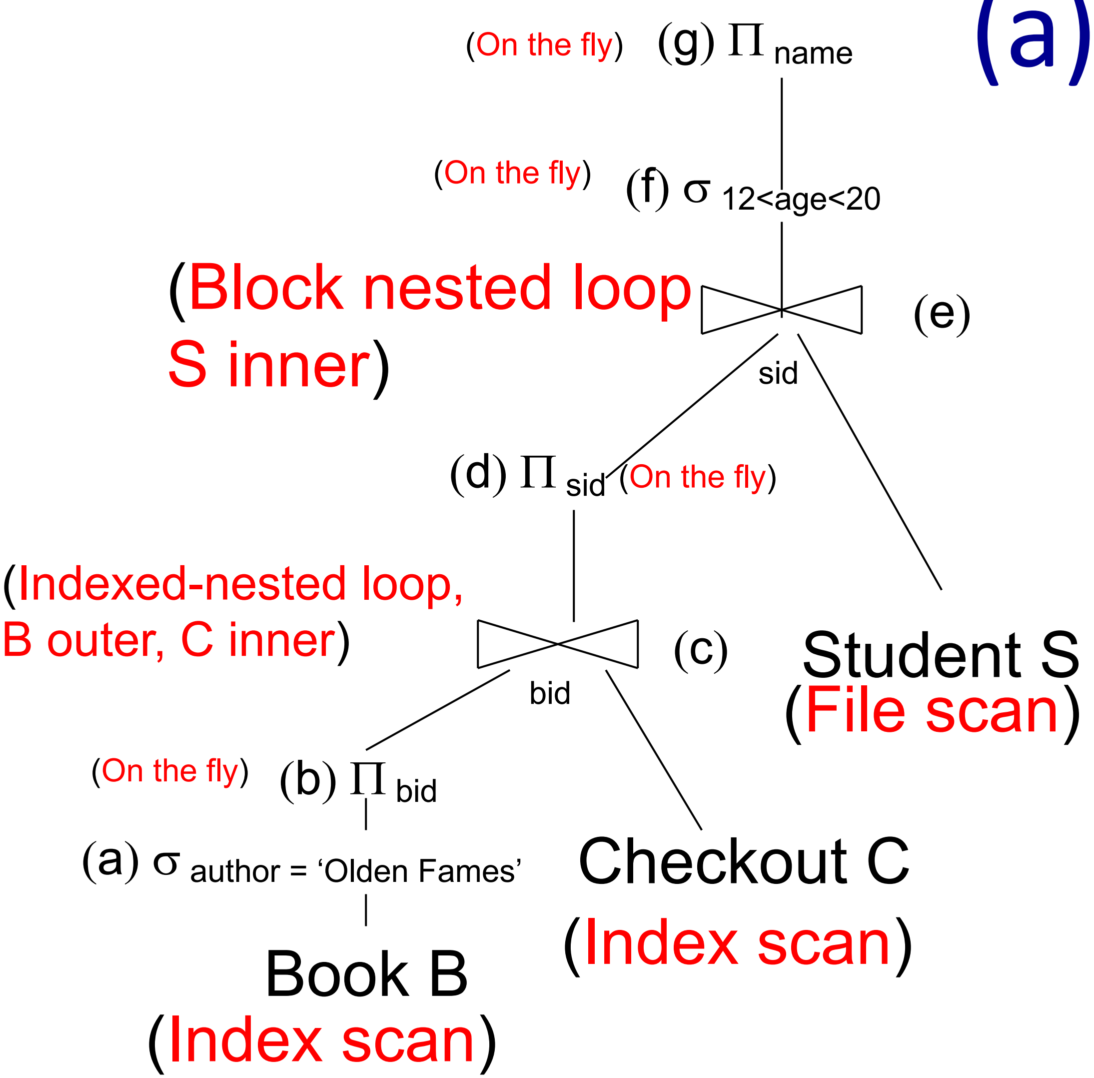
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author): Un. B+ on author
C(<u>sid,bid</u>,date): Cl. B+ on bid

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(a)



Cost =
T(B) / V(B, author)
= 50,000/500
= 100 (unclustered)

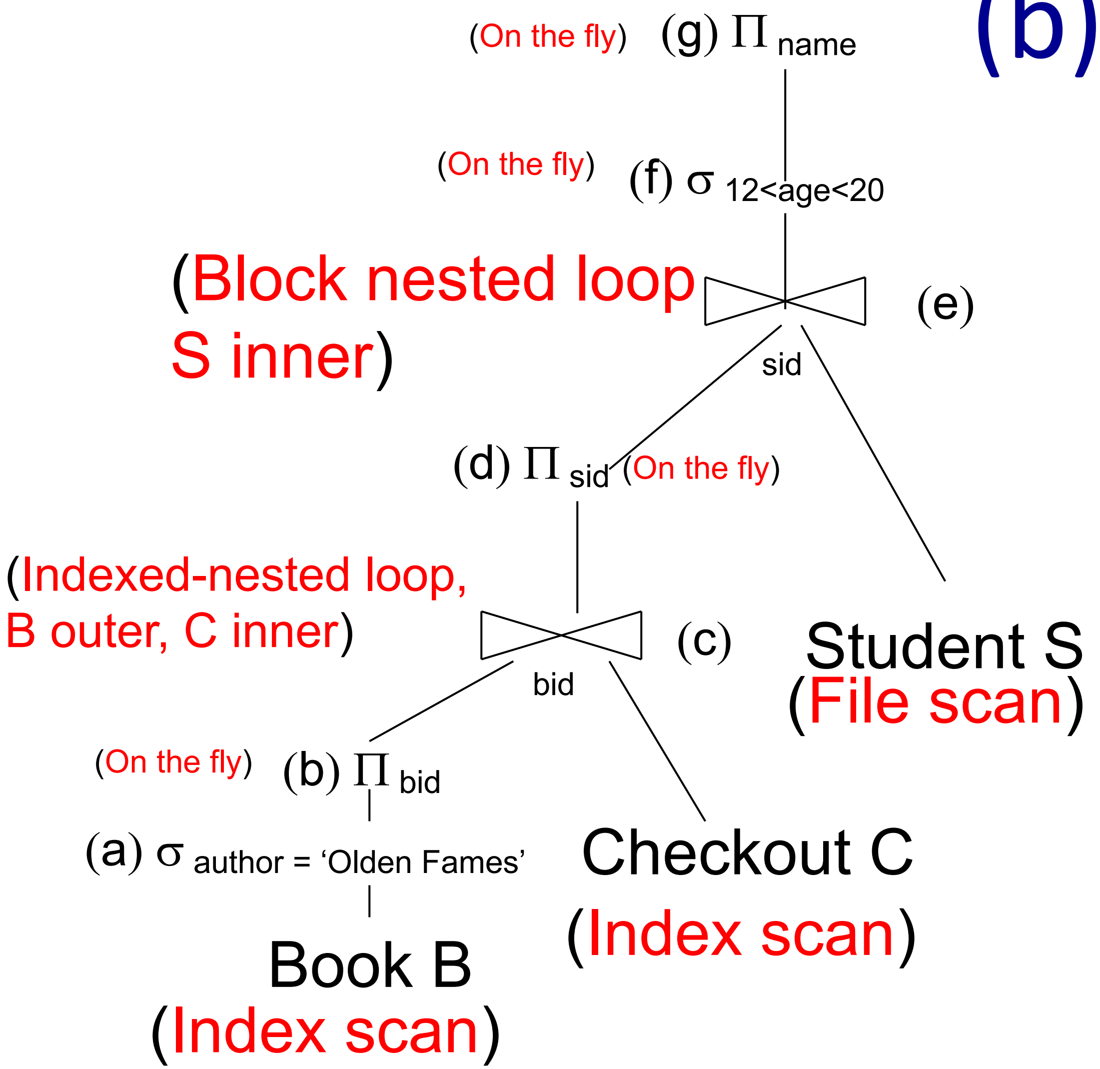
Cardinality =
100

S(sid,name,age,addr)
B(bid,title,author): Un. B+ on author
C(sid,bid,date): Cl. B+ on bid

T(S)=10,000 B(S)=1,000
T(B)=50,000 B(B)=5,000
T(C)=300,000 B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(b)



Cost =
0 (on the fly)

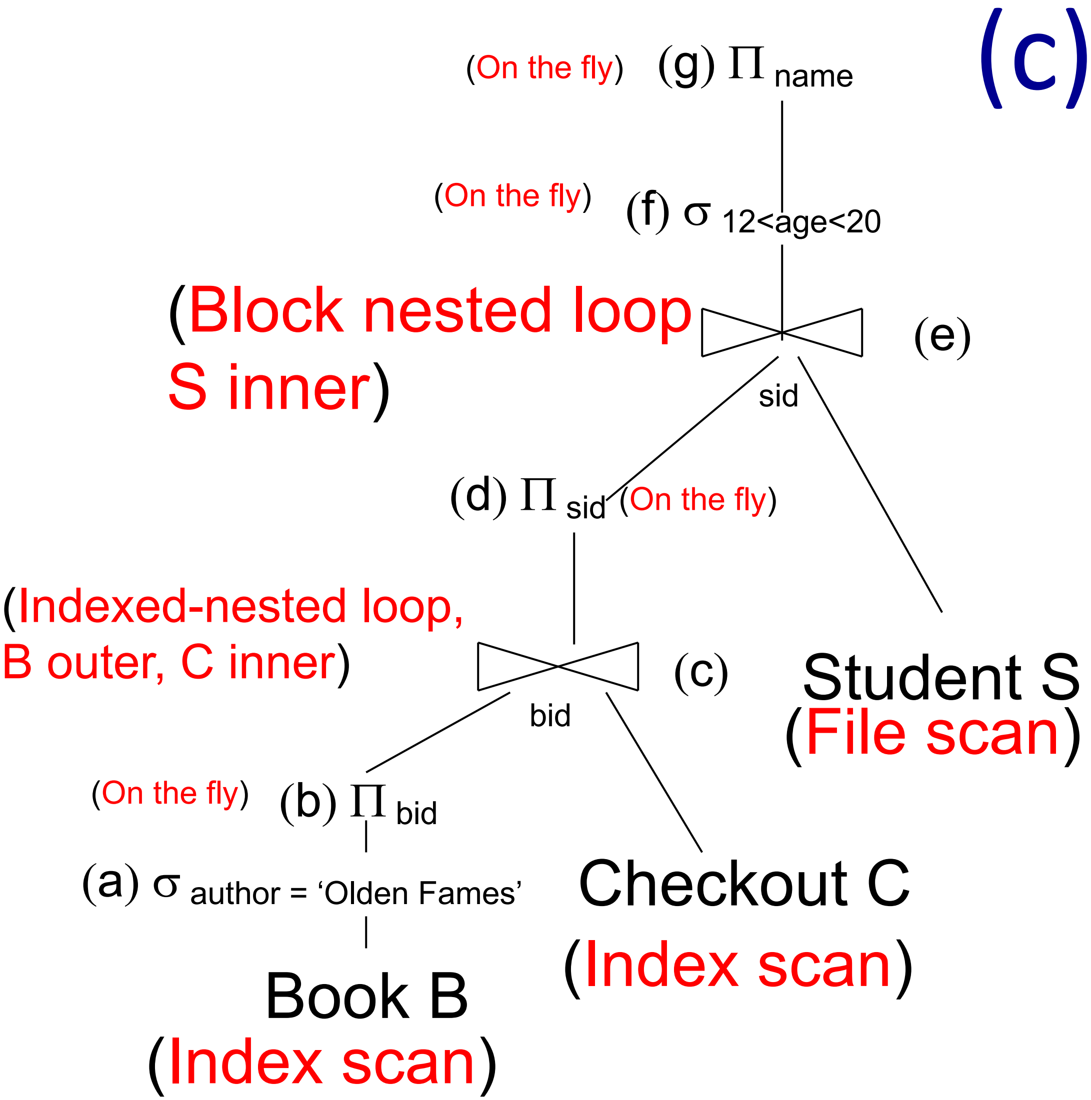
Cardinality =
100

S(sid,name,age,addr)
B(bid,title,author): Un. B+ on author
C(sid,bid,date): Cl. B+ on bid

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24



- one index lookup per outer B tuple
- 1 book has T(C)/ T(B) = 6 checkouts (uniformity)
- # C tuples per page = T(C)/B(C) = 20
- 6 tuples fit in at most 2 consecutive pages (clustered) could assume 1 page as well

Cost <=

100 * 2= 200

Cardinality =

100 * 6 = 600

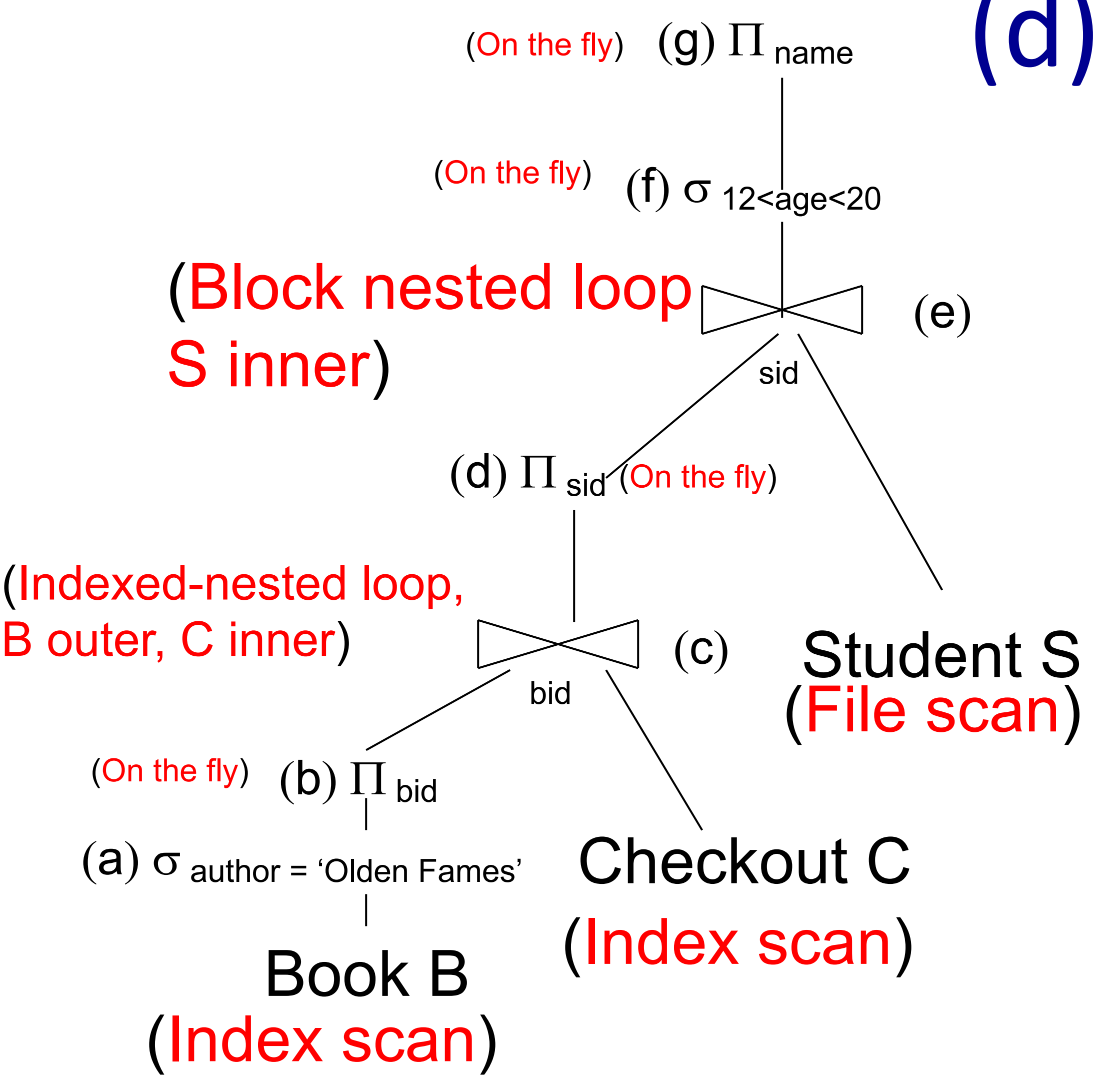
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author): Un. B+ on author
C(<u>sid,bid</u>,date): Cl. B+ on bid

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(d)



Cost =
0 (on the fly)

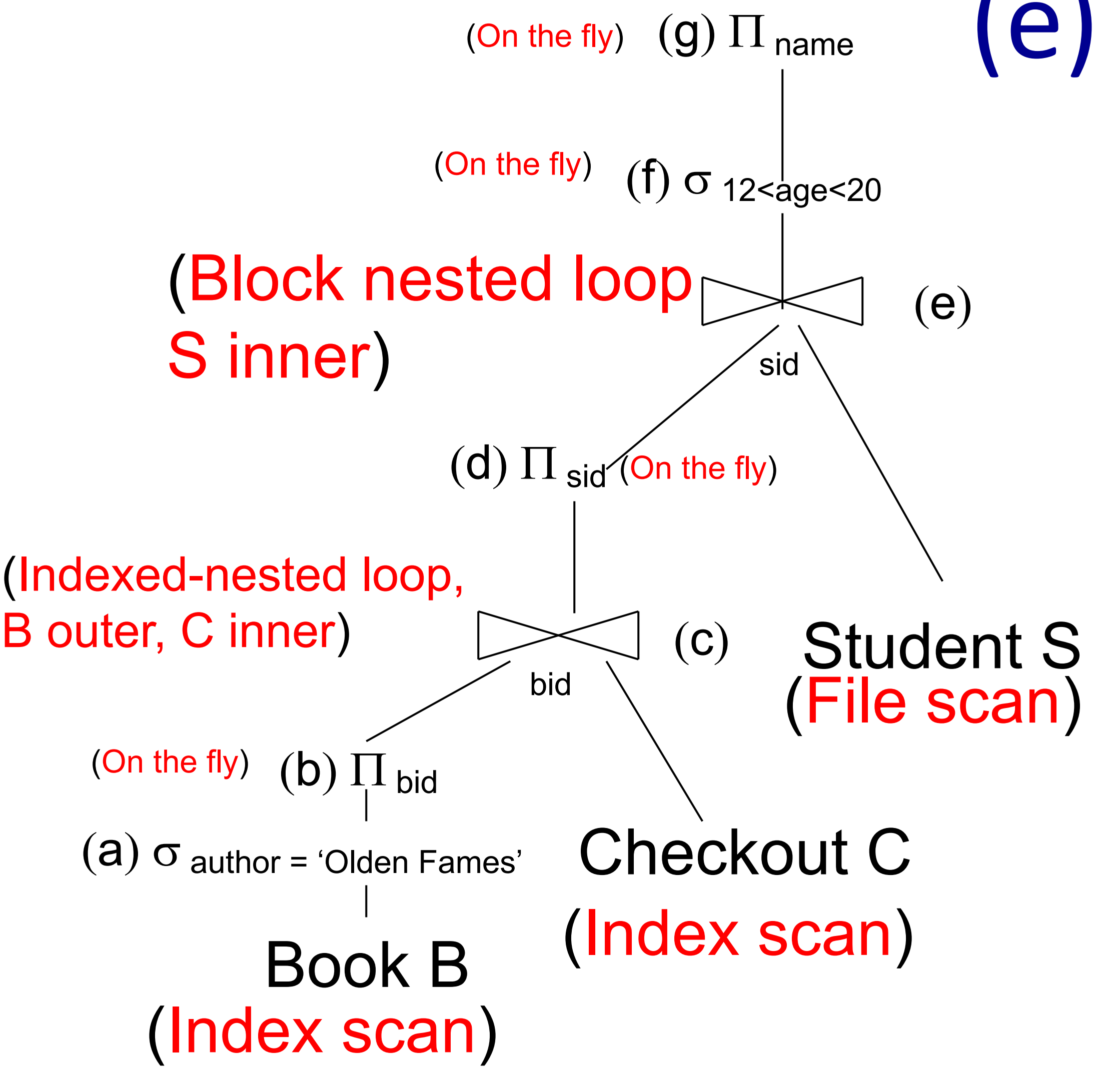
Cardinality =
600

S(sid,name,age,addr)
B(bid,title,author): Un. B+ on author
C(sid,bid,date): Cl. B+ on bid

T(S)=10,000 B(S)=1,000
T(B)=50,000 B(B)=5,000
T(C)=300,000 B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(e)



Outer relation is already in (unlimited) memory
need to scan S relation

Cost =
B(S) = 1000

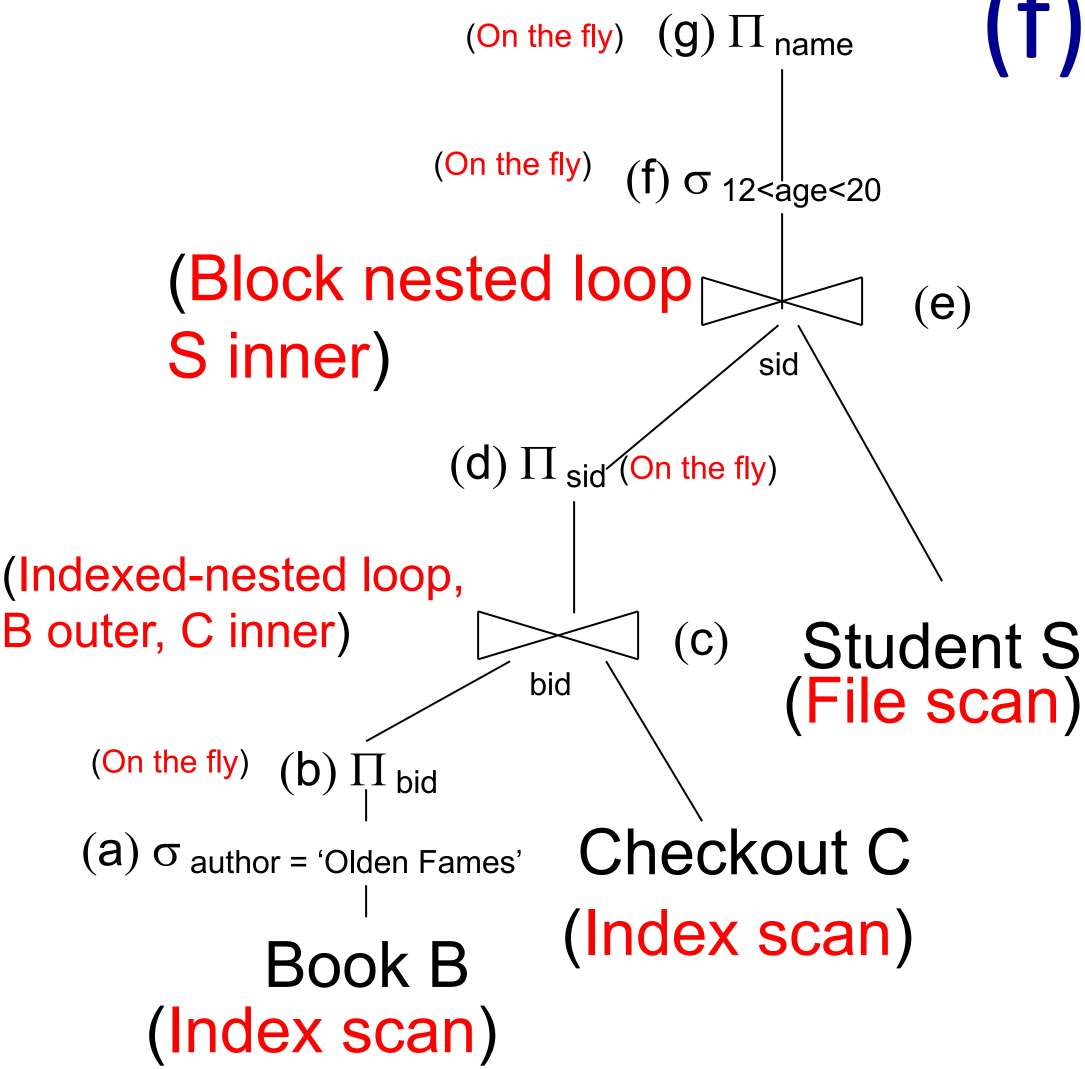
Cardinality =
600
(one student per checkout)

S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author): Un. B+ on author
C(<u>sid,bid</u>,date): Cl. B+ on bid

T(S)=10,000 B(S)=1,000
T(B)=50,000 B(B)=5,000
T(C)=300,000 B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(f)



Cost =
0 (on the fly)

Cardinality =
600 * 7/18 = 234 (approx)

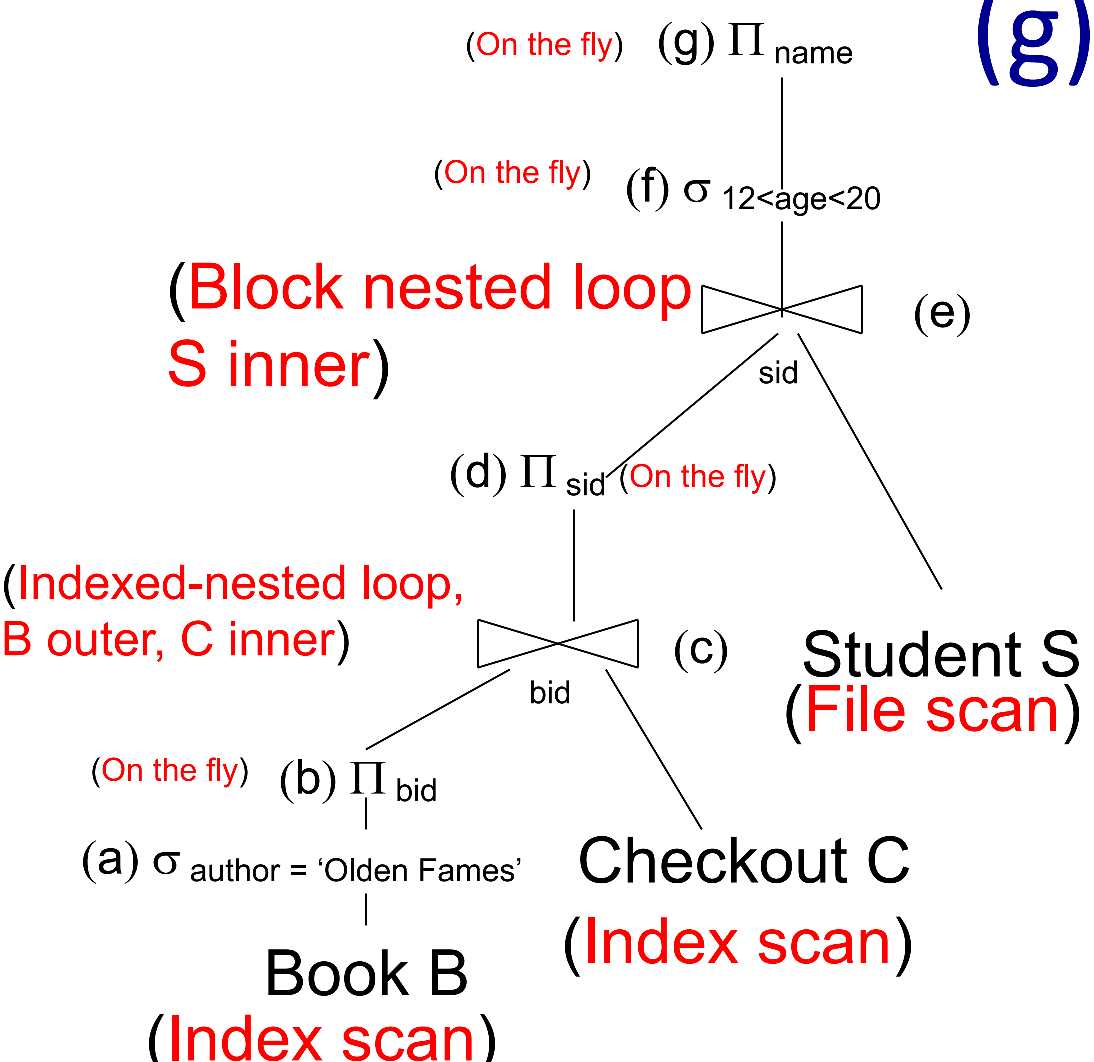
S(sid,name,age,addr)
B(bid,title,author): Un. B+ on author
C(sid,bid,date): Cl. B+ on bid

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(g)



Cost =
0 (on the fly)

Cardinality =
234

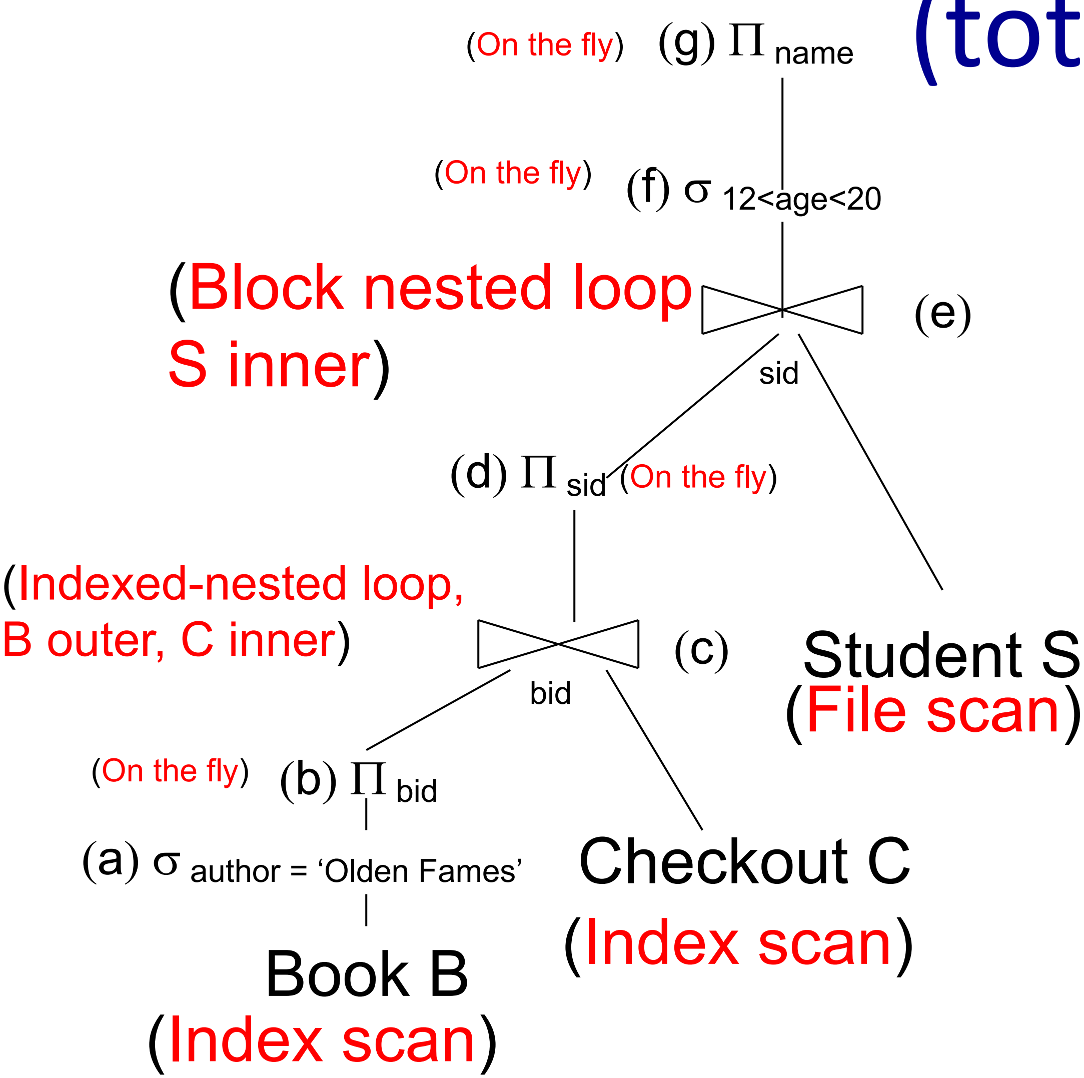
S(<u>sid</u>,name,age,addr)
B(<u>bid</u>,title,author): Un. B+ on author
C(<u>sid,bid</u>,date): Cl. B+ on bid

T(S)=10,000
T(B)=50,000
T(C)=300,000

B(S)=1,000
B(B)=5,000
B(C)=15,000

V(B,author) = 500
7 <= age <= 24

(total)



Total cost =
1300
(compare with 1,515,001,000 for plan 1!)

Final cardinality =
234 (approx)
(same as plan 1!)

Task 4:
Efficiently searching the plan space

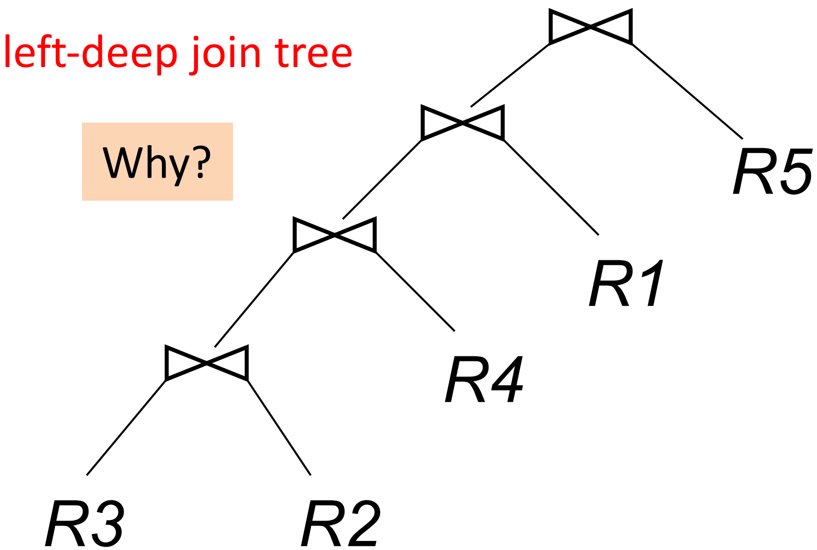
Use dynamic-programming based
Selinger's algorithm!

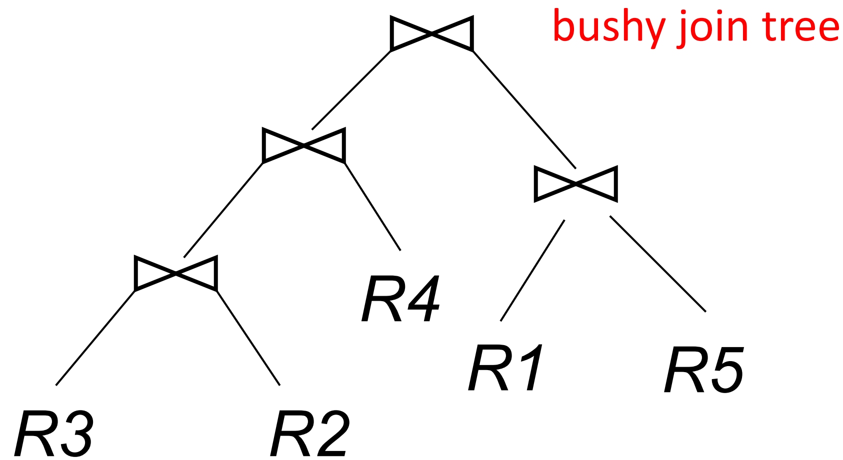
Heuristics for pruning plan space

- Apply predicates as early as possible
- Avoid plans with cross products
- Consider only left-deep join trees

Join Trees

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4 \bowtie R5$





(logical plan space)

- Several possible structure of the trees
- Each tree can have n! permutations of relations on leaves

(physical plan space)

- Different implementation and scanning of intermediate operators for each logical plan

Selinger Algorithm

- Dynamic Programming based

- Dynamic Programming:
  - General algorithmic paradigm
  - Exploits "principle of optimality"
    - Useful reading: Chapter 16, Introduction to Algorithms, Cormen, Leiserson, Rivest

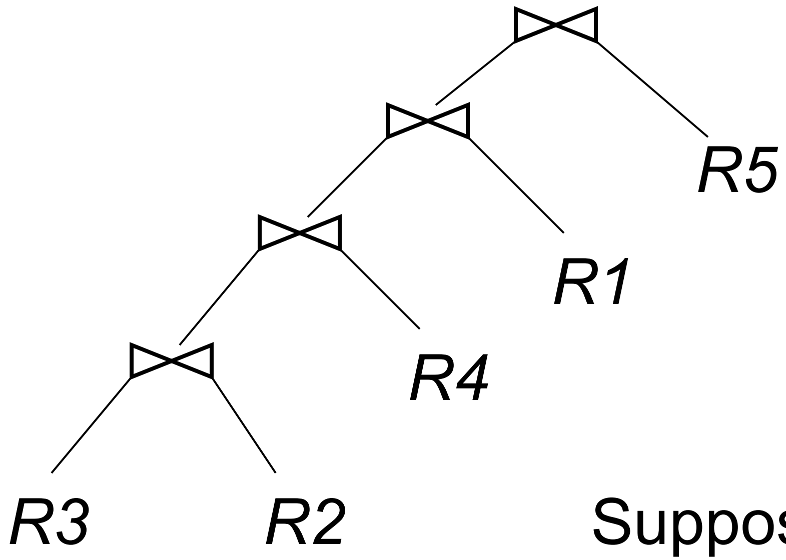
- Considers the search space of left-deep join trees
  - reduces search space (only one structure)
  - but still n! permutations
  - interacts well with join algos (esp. NLJ)
  - e.g., might not need to write tuples to disk if enough memory

Principle of Optimality

Optimal for “whole” made up from optimal for “parts”

Principle of Optimality

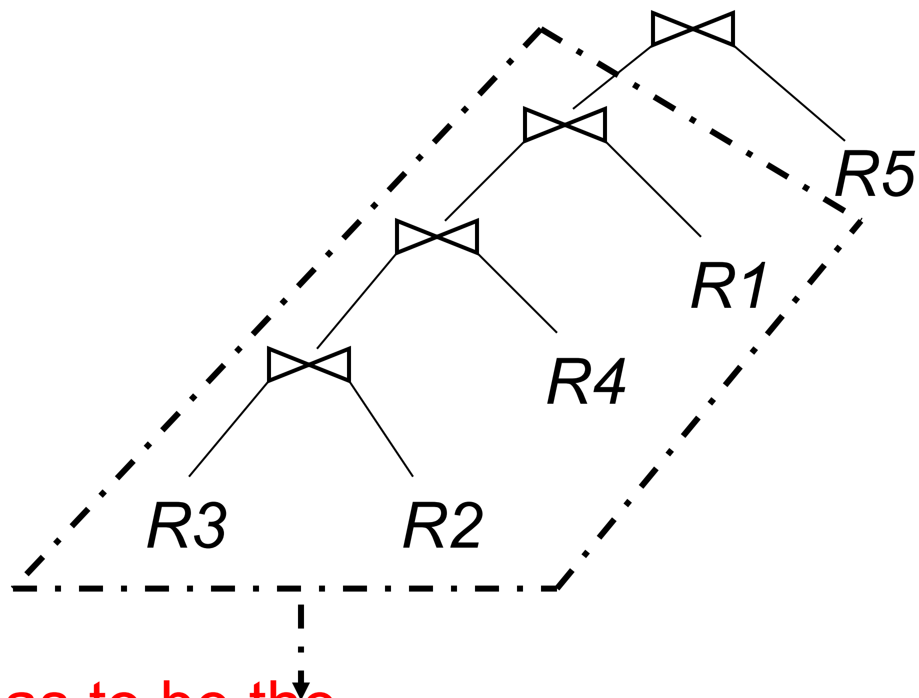
Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4 \bowtie R5$



Suppose,
this is an Optimal Plan
for joining R1…R5:

Principle of Optimality

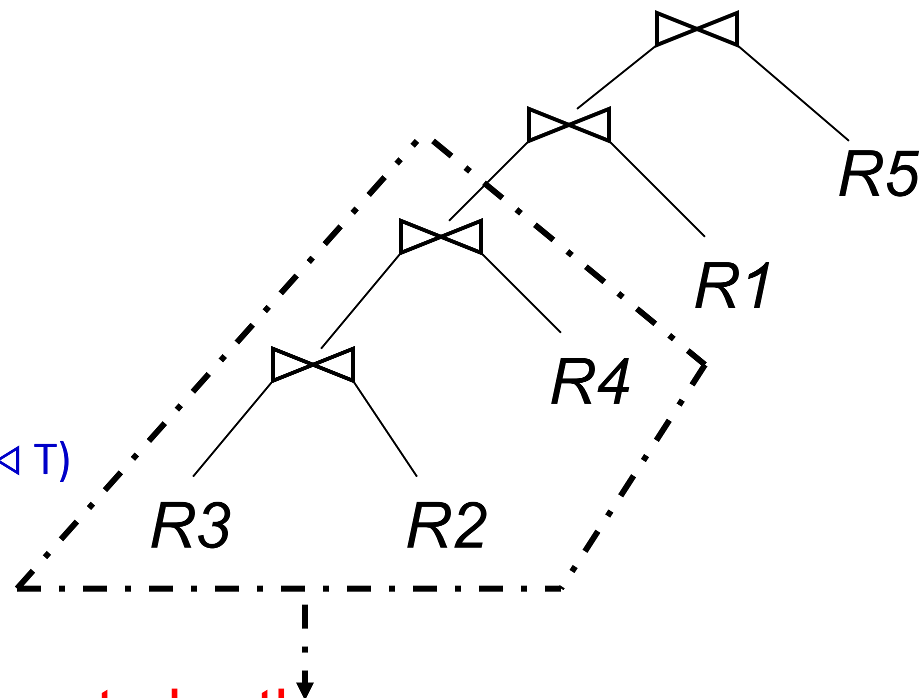
Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4 \bowtie R5$



This has to be the
optimal plan for joining *R3, R2, R4, R1*

Principle of Optimality

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4 \bowtie R5$



We are using the associativity and commutativity of joins

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

$R \bowtie S = S \bowtie R$

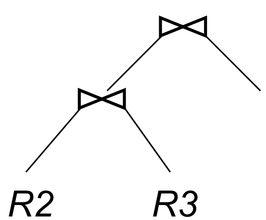
This has to be the optimal plan for joining *R3, R2, R4*

Exploiting Principle of Optimality

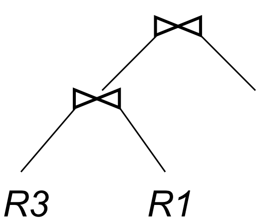
Query: $R1 \bowtie R2 \bowtie \quad \ldots \quad \bowtie Rn$

Both are giving the same result

R2 ⋈ R3 ⋈ R1 = R3 ⋈ R1 ⋈ R2

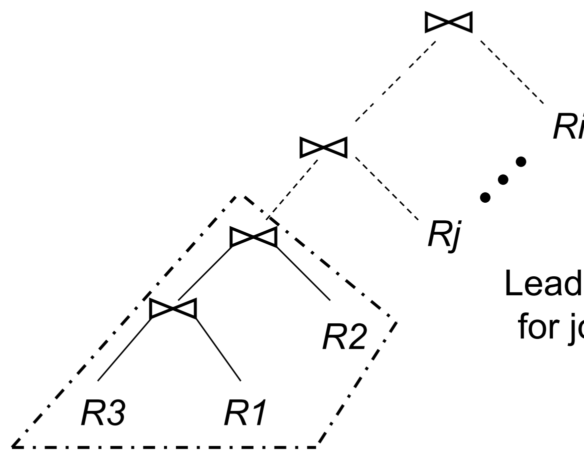


Optimal
for joining *R1, R2, R3*



Sub-Optimal
for joining *R1, R2, R3*

Suppose you chose the sub-optimal one



Leads to sub-Optimal for joining R1,…,Rn

Notation

OPT ({ *R1, R2, R3* }):

Cost of optimal plan to join *R1,R2,R3*

T ({ *R1, R2, R3* }):

Number of tuples in $R1 \bowtie R2 \bowtie R3$

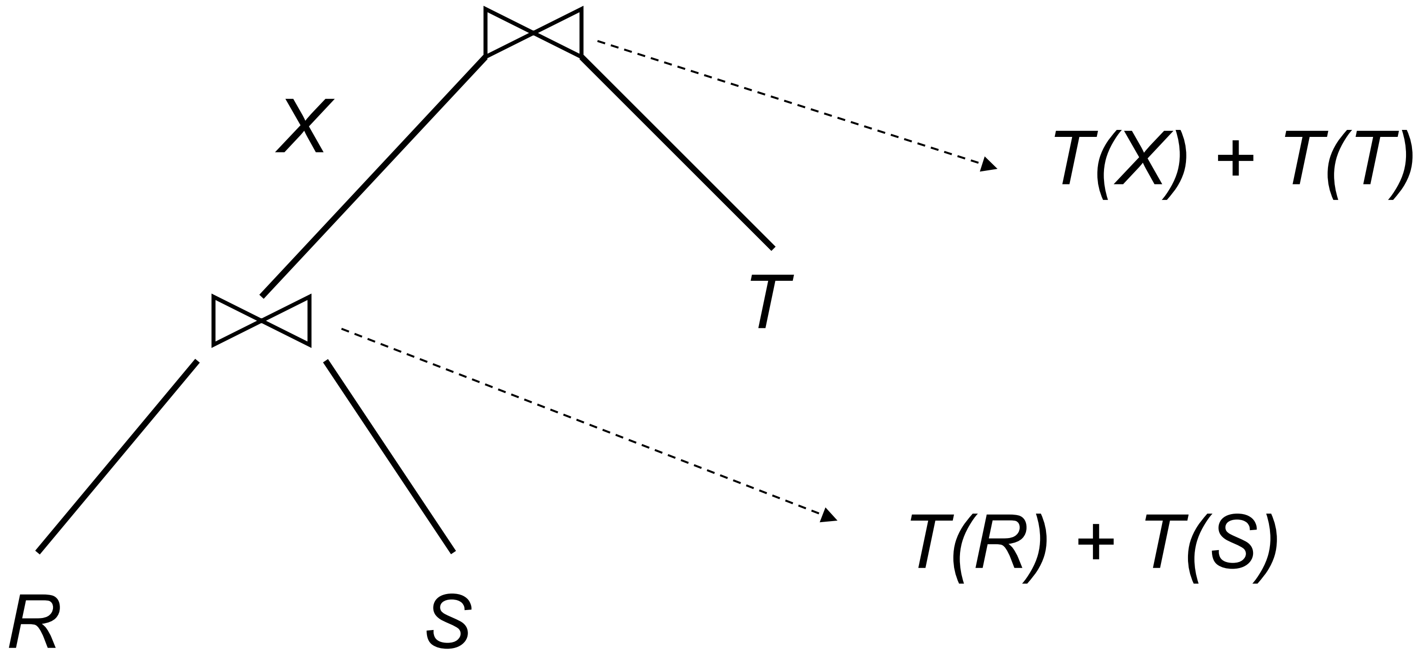
Simple Cost Model

$$\text{Cost}\ (R \bowtie S) = T(R) + T(S)$$

All other operators have 0 cost

Note: The simple cost model used for illustration only, it is not used in practice

Cost Model Example



$$\boxed{\text{Total Cost: } T(R) + T(S) + T(T) + T(X)}$$

Selinger Algorithm:

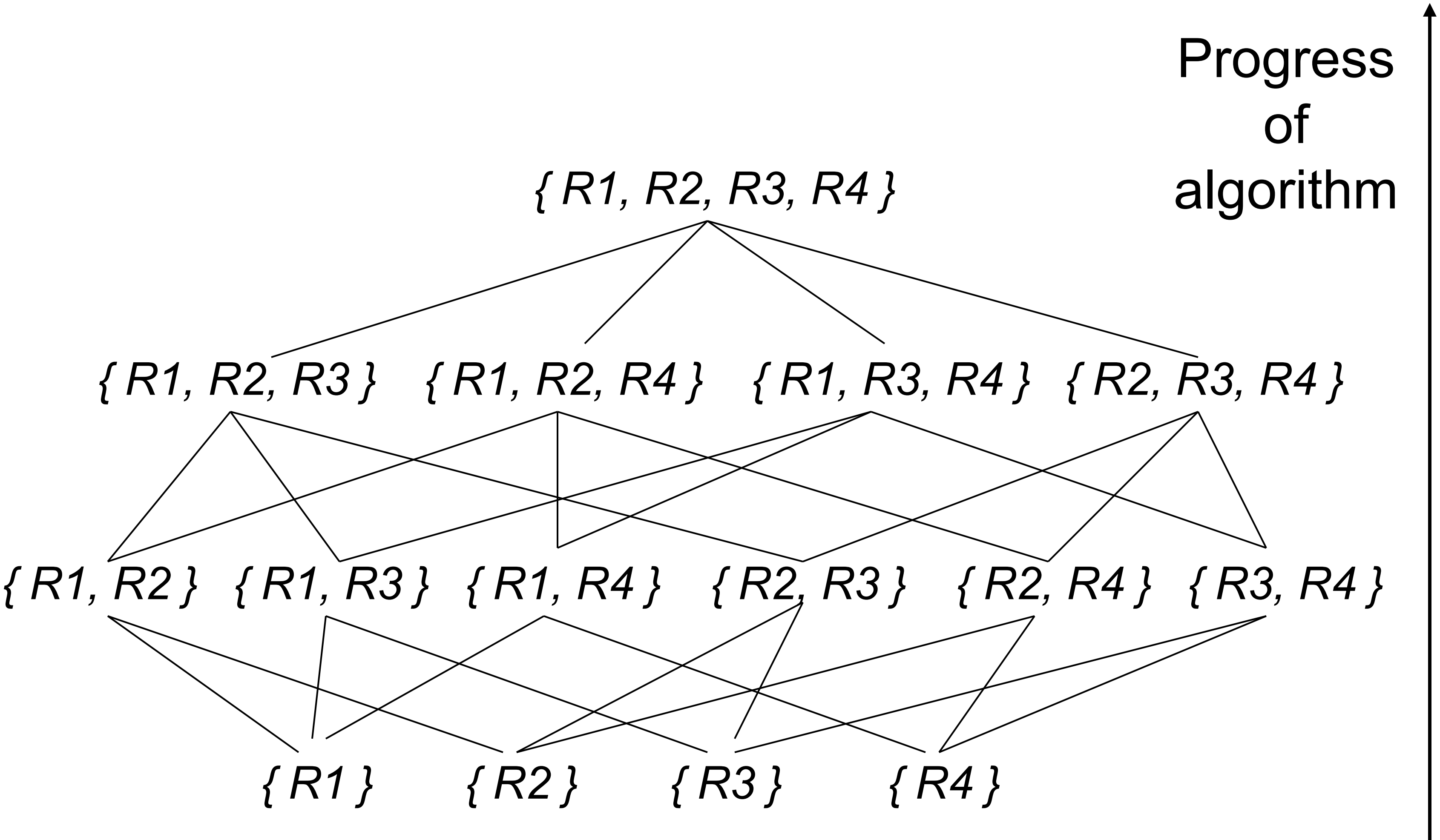
OPT ({ R1, R2, R3 }):

$$\text{Min} \begin{cases} \text{OPT}(\{R1, R2\}) + T(\{R1, R2\}) + T(R3) \\ \text{OPT}(\{R2, R3\}) + T(\{R2, R3\}) + T(R1) \\ \text{OPT}(\{R1, R3\}) + T(\{R1, R3\}) + T(R2) \end{cases}$$

Note: Valid only for the simple cost model

Selinger Algorithm:

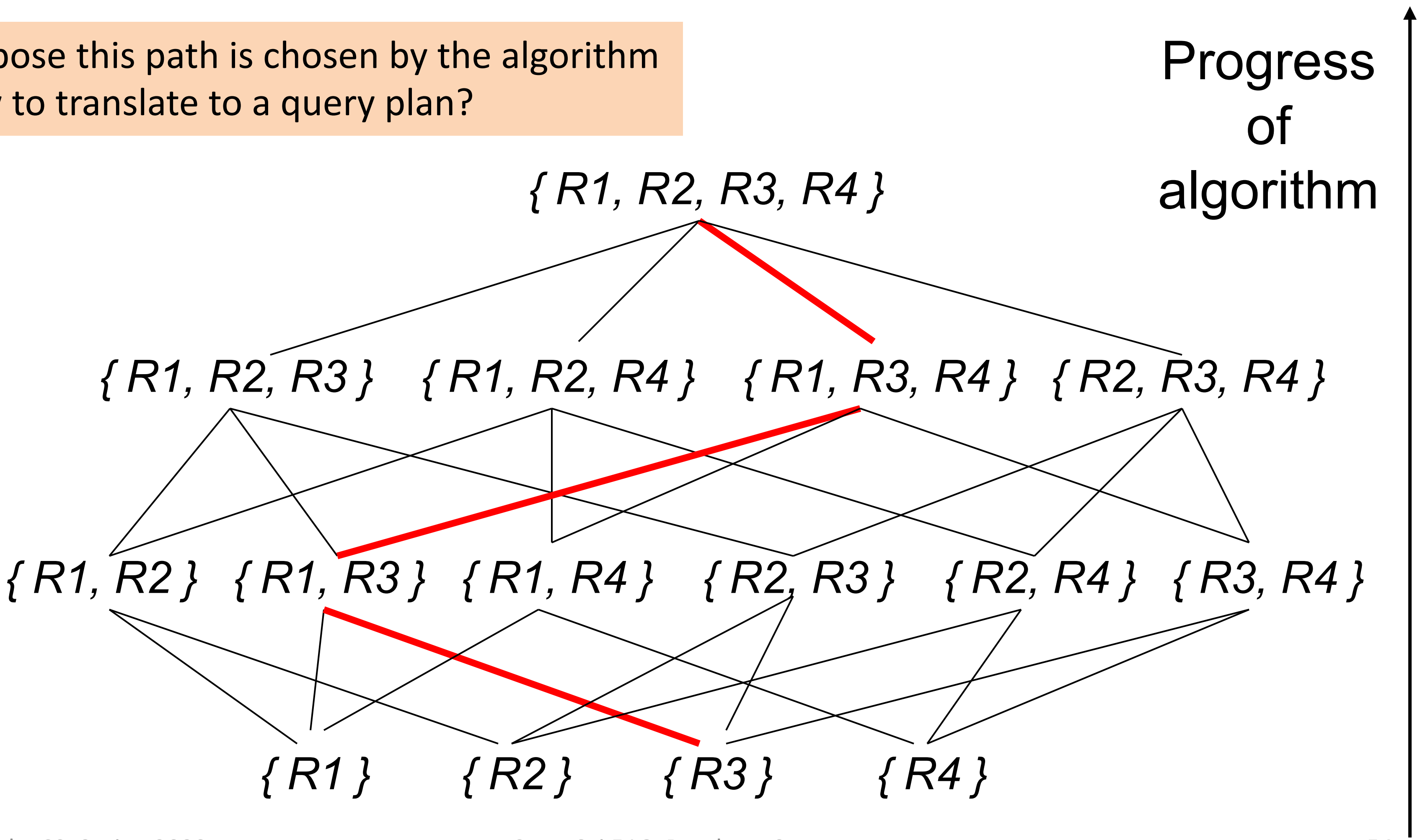
Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$



Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Suppose this path is chosen by the algorithm
How to translate to a query plan?

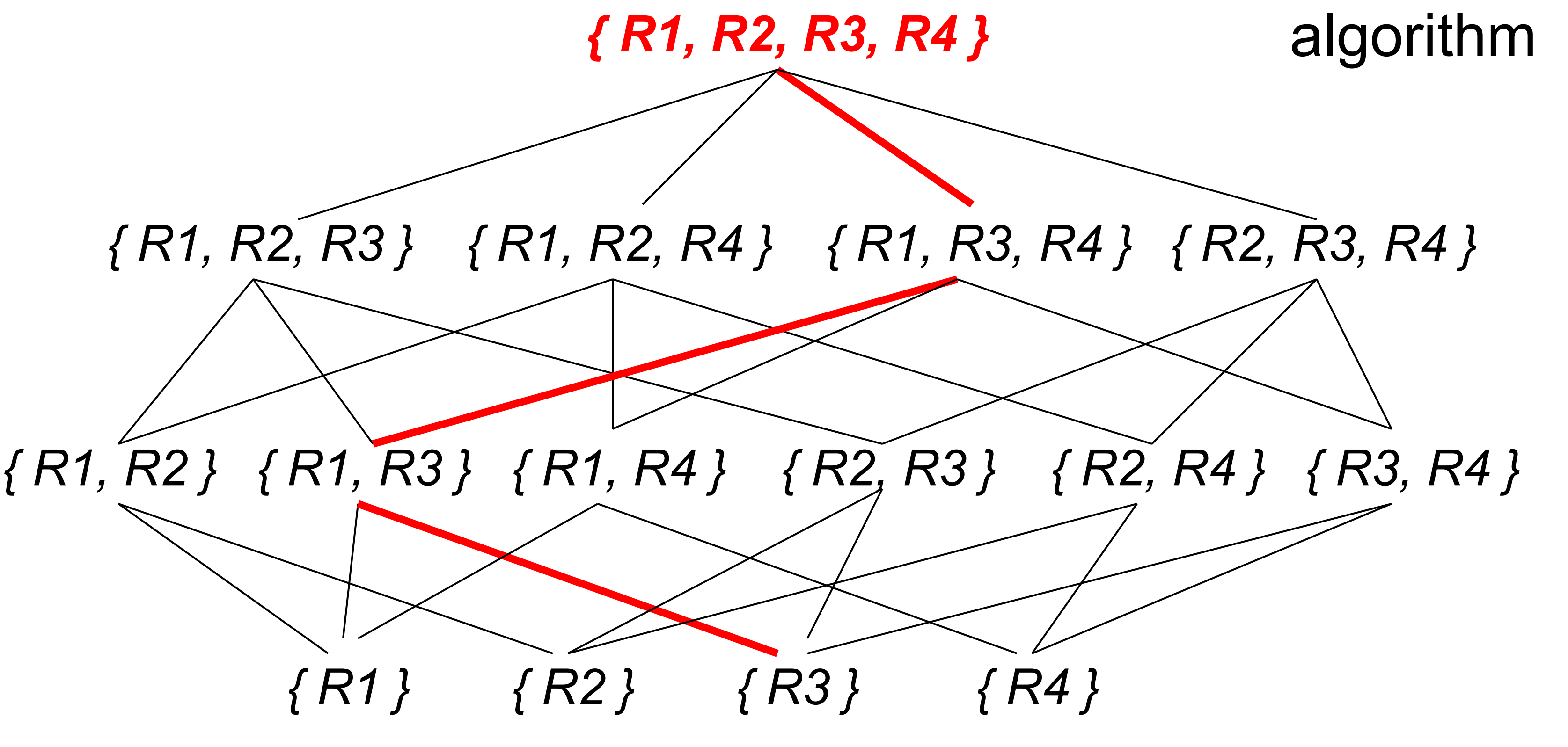


Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Q. How to optimally compute join of {R1, R2, R3, R4}?

Ans: First optimally join {R1, R3, R4} then join with R2 as inner.

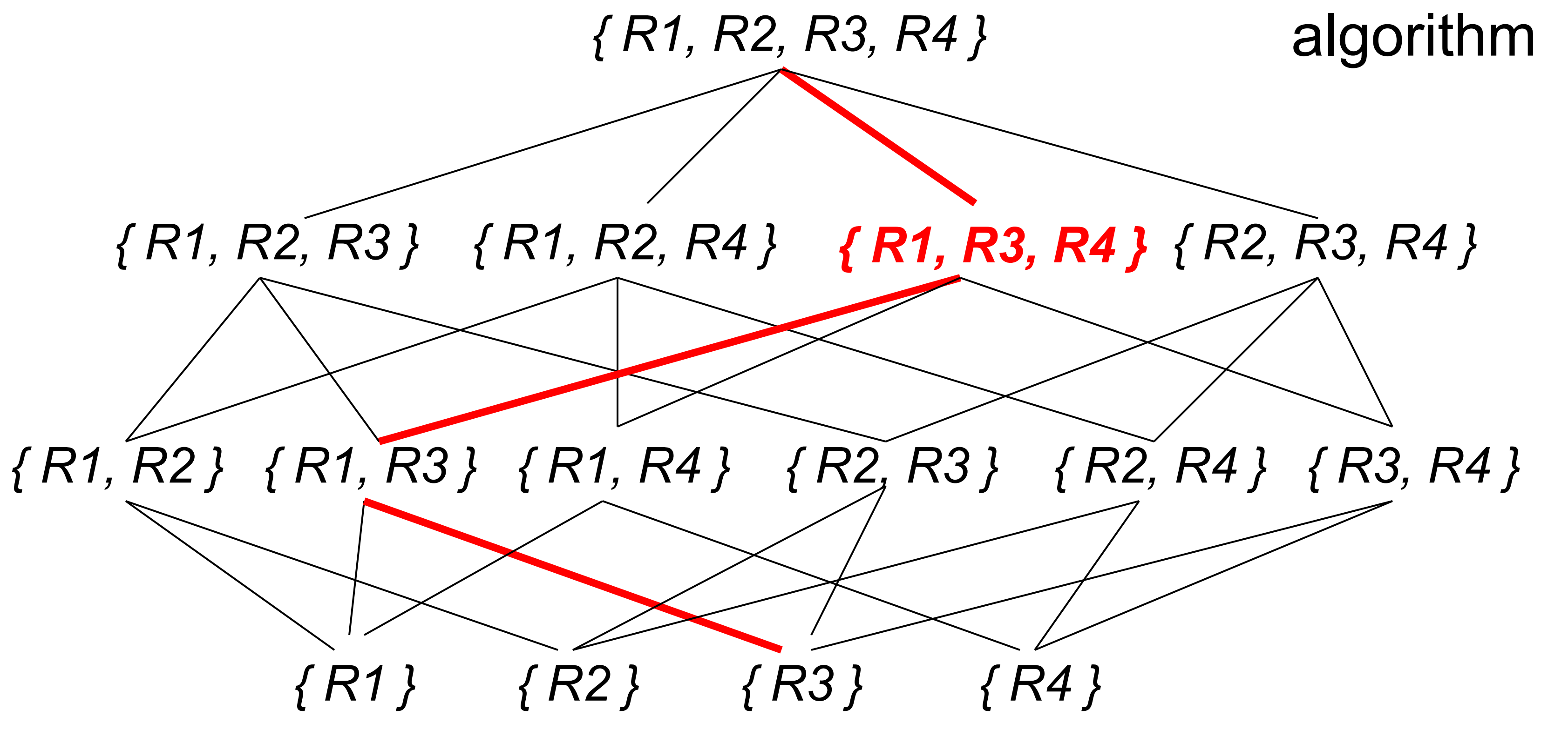


Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Q. How to optimally compute join of {R1, R3, R4}?

Ans: First optimally join {R1, R3}, then join with R4 as inner.

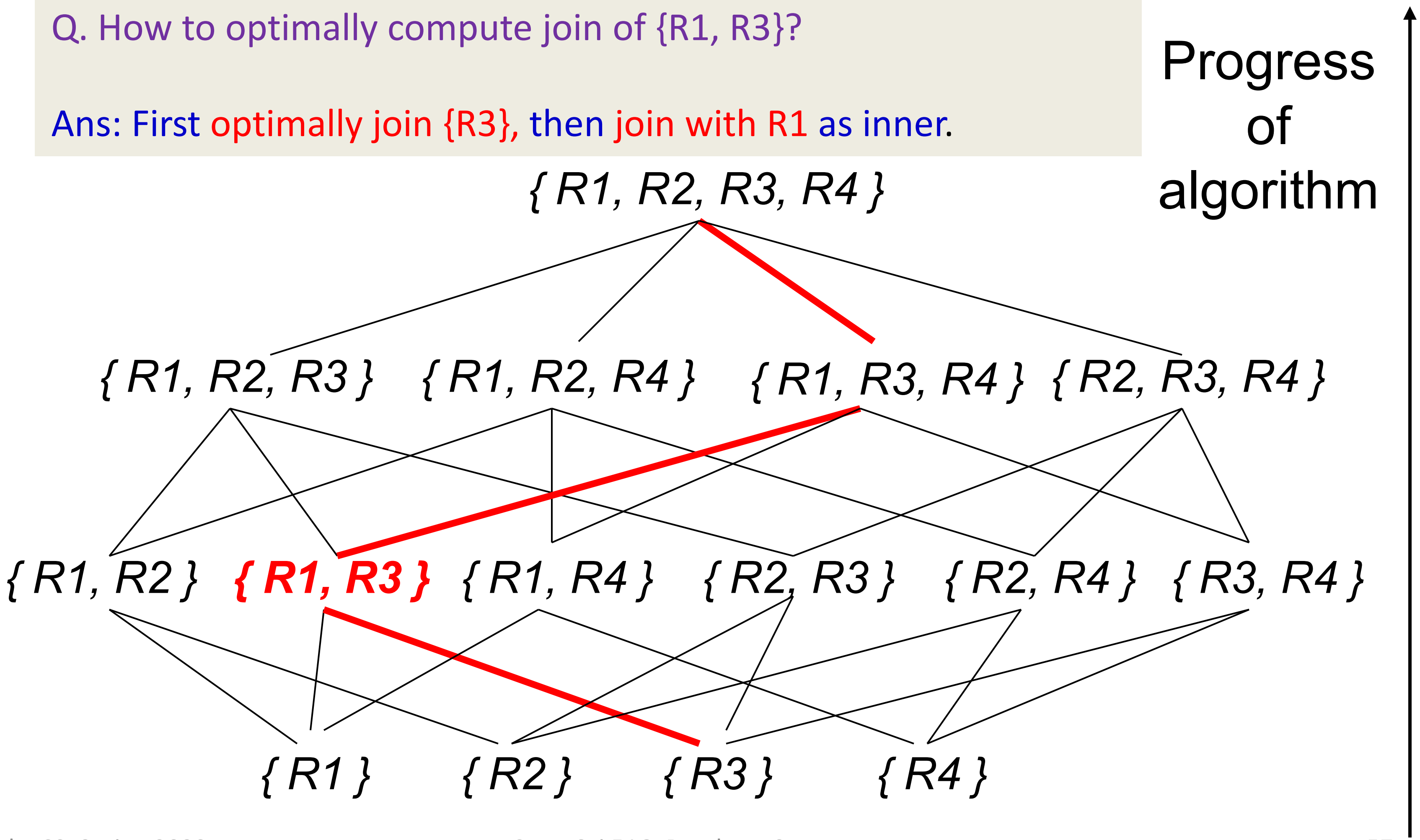


Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Q. How to optimally compute join of {R1, R3}?

Ans: First optimally join {R3}, then join with R1 as inner.

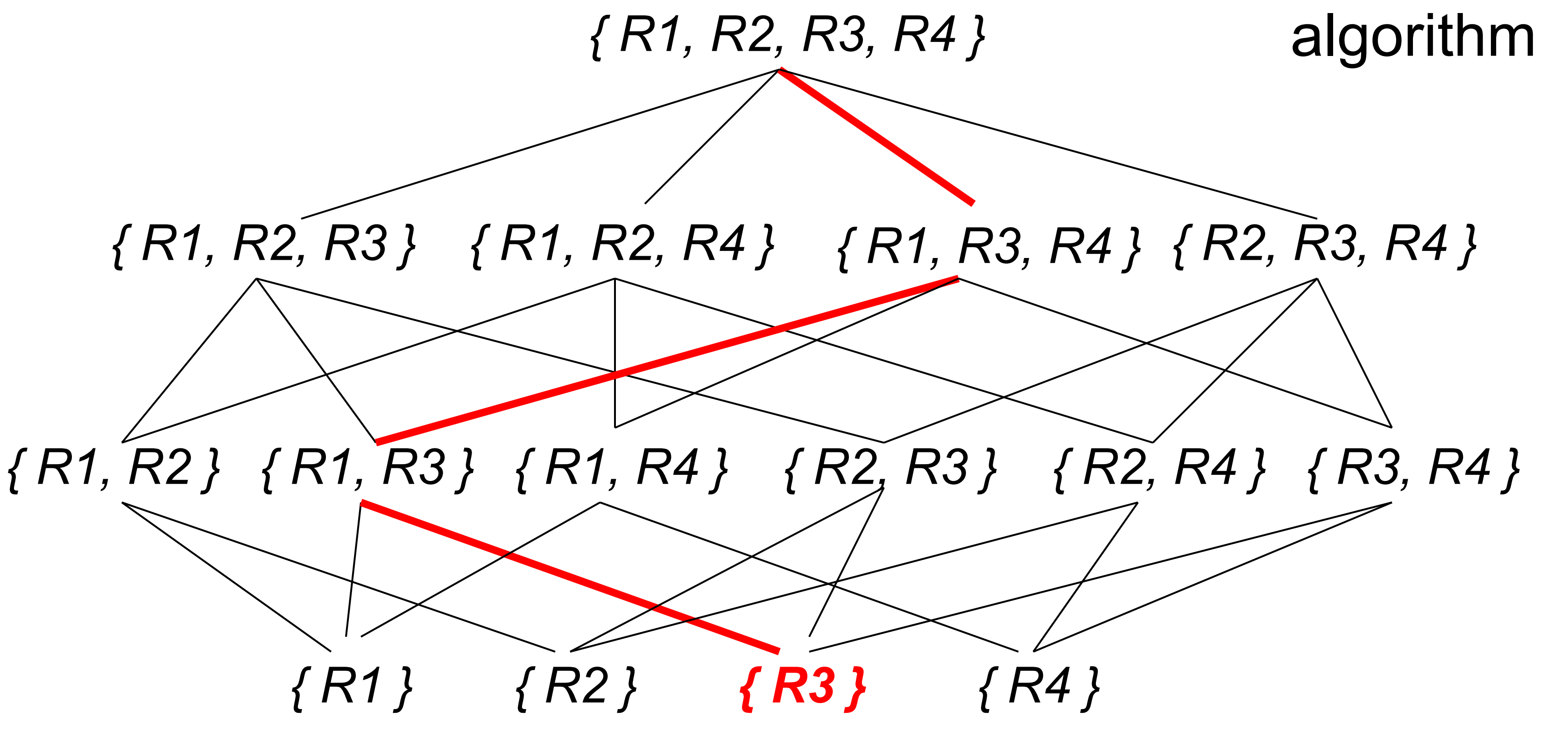


Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Q. How to optimally compute join of {R3}?

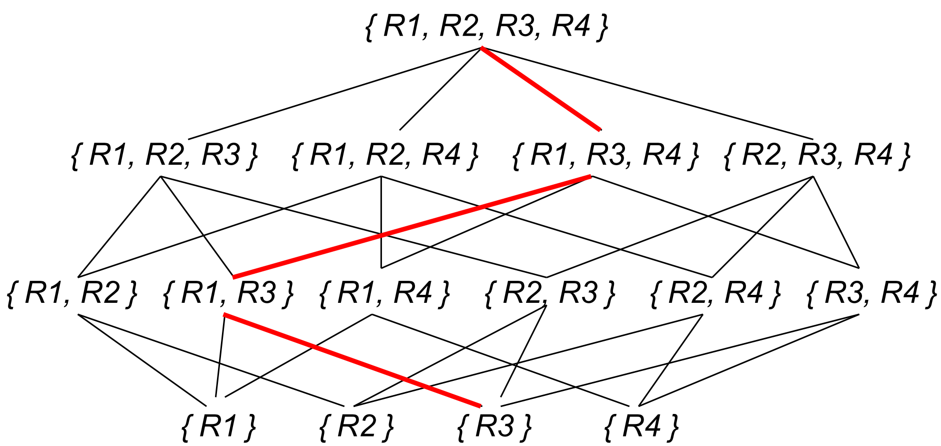
Ans: Single relation – so optimally scan R3.

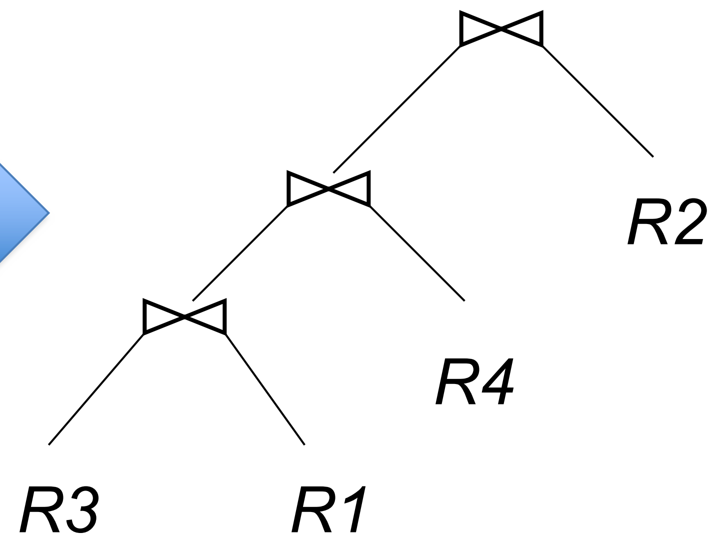


Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

Final optimal plan:





NOTE : There is a one-one correspondence between the permutation (R3, R1, R4, R2) and the above left deep plan

Selinger Algorithm:

Query: $R1 \bowtie R2 \bowtie R3 \bowtie R4$

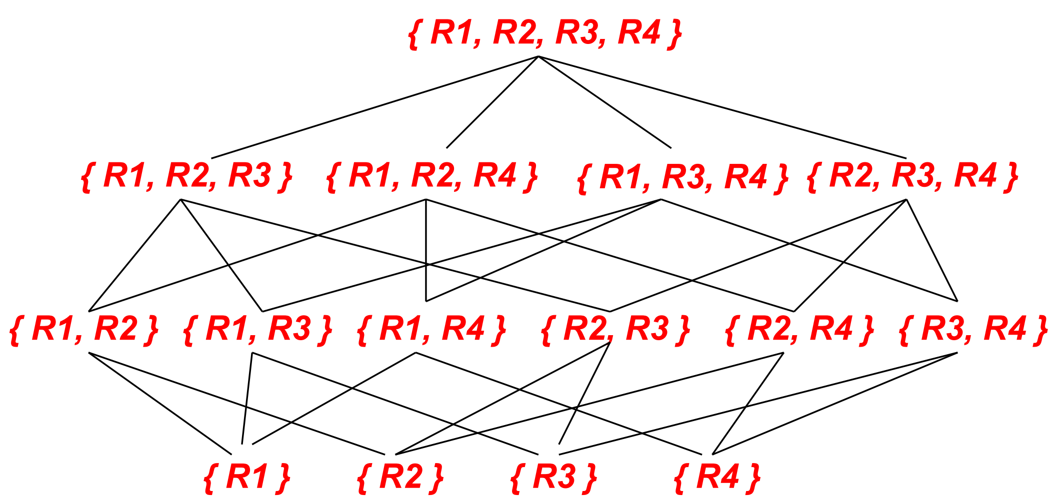
NOTE:

This is *NOT* done by top-down recursive calls.

- This is done BOTTOM-UP computing the optimal cost of *all* nodes in this lattice only once (dynamic programming).

Progress of algorithm

Is it efficient? ☺



Reduces n! to 2^n

Other optimizations employed too..

More on Query Optimizations

- See the survey:

"An Overview of Query Optimization in Relational Systems" by Surajit Chaudhuri (link)

  - Pushing group by before joins
  - Merging views and nested queries
  - "Semi-join"-like techniques for multi-block queries
    - Recall joins in distributed databases
  - Statistics and optimizations
  - Starbust and Volcano/Cascade architecture, etc
- New research topics: Robust query optimization, "learned" query optimization, approximate selectivity estimation…