




CS 525: Advanced Database Organization

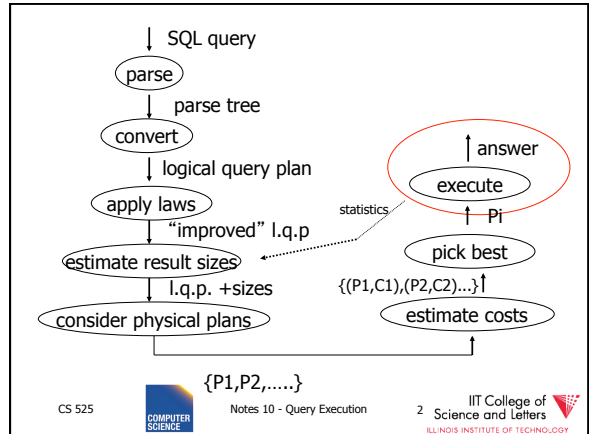
10: Query Execution

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Slides: adapted from a [course](#) taught by [Hector Garcia-Molina](#), Stanford InfoLab

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Query Execution

- Here only:
 - how to implement operators
 - what are the costs of implementations
 - how to implement queries
 - Data flow between operators
- Next part:
 - How to choose good plan

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Execution Plan

- A tree (DAG) of physical operators that implement a query
- May use indices
- May create temporary relations
- May create indices on the fly
- May use auxiliary operations such as sorting

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How to estimate costs

- If everything fits into memory
 - Standard computational complexity
- If not
 - Assume fixed memory available for buffering pages
 - Count I/O operations
 - Real systems combine this with CPU estimations

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Estimating IOs:

- Count # of disk blocks that must be read (or written) to execute query plan

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To estimate costs, we may have additional parameters:

$B(R)$ = # of blocks containing R tuples

$f(R)$ = max # of tuples of R per block

M = # memory blocks available

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To estimate costs, we may have additional parameters:

$B(R)$ = # of blocks containing R tuples

$f(R)$ = max # of tuples of R per block

M = # memory blocks available

$HT(i)$ = # levels in index i

$LB(i)$ = # of leaf blocks in index i

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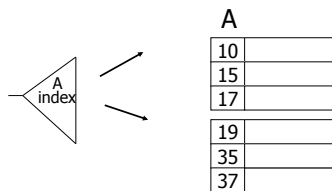


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Clustered index

Index that allows tuples to be read in an order that corresponds to physical order



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Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, ...)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

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Operator Profiles

- Algorithm
- In-memory complexity: e.g., $O(n^2)$
- Memory requirements
 - Runtime based on available memory
- #I/O if operation needs to go to disk
- Disk space needed
- Prerequisites
 - Conditions under which the operator can be applied

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Execution Strategies

- Compiled
 - Translate into C/C++/Assembler code
 - Compile, link, and execute code
- Interpreted
 - Generic operator implementations
 - Generic executor
 - Interprets query plan

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Virtual Machine Approach

- Implement virtual machine of low-level DBMS operations
- Compile query into machine-code for that machine

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Iterator Model

- Need to be able to combine operators in different ways
 - E.g., join inputs may be scans, or outputs of other joins, ...
 - -> define generic interface for operators
 - be able to arbitrarily compose complex plans from a small set of operators

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Iterator Model - Interface

- **Open**
 - Prepare operator to read outputs
- **Close**
 - Close operator and clean up
- **Next**
 - Return next result tuple

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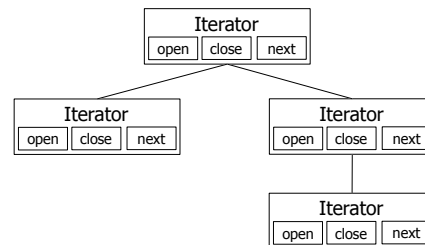


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Query Execution – Iterator Model



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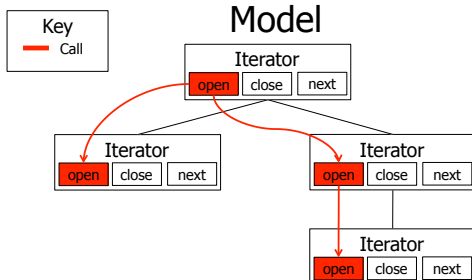


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Query Execution – Iterator Model



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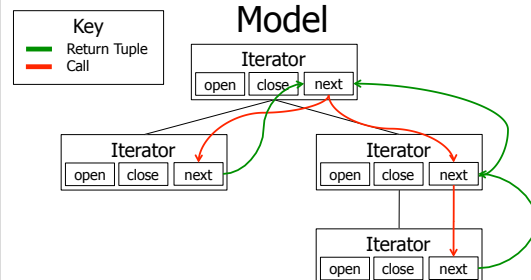


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Query Execution – Iterator Model



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Parallelism

- Iterator Model
 - **Pull-based** query execution
- Potential types of parallelism
 - Inter-query (every multiuser system)
 - Intra-operator
 - Inter-operator

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Intra-Operator Parallelism

- Execute portions of an operator in parallel
 - Merge-Sort
 - Assign a processor to each merge phase
 - Scan
 - Partition tables
 - Each process scans one partition

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Inter-Operator Parallelism

- Each process executes one or more operators
- **Pipelining**
 - **Push-based** query execution
 - Chain operators directly produce results
 - Pipeline-breakers
 - Operators that need to consume the whole input (or large parts) before producing outputs

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Pipelining Communication

- Queues
 - Operators push their results to queues
 - Operators read their inputs from queues
- Direct call
 - Operator calls its parent in the tree with results
 - Within one process

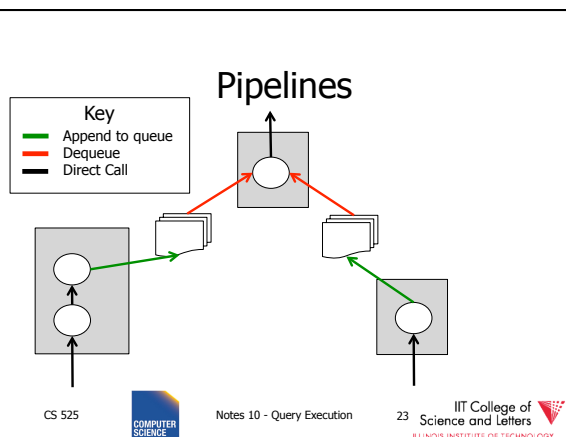
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Pipeline-breakers

- Sorting
 - All operators that apply sorting
- Aggregation
- Set Difference
- Some implementations of
 - Join
 - Union

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Sorting

- Why do we want/need to sort
 - Query requires sorting (ORDER BY)
 - Operators require sorted input
 - Merge-sort
 - Aggregation by sorting
 - Duplicate removal using sorting

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In-memory sorting

- Algorithms from data structures 101
 - Quick sort
 - Merge sort
 - Heap sort
 - Intro sort
 - ...

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External sorting

- Problem:
 - Sort **N** pages of data with **M** pages of memory
- Solutions?

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First Idea

- Split data into runs of size **M**
- Sort each run in memory and write back to disk
 - $\lceil N/M \rceil$ sorted runs of size **M**
- Now what?



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Merging Runs

- Need to create bigger sorted runs out of sorted smaller runs
 - Divide and Conquer
 - Merge Sort?
- How to merge two runs that are bigger than **M**?

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Merging Runs using 3 pages

- Merging runs R_1 and R_2
- Need 3 pages
 - One page to buffer pages from R_1
 - One page to buffer pages from R_2
 - One page to buffer the result
 - Whenever this buffer is full, write it to disk

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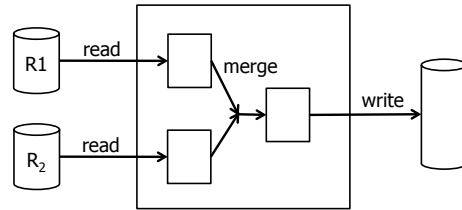


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Merging Runs



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2-Way External Mergesort

- Repeat process until we have one sorted run
- Each iteration (pass) reads and writes the whole table once: $2 B(R)$ I/Os
- Each pass doubles the run size
 - $1 + \lceil \log_2 (B(R) / M) \rceil$ runs
 - $2 B(R) * (1 + \lceil \log_2 (B(R) / M) \rceil)$ I/Os

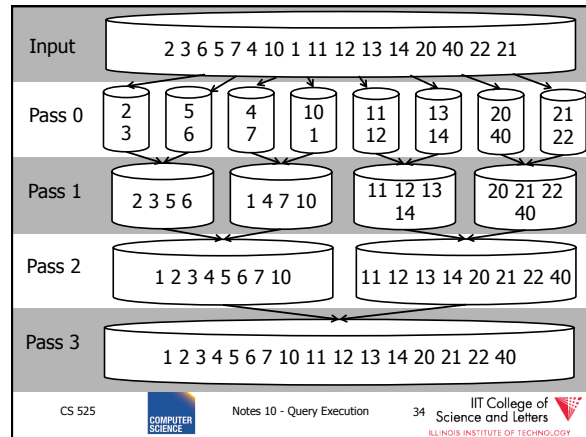
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N-Way External Mergesort

- How to utilize M buffer during merging?
- Each pass merges $M-1$ runs at once
 - One memory page as buffer for each run
- #I/Os
 - $1 + \lceil \log_{M-1} (B(R) / M) \rceil$ runs
 - $2 B(R) * (1 + \lceil \log_{M-1} (B(R) / M) \rceil)$ I/Os

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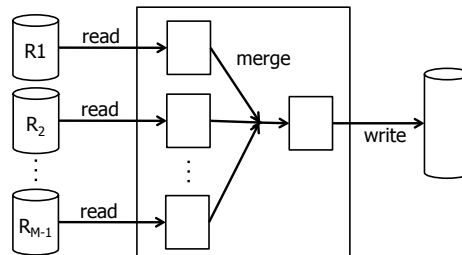


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Merging Runs



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How many passes do we need?

N	M=17	M=129	M=257	M=513	M=1025
100	2	1	1	1	1
1,000	3	2	2	2	1
10,000	4	2	2	2	2
100,000	5	3	3	2	2
1,000,000	5	3	3	3	2
10,000,000	6	4	3	3	3
100,000,000	7	4	4	3	3
1,000,000,000	8	5	4	4	3

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To put into perspective

- Scenario
 - Page size 4KB
 - 1TB of data (250,000,000)
 - 10MB of buffer for sorting (250)
- Passes
 - 4 passes

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Merge

- In practice would want larger I/O buffer for each run
- Trade-off between number of runs and efficiency of I/O

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Improving in-memory merging

- Merging **M** runs
 - To choose next element to output
 - Have to compare **M** elements
 - \rightarrow complexity linear in **M**: **O(M)**
- How to improve that?
 - Use priority queue to store current element from each run
 - \rightarrow **O(log₂(M))**

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Priority Queue

- Queue for accessing elements in some given order
 - **pop-smallest** = return and remove smallest element in set
 - **Insert(e)** = insert element into queue

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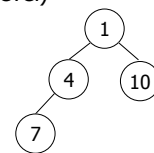
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Min-Heap

- Implementation of priority queue
 - Store elements in a binary tree
 - All levels are full (except leaf level)
 - Heap property
 - Parent is smaller than child
- Example: { 1, 4, 7, 10 }



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Min-Heap Insertion

- **insert(e)**

1. Add element at next free leaf node
 - This may invalidate heap property
2. If node smaller than parent then
 - Switch node with parent
3. Repeat until 2) cannot be applied anymore

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Min-Heap Dequeue

- **pop-smallest**

1. Return Root and use right-most leaf as new root
 - This may invalidate heap property
2. If node smaller than child then
 - Switch node with smaller child
3. Repeat until 2) cannot be applied anymore

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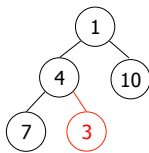
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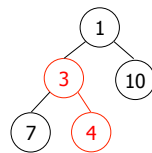
Insertion

- **Insert 3**

Insert at first free position



Restore heap property



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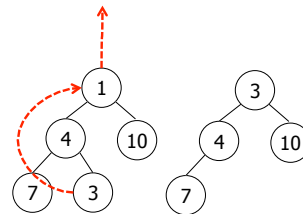


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Dequeue



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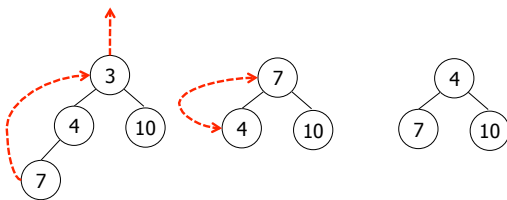


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Dequeue



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Min/Max-Heap Complexity

- Head is a complete tree
 - Height is $O(\log_2(n))$
- Insertion
 - Maximal height of the tree switches
 - $\rightarrow O(\log_2(n))$
- Dequeue
 - Maximal height of the tree switches
 - $\rightarrow O(\log_2(n))$

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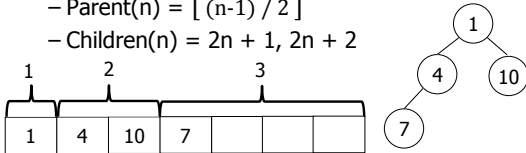
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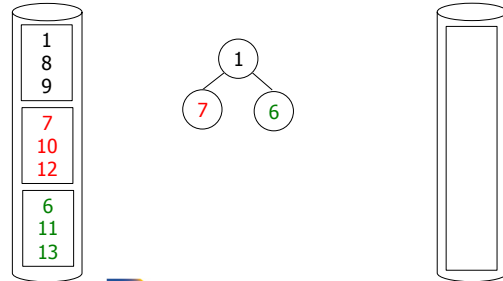
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Min-Heap Implementation

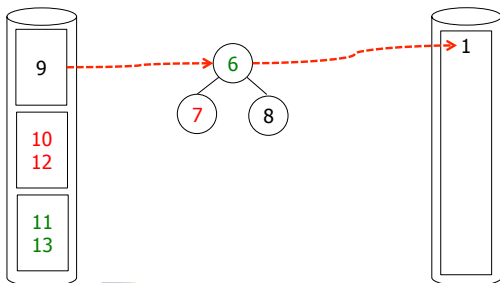
- Full tree
 - Use array to implement tree
- Compute positions
 - $\text{Parent}(n) = \lfloor (n-1) / 2 \rfloor$
 - $\text{Children}(n) = 2n + 1, 2n + 2$



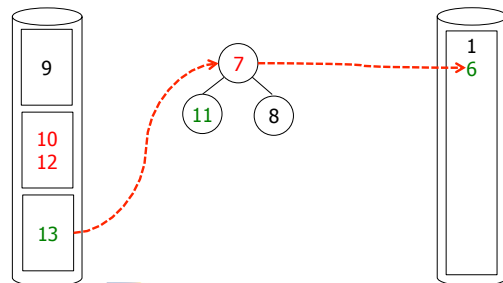
Merging with Priority Queue



Merging with Priority Queue

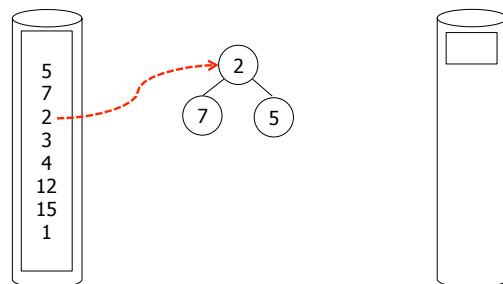


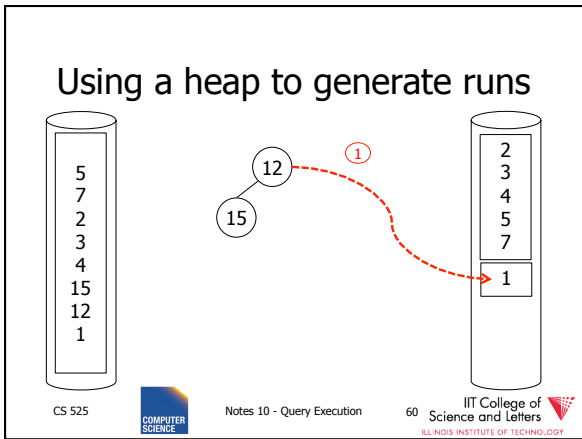
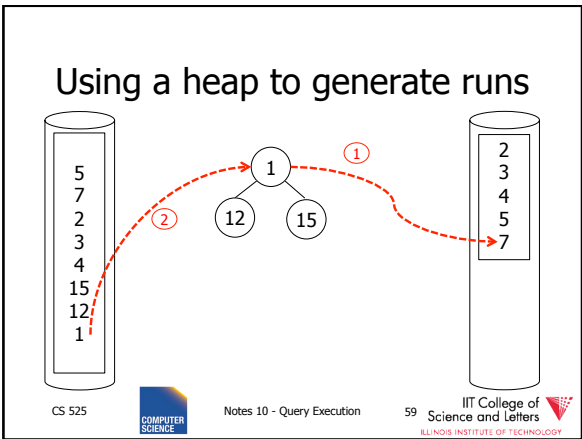
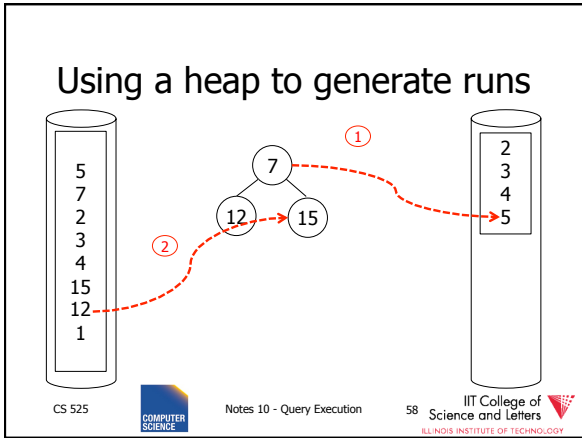
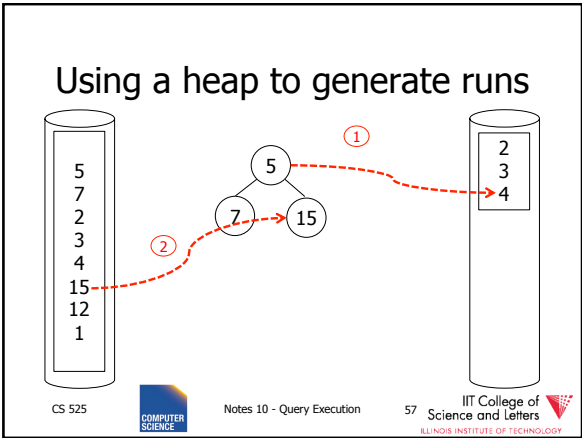
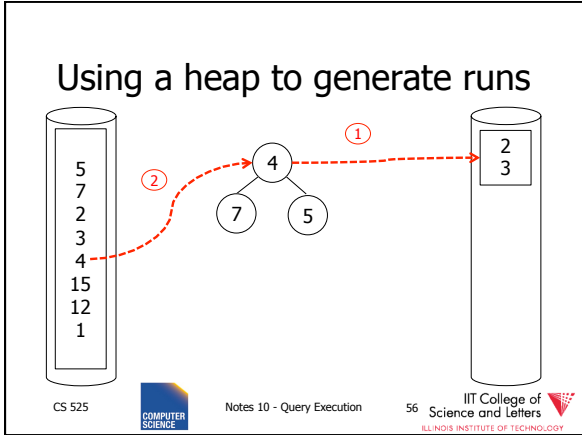
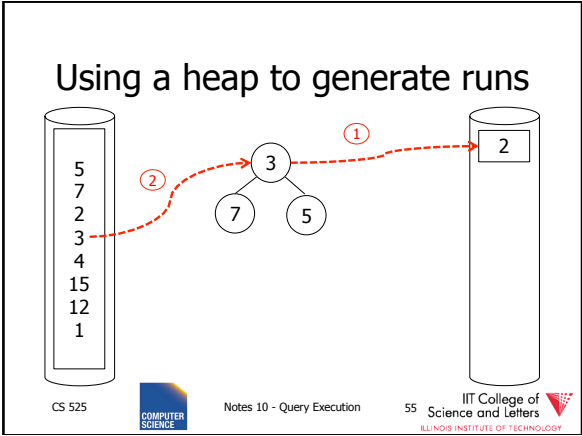
Merging with Priority Queue



Using a heap to generate runs

- Read inputs into heap
 - Until available memory is full
- Replace elements
 - Remove smallest element from heap
 - If larger then last element written to current run then write to current run
 - Else create a new run
 - Add new element from input to heap





Using a heap to generate runs

- Increases the run-length
 - On average by a factor of 2 (see Knuth)

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Use clustered B+-tree

- Keys in the B+-tree **I** are in sort order
 - If B+-tree is clustered traversing the leaf nodes is sequential I/O!
 - \mathbf{K} = #keys/leaf node
- Approach
 - Traverse from root to first leaf: **HT(I)**
 - Follow sibling pointers: $\mathbf{|R| / K}$
 - Read data blocks: **B(R)**

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I/O Operations

- HT(I) + |R| / K + B(R)** I/Os
- Less than **2 B(R)** = 1 pass external mergesort
- > Better than external merge-sort!

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Unclustered B+-tree?

- Each entry in a leaf node may point to different page of relation R
 - For each leaf page we may read up to **K** pages from relation R
 - Random I/O
- In worst-case we have
 - $\mathbf{K * B(R)}$
 - $\mathbf{K = 500}$
 - $\mathbf{500 * B(R)}$ = 250 merge passes

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Sorting Comparison

B(R) = number of block of R
M = number of available memory blocks
#RB = records per page
HT = height of B+-tree (logarithmic)
K = number of keys per leaf node

Property	Ext. Mergesort	B+ (clustered)	B+ (unclustered)
Runtime	$O(N \log_{M-1}(N))$	$O(N)$	$O(N)$
#I/O (random)	$2 B(R) * (1 + \lceil \log_{M-1}(B(R)/M) \rceil)$	$HT + R / K + B(R)$	$HT + R / K + K * \#RB$
Memory	M	1 (better HT + X)	1 (better HT + X)
Disk Space	$2 B(R)$	0	0
Variants	1) Merge with heap 2) Run generation with heap 3) Larger Buffer		

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Scan

- Implements access to a table
 - Combined with selection
 - Probably projection too
- Variants
 - **Sequential**
 - Scan through all tuples of relation
 - **Index**
 - Use index to find tuples that match selection

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Options

- Transformations: $R_1 \bowtie_c R_2, R_2 \bowtie_c R_1$
- Joint algorithms:
 - Nested loop
 - Merge join
 - Join with index
 - Hash join
- Outer join algorithms

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Nested Loop Join (conceptually)

```
for each r ∈ R1 do
  for each s ∈ R2 do
    if (r,s) ⊨ C then output (r,s)
```

Applicable to:

- Any join condition C
- Cross-product

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Merge Join (conceptually)

- (1) if R_1 and R_2 not sorted, sort them
- (2) $i \leftarrow 1; j \leftarrow 1;$
While $(i \leq T(R_1)) \wedge (j \leq T(R_2))$ do
if $R_1\{i\}.C = R_2\{j\}.C$ then outputTuples
else if $R_1\{i\}.C > R_2\{j\}.C$ then $j \leftarrow j+1$
else if $R_1\{i\}.C < R_2\{j\}.C$ then $i \leftarrow i+1$

Applicable to:

- C is conjunction of equalities or $</>$:
 $A_1 = B_1 \text{ AND } \dots \text{ AND } A_n = B_n$

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Procedure Output-Tuples

```
While  $(R_1\{i\}.C = R_2\{j\}.C) \wedge (i \leq T(R_1))$  do
  [  $jj \leftarrow j;$ 
    while  $(R_1\{i\}.C = R_2\{jj\}.C) \wedge (jj \leq T(R_2))$  do
      [output pair  $R_1\{i\}, R_2\{jj\};$ 
         $jj \leftarrow jj+1$  ]
    ]
   $i \leftarrow i+1$  ]
```

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Example

i	$R_1\{i\}.C$	$R_2\{j\}.C$	j
1	10	5	1
2	20	20	2
3	20	20	3
4	30	30	4
5	40	30	5
		50	6
		52	7

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Index nested loop (Conceptually)

```

For each r ∈ R1 do
    [ X ← index (R2, C, r.C)
    for each s ∈ X do
        output (r,s) pair]
    
```

Note: $X \leftarrow \text{index}(\text{rel}, \text{attr}, \text{value})$
then $X = \text{set of rel tuples with attr} = \text{value}$

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Hash join (conceptual)

Hash function h , range $0 \rightarrow k$
Buckets for R_1 : G_0, G_1, \dots, G_k
Buckets for R_2 : H_0, H_1, \dots, H_k

Applicable to:

- C is conjunction of equalities
 $A_1 = B_1 \text{ AND } \dots \text{ AND } A_n = B_n$

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Hash join (conceptual)

Hash function h , range $0 \rightarrow k$
Buckets for R_1 : G_0, G_1, \dots, G_k
Buckets for R_2 : H_0, H_1, \dots, H_k

Algorithm

- (1) Hash R_1 tuples into G buckets
- (2) Hash R_2 tuples into H buckets
- (3) For $i = 0$ to k do
match tuples in G_i, H_i buckets

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Simple example hash: even/odd

R_1	R_2	Buckets	
2	5	Even: 2 4 8	4 12 8 14
4	4		R_1 R_2
3	12	Odd: 3 5 9	5 3 13 11
5	3		
8	13		
9	8		
	11		
	14		

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Factors that affect performance

- (1) Tuples of relation stored physically together?
- (2) Relations sorted by join attribute?
- (3) Indexes exist?

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Example 1(a) Iteration Join $R_1 \bowtie R_2$

- Relations not contiguous
- Recall $\begin{cases} T(R_1) = 10,000 & T(R_2) = 5,000 \\ S(R_1) = S(R_2) = 1/10 \text{ block} \\ \text{MEM} = 101 \text{ blocks} \end{cases}$

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Example 1(a)

Nested Loop Join $R_1 \bowtie R_2$

- Relations not contiguous
- Recall $\begin{cases} T(R_1) = 10,000 & T(R_2) = 5,000 \\ S(R_1) = S(R_2) = 1/10 \text{ block} \\ \text{MEM} = 101 \text{ blocks} \end{cases}$

Cost: for each R_1 tuple:

[Read tuple + Read R_2]

Total = $10,000 [1 + 500] = 5,010,000$ IOs

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- Can we do better?

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- Can we do better?

Use our memory

- (1) Read 100 blocks of R_1
- (2) Read all of R_2 (using 1 block) + join
- (3) Repeat until done

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Cost: for each R_1 chunk:

Read chunk: 100 IOs
Read R_2 : $\frac{500 \text{ IOs}}{600}$

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Cost: for each R_1 chunk:

Read chunk: 100 IOs
Read R_2 : $\frac{500 \text{ IOs}}{600}$

Total = $\frac{1,000}{100} \times 600 = 6,000$ IOs

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- Can we do better?

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- Can we do better?

• Reverse join order: $R_2 \bowtie R_1$

$$\text{Total} = \frac{500}{100} \times (100 + 1,000) =$$

$$5 \times 1,100 = 5,500 \text{ IOs}$$

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Block-Nested Loop Join (conceptual)

for each M-1 blocks of R_1 do
 read M-1 blocks of R_1 into buffer
 for each block of R_2 do
 read next block of R_2
 for each tuple r in R_1 block
 for each tuple s in R_2 block
 if $(r,s) \models C$ then output (r,s)

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Note

- How much memory for buffering inner and for outer chunks?
 - 1 for inner would minimize I/O
 - But, larger buffer better for I/O

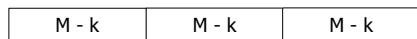
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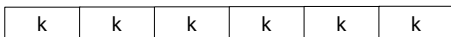
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R_1



R_2



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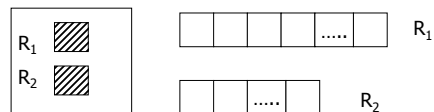
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Example 1(b) Merge Join

- Both R_1, R_2 ordered by C ; relations contiguous

Memory



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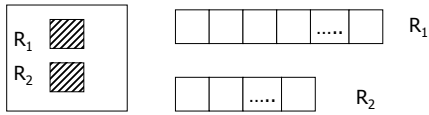
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Example 1(b) Merge Join

- Both R_1, R_2 ordered by C; relations contiguous

Memory



Total cost: Read R_1 cost + read R_2 cost
 = 1000 + 500 = 1,500 IOs

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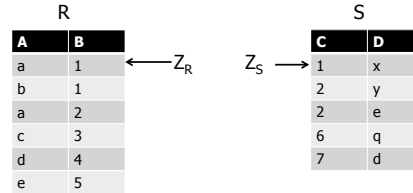
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Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,1,1,X)



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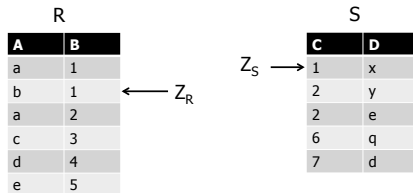
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Merge Join Example

$R \bowtie_{B=C} S$

Output: (b,1,1,X)



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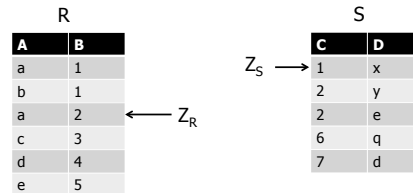
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Merge Join Example

$R \bowtie_{B=C} S$

R.B > S.C: advance Z_S



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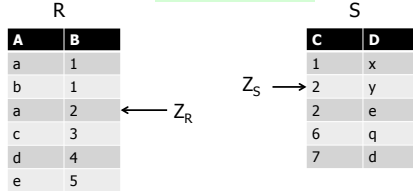
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Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,2,2,y)



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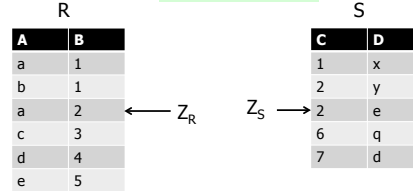
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Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,2,2,e)



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Merge Join Example

$R \bowtie_{B=C} S$

R.B > S.C: advance Z_S

R		S	
A	B	C	D
a	1	1	x
b	1	2	y
a	2	2	e
c	3	6	q
d	4	7	d
e	5		

$Z_S \rightarrow$ (from S row 2 to S row 3)
 $Z_R \leftarrow$ (to R row 3)

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Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: advance Z_R

R		S	
A	B	C	D
a	1	1	x
b	1	2	y
a	2	2	e
c	3	6	q
d	4	7	d
e	5		

$Z_S \rightarrow$ (from S row 2 to S row 3)
 $Z_R \leftarrow$ (to R row 3)

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Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: advance Z_R

R		S	
A	B	C	D
a	1	1	x
b	1	2	y
a	2	2	e
c	3	6	q
d	4	7	d
e	5		

$Z_S \rightarrow$ (from S row 2 to S row 3)
 $Z_R \leftarrow$ (to R row 3)

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Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: **DONE**

R		S	
A	B	C	D
a	1	1	x
b	1	2	y
a	2	2	e
c	3	6	q
d	4	7	d
e	5		


$Z_S \rightarrow$ (from S row 2 to S row 3)
 $Z_R \leftarrow$ (to R row 3)

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Example 1(c) Merge Join

- R_1, R_2 not ordered, but contiguous

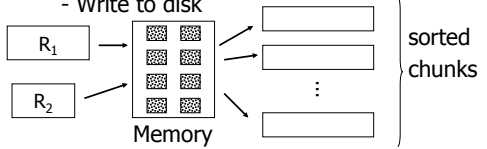
--> Need to sort R_1, R_2 first

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One way to sort: Merge Sort

(i) For each 100 blk chunk of R:

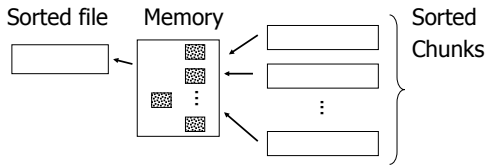
- Read chunk
- Sort in memory
- Write to disk



sorted chunks

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(ii) Read all chunks + merge + write out



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Cost: Sort

Each tuple is read, written,
read, written

SO...

Sort cost R_1 : $4 \times 1,000 = 4,000$

Sort cost R_2 : $4 \times 500 = 2,000$

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Example 1(d) Merge Join (continued)

R_1, R_2 contiguous, but unordered

Total cost = sort cost + join cost
= $6,000 + 1,500 = 7,500$ IOs

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Example 1(c) Merge Join (continued)

R_1, R_2 contiguous, but unordered

Total cost = sort cost + join cost
= $6,000 + 1,500 = 7,500$ IOs

But: Iteration cost = 5,500
so merge joint does not pay off!

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But say $R_1 = 10,000$ blocks contiguous
 $R_2 = 5,000$ blocks not ordered

Iterate: $\frac{5000}{100} \times (100 + 10,000) = 50 \times 10,100$
= 505,000 IOs

Merge join: $5(10,000 + 5,000) = 75,000$ IOs

Merge Join (with sort) WINS!

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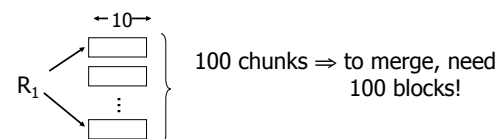
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How much memory do we need for merge sort?

E.g: Say I have 10 memory blocks



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In general:

Say k blocks in memory
 x blocks for relation sort
chunks = (x/k) size of chunk = k

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In general:

Say k blocks in memory
 x blocks for relation sort
chunks = (x/k) size of chunk = k
chunks < buffers available for merge

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Notes 10 - Query Execution

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In general:

Say k blocks in memory
 x blocks for relation sort
chunks = (x/k) size of chunk = k
chunks < buffers available for merge

so... $(x/k) \leq k$
or $k^2 \geq x$ or $k \geq \sqrt{x}$

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In our example

R_1 is 1000 blocks, $k \geq 31.62$
 R_2 is 500 blocks, $k \geq 22.36$

Need at least 32 buffers

Again: in practice we would not want to use only one buffer per run!

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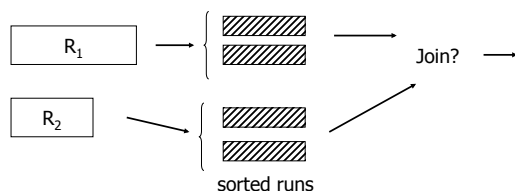
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Can we improve on merge join?

Hint: do we really need the fully sorted files?



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Cost of improved merge join:

$C = \text{Read } R_1 + \text{write } R_1 \text{ into runs}$
 $+ \text{read } R_2 + \text{write } R_2 \text{ into runs}$
 $+ \text{join}$
 $= 2,000 + 1,000 + 1,500 = 4,500$

--> Memory requirement?

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Example 1(d) Index Join

- Assume $R_1.C$ index exists; 2 levels
- Assume R_2 contiguous, unordered

- Assume $R_1.C$ index fits in memory

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Cost: Reads: 500 IOs

for each R_2 tuple:

- probe index - free
- if match, read R_1 tuple: 1 IO

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What is expected # of matching tuples?

(a) say $R_1.C$ is key, $R_2.C$ is foreign key
then expect = 1

(b) say $V(R_1.C) = 5000$, $T(R_1) = 10,000$
with uniform assumption
expect = $10,000/5,000 = 2$

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What is expected # of matching tuples?

(c) Say $DOM(R_1, C) = 1,000,000$

$$T(R_1) = 10,000$$

with alternate assumption

$$\text{Expect} = \frac{10,000}{1,000,000} = \frac{1}{100}$$

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Total cost with index join

(a) Total cost = $500 + 5000(1)1 = 5,500$

(b) Total cost = $500 + 5000(2)1 = 10,500$

(c) Total cost = $500 + 5000(1/100)1 = 550$

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What if index does not fit in memory?

Example: say $R_1.C$ index is 201 blocks

- Keep root + 99 leaf nodes in memory
- Expected cost of each probe is

$$E = (0)\frac{99}{200} + (1)\frac{101}{200} \approx 0.5$$

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Total cost (including probes)

$$\begin{aligned}
 &= 500+5000 \text{ [Probe + get records]} \\
 &= 500+5000 [0.5+2] \quad \text{uniform assumption} \\
 &= 500+12,500 = 13,000 \quad \text{(case b)}
 \end{aligned}$$

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Total cost (including probes)

$$\begin{aligned}
 &= 500+5000 \text{ [Probe + get records]} \\
 &= 500+5000 [0.5+2] \quad \text{uniform assumption} \\
 &= 500+12,500 = 13,000 \quad \text{(case b)}
 \end{aligned}$$

For case (c):

$$\begin{aligned}
 &= 500+5000[0.5 \times 1 + (1/100) \times 1] \\
 &= 500+2500+50 = 3050 \text{ IOs}
 \end{aligned}$$

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So far

{	Nested Loop	5500
	Merge join	1500
	Sort+Merge Join	7500 → 4500
	R ₁ .C Index	5500 → 3050 → 550
	R ₂ .C Index	_____

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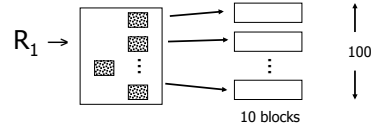


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Example 1(e) Partition Hash Join

- R₁, R₂ contiguous (un-ordered)
- Use 100 buckets
- Read R₁, hash, + write buckets



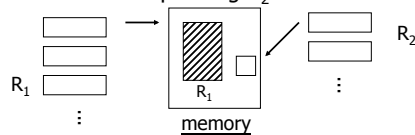
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- > Same for R₂
- > Read one R₁ bucket; build memory hash table -using different hash function h'
- > Read corresponding R₂ bucket + hash probe



Then repeat for all buckets

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Cost:

“Bucketize:” Read R₁ + write
Read R₂ + write
Join: Read R₁, R₂

$$\text{Total cost} = 3 \times [1000+500] = 4500$$

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Cost:

“Bucketize:” Read R_1 + write

Read R_2 + write

Join: Read R_1, R_2

Total cost = $3 \times [1000+500] = 4500$

Note: this is an approximation since buckets will vary in size and we have to round up to blocks

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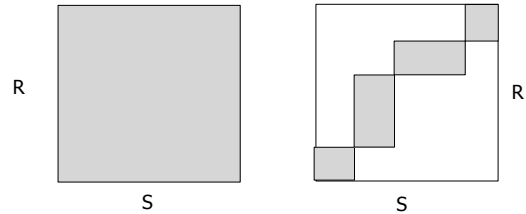


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Why is Hash Join good?



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Minimum memory requirements:

Size of R_1 bucket = (x/k)

k = number of memory buffers

x = number of R_1 blocks

So... $(x/k) < k$

$k > \sqrt{x}$ need: $k+1$ total memory buffers

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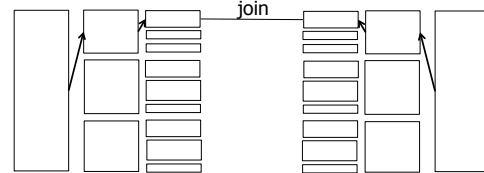
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Can we use Hash-join when buckets do not fit into memory?:

- Treat buckets as relations and apply Hash-join recursively



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Duality Hashing-Sorting

- Both partition inputs
- Until input fits into memory
- Logarithmic number of phases in memory size

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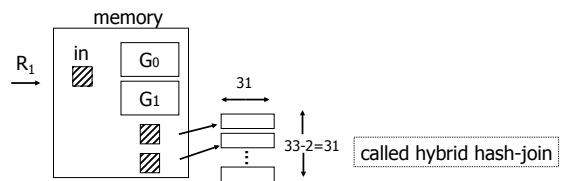
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Trick: keep some buckets in memory

E.g., $k' = 33$ R_1 buckets = 31 blocks keep 2 in memory



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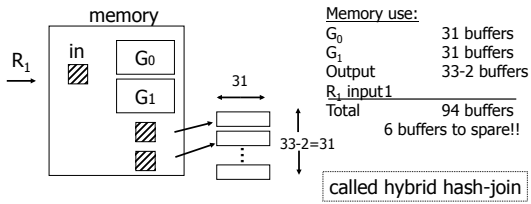
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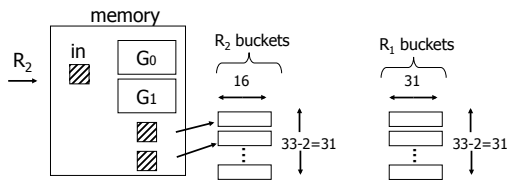
Trick: keep some buckets in memory

E.g., $k' = 33$ R_1 buckets = 31 blocks
keep 2 in memory



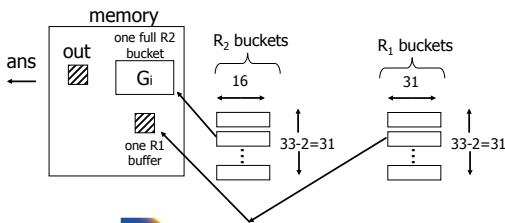
Next: Bucketize R_2

- R_2 buckets = $500/33 = 16$ blocks
- Two of the R_2 buckets joined immediately with G_0, G_1



Finally: Join remaining buckets

- for each bucket pair:
 - read one of the buckets into memory
 - join with second bucket

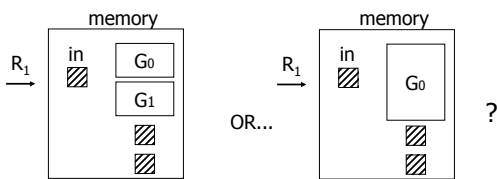


Cost

- Bucketize $R_1 = 1000 + 31 \times 31 = 1961$
- To bucketize R_2 , only write 31 buckets:
so, cost = $500 + 31 \times 16 = 996$
- To compare join (2 buckets already done)
read $31 \times 31 + 31 \times 16 = 1457$

Total cost = $1961 + 996 + 1457 = 4414$

How many buckets in memory?



See textbook for answer...

Another hash join trick:

- Only write into buckets $\langle val, ptr \rangle$ pairs
- When we get a match in join phase, must fetch tuples

- To illustrate cost computation, assume:
 - 100 <val,ptr> pairs/block
 - expected number of result tuples is 100

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- To illustrate cost computation, assume:
 - 100 <val,ptr> pairs/block
 - expected number of result tuples is 100
- Build hash table for R_2 in memory
5000 tuples \rightarrow $5000/100 = 50$ blocks
- Read R_1 and match
- Read $\sim 100 R_2$ tuples

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- To illustrate cost computation, assume:
 - 100 <val,ptr> pairs/block
 - expected number of result tuples is 100
- Build hash table for R_2 in memory
5000 tuples \rightarrow $5000/100 = 50$ blocks
- Read R_1 and match
- Read $\sim 100 R_2$ tuples

<u>Total cost</u> =	Read R_2 :	500
	Read R_1 :	1000
	Get tuples:	<u>100</u>
		1600

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So far:

Iterate	5500
Merge join	1500
Sort+merge join	7500
R_1, C index	5500 \rightarrow 550
R_2, C index	_____
Build R_1, C index	_____
Build R_2, C index	_____
Hash join	<u>4500+</u>
with trick, R_1 first	4414
with trick, R_2 first	_____
Hash join, pointers	<u>1600</u>

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Yet another hash join trick:

- Combine the ideas of
 - block nested-loop with hash join
- Use memory to build hash-table for one chunk of relation
- Find join partners in $O(1)$ instead of $O(M)$
- Trade-off
 - Space-overhead of hash-table
 - Time savings from look-up

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Summary

- Nested Loop ok for “small” relations
(relative to memory size)
 - Need for complex join condition
- For equi-join, where relations not sorted and no indexes exist,
hash join usually best

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- Sort + merge join good for non-equi-join (e.g., $R_1.C > R_2.C$)
- If relations already sorted, use merge join
- If index exists, it could be useful (depends on expected result size)

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Join Comparison

N_i = number of tuples in R_i
 $B(R_i)$ = number of blocks of R_i
 $\#P$ = number of partition steps for hash join
 P_{ij} = average number of join partners

Algorithm	#I/O	Memory	Disk Space
Nested Loop (block)	$B(R_1) * B(R_2) / M$	3	0
Index Nested Loop	$B(R_1) + N_1 * P_{12}$	$B(\text{Index}) + 2$	0
Merge (sorted)	$B(R_1) + B(R_2)$	Max tuples =	0
Merge (unsorted)	$B(R_1) + B(R_2) + (\text{sort} - 1 \text{ pass})$	sort	$B(R_1) + B(R_2)$
Hash	$(2\#P + 1) (B(R_1) + B(R_2))$	$\text{root}(\max(B(R_1), B(R_2)), \#P + 1)$	$\sim B(R_1) + B(R_2)$

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Why do we need nested loop?

- Remember not all join implementations work for all types of join conditions

Algorithm	Type of Condition	Example
Nested Loop	any	a LIKE '%hello%'
Index Nested Loop	Supported by index: Equi-join (hash) Equi or range (B-tree)	a = b a < b
Merge	Equalities and ranges	a < b, a = b AND c = d
Hash	Equi-join	a = b

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Outer Joins

- How to implement (left) outer joins?
- Nested Loop and Merge
 - Use a flag that is set to true if we find a match for an outer tuple
 - If flag is false fill with NULL
- Hash
 - If no matching tuple fill with NULL

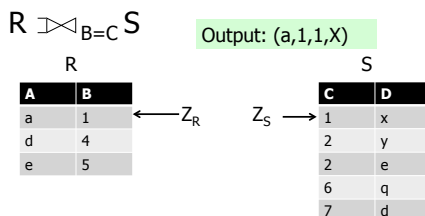
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Merge Left Outer Join



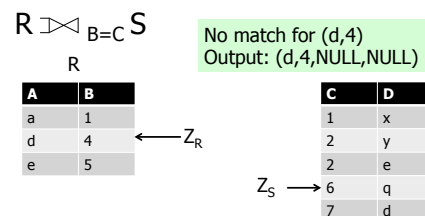
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Merge Left Outer Join



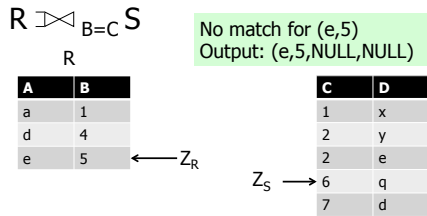
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Merge Left Outer Join



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Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, ...)
- **Aggregation (Sorting, Hash)**
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

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Aggregation

- Have to compute aggregation functions
 - for each group of tuples from input
- Groups
 - Determined by equality of group-by attributes

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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

a	b
3	1
4	2
3	1
1	2
1	2

sum(a)	b
6	1
6	2

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Aggregation Function Interface

- `init()`
 - Initialize state
- `update(tuple)`
 - Update state with information from tuple
- `close()`
 - Return result and clean-up

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Implementation SUM(A)

- `init()`
 - `sum := 0`
- `update(tuple)`
 - `sum += tuple.A`
- `close()`
 - **return** sum

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Aggregation Implementations

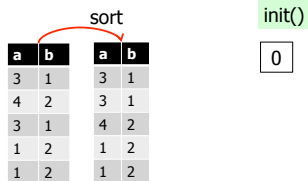
- Sorting
 - Sort input on group-by attributes
 - On group boundaries output tuple
- Hashing
 - Store current aggregated values for each group in hash table
 - Update with newly arriving tuples
 - Output result after processing all inputs

Grouping by sorting

- Similar to Merge join
- Sort R on group-by attribute
- Scan through sorted input
 - If group-by values change
 - Output using close() and call init()
 - Otherwise
 - Call update()

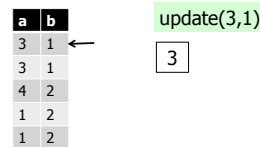
Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```



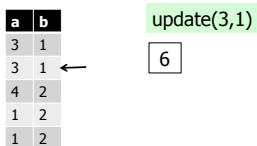
Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```



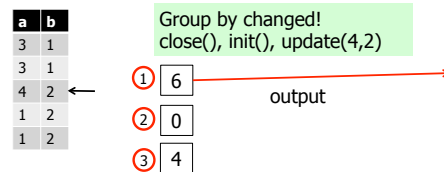
Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```



Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```



Grouping by Hashing

- Create in-memory hash-table
- For each input tuple probe hash table with group by values
 - If no entry exists then call `init()`, `update()`, and add entry
 - Otherwise call `update()` for entry
- Loop through all entries in hash-table and output calling `close()`

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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

a	b
3	1
4	2
3	1
1	2
1	2



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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

Init() and update(3,1)

a	b
3	1
4	2
3	1
1	2
1	2



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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

Init() and update(4,2)

a	b
3	1
4	2
3	1
1	2
1	2



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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

update(3,1)

a	b
3	1
4	2
3	1
1	2
1	2



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Aggregation Example

```
SELECT sum(a), b
FROM R
GROUP BY b
```

- Loop through hash table entries
- Output tuples

a	b
3	1
4	2
3	1
1	2
1	2



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Aggregation Summary

- Hashing
 - No sorting -> no extra I/O
 - Hash table has to fit into memory
 - No outputs before all inputs have been processed
- Sorting
 - No memory required
 - Output one group at a time

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Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, ...)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

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Duplicate Elimination

- Equivalent to group-by on all attributes
- -> Can use aggregation implementations
- Optimization
 - Hash
 - Directly output tuple and use hash table only to avoid outputting duplicates

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Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, ...)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
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Set Operations

- Can be modeled as join
 - with different output requirements
- As aggregation/group by on all columns
 - with different output requirements

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Union

- Bag union
 - Append the two inputs
 - E.g., using three buffers
- Set union
 - Apply duplicate removal to result

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Intersection

- Set version
 - Equivalent to join + project + duplicate removal
 - 3-state aggregate function (found left, found right, found both)
- Bag version
 - Join + project + $\min(i,j)$
 - Aggregate $\min(\text{count}(i), \text{count}(j))$

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Set Difference

- Using join methods
 - Find matching tuples
 - If no match found, then output
- Using aggregation
 - $\text{count}(i) - \text{count}(j)$ (**bag**)
 - $\text{true}(i) \text{ AND } \text{false}(j)$ (**set**)

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Summary

- Operator implementations
 - Joins!
 - Other operators
- Cost estimations
 - I/O
 - memory
- Query processing architectures

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Next

- Query Optimization Physical
- -> How to **efficiently** choose an **efficient** plan

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