External sorting

R & G – Chapter 13

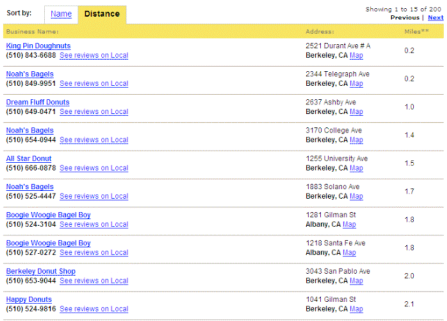
Guest Lecturer:

Brian Cooper
Yahoo! Research

A little bit about Y!

- Yahoo! is the most visited website in the world
  - Sorry Google
  - 500 million unique visitors per month
  - 74 percent of U.S. users use Y! (per month)
  - 13 percent of U.S. users' online time is on Y!

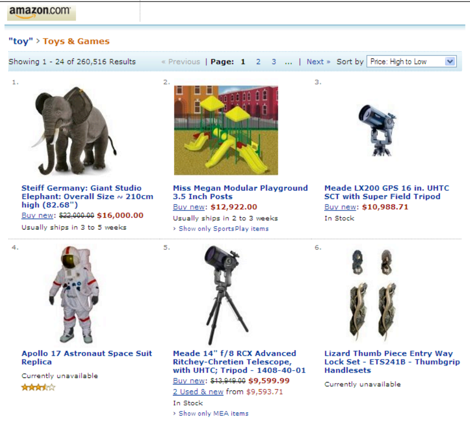
Why sort?



Sort by: Name **Distance**

Showing 1 to 15 of 200
Previous | **Next**

Business Name:	Address:	Miles**
King Pin Doughnuts (510) 843-6688 See reviews on Local	2521 Durant Ave # A Berkeley, CA Map	0.2
Noah's Bagels (510) 849-9951 See reviews on Local	2344 Telegraph Ave Berkeley, CA Map	0.2
Dream Fluff Donuts (510) 649-0471 See reviews on Local	2637 Ashby Ave Berkeley, CA Map	1.0
Noah's Bagels (510) 654-0944 See reviews on Local	3170 College Ave Berkeley, CA Map	1.4
All Star Donut (510) 666-0878 See reviews on Local	1255 University Ave Berkeley, CA Map	1.5
Noah's Bagels (510) 525-4447 See reviews on Local	1883 Solano Ave Berkeley, CA Map	1.7
Boogie Woogie Bagel Boy (510) 524-3104 See reviews on Local	1281 Gilman St Albany, CA Map	1.8
Boogie Woogie Bagel Boy (510) 527-0272 See reviews on Local	1218 Santa Fe Ave Albany, CA Map	1.8
Berkeley Donut Shop (510) 653-9044 See reviews on Local	3043 San Pablo Ave Berkeley, CA Map	2.0
Happy Donuts (510) 524-9816 See reviews on Local	1041 Gilman St Berkeley, CA Map	2.1



amazon.com

"toy" > Toys & Games

Showing 1 - 24 of 260,516 Results « Previous | **Page:** **1** 2 3 ... | Next » Sort by Price: High to Low

1. **Steiff Germany: Giant Studio Elephant: Overall Size ~ 210cm high (82.68")**
   Buy new: ~~$22,000.00~~ **$16,000.00**
   Usually ships in 3 to 5 weeks

2. **Miss Megan Modular Playground 3.5 Inch Posts**
   Buy new: **$12,922.00**
   Usually ships in 2 to 3 weeks
   › Show only SportsPlay items

3. **Meade LX200 GPS 16 in. UHTC SCT with Super Field Tripod**
   Buy new: **$10,988.71**
   In Stock

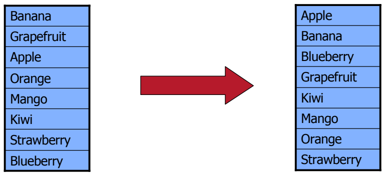
4. **Apollo 17 Astronaut Space Suit Replica**
   Currently unavailable
   ★★★½☆

5. **Meade 14" f/8 RCX Advanced Ritchey-Chretien Telescope, with UHTC; Tripod - 1408-40-01**
   Buy new: ~~$13,949.00~~ **$9,599.99**
   2 Used & new from $9,593.71
   In Stock
   › Show only MEA items

6. **Lizard Thumb Piece Entry Way Lock Set - ETS241B - Thumbgrip Handlesets**
   Currently unavailable

Why sort?

- Users usually want data sorted
- Sorting is first step in bulk-loading a B+ tree
- Sorting useful for eliminating duplicates
- Sort-merge join algorithm involves sorting



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So?

- Don't we know how to sort?
  - Quicksort
  - Mergesort
  - Heapsort
  - Selection sort
  - Insertion sort
  - Radix sort
  - Bubble sort
  - Etc.
- Why don't these work for databases?

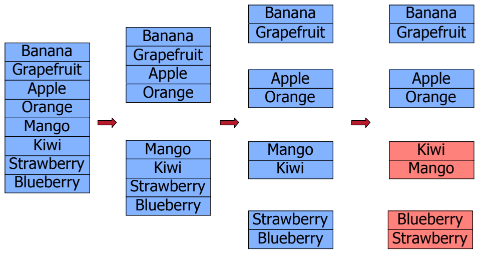
Key problem in database sorting

4 GB: $300

480 GB: $300

- How to sort data that does not fit in memory?

Example: merge sort



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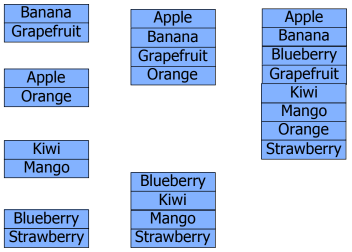

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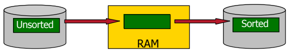
Isn't that good enough?

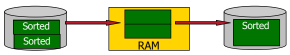
- Consider a file with N records
- Merge sort is O(N lg N) comparisons
- We want to minimize disk I/Os
  - Don't want to go to disk O(N lg N) times!
- Key insight: sort based on pages, not records
  - Read whole pages into RAM, not individual records
  - Do some in-memory processing
  - Write processed blocks out to disk
  - Repeat

2-way sort

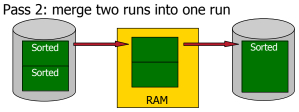
- Pass 0: sort each page



- Pass 1: merge two pages into one run



- Pass 2: merge two runs into one run



- …
- Sorted!

What did that cost us?

- P pages in the file
- Each pass: read and wrote P pages
- How many passes?
  - Pass 0
  - Pass 1: went from P pages to P/2 runs
  - Pass 2: went from P/2 runs to P/4 runs
  - …
  - Total number of passes: $\lceil \text{Log}_2 P \rceil + 1$
- Total cost: $2P * (\lceil \text{Log}_2 P \rceil + 1)$

What did that cost us?

- Why is this better than plain old merge sort?
  - N >> P
  - So O(N lg N) >> O(P lg P)
- Example:
  - 1,000,000 record file
    - 8 KB pages
    - 100 byte records
    - = 80 records per page
    - = 12,500 pages
  - Plain merge sort: 41,863,137 disk I/O’s
  - 2-way external merge sort: 365,241 disk I/O’s
  - 4.8 days versus 1 hour

Can we do better?

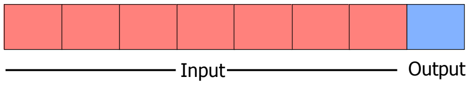
- 2-way merge sort only uses 3 memory buffers
  - Two buffers to hold input records
  - One buffer to hold output records
    - When that buffer fills up, flush to disk
- Usually we have a lot more memory than that
  - Set aside 100 MB for sort scratch space = 12,800 buffer pages
- Idea: read as much data into memory as possible each pass
  - Thus reducing the number of passes
  - Recall total cost:

2P * Passes

External merge sort

- Assign B input buffers and 1 output buffer
- Pass 0: Read in runs of B pages, sort, write to disk
- Pass 1: Merge B runs into one
  - For each run, read one block
  - When a block is used up, read next block of run
- Pass 2: Merge B runs into one
- …
- Sorted!

Example



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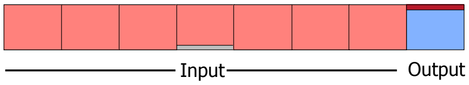

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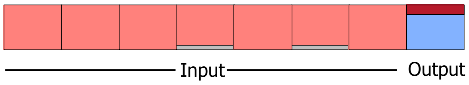

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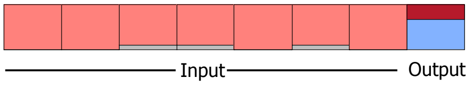

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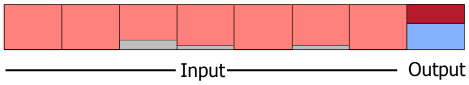

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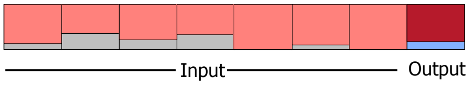

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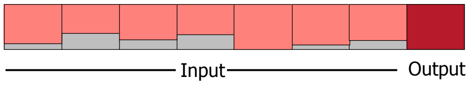

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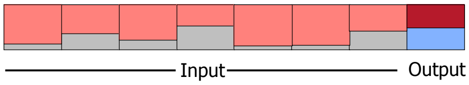

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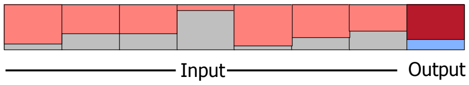

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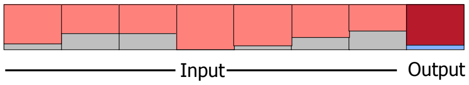

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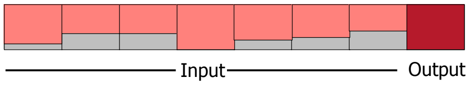

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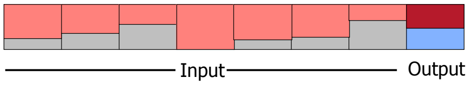

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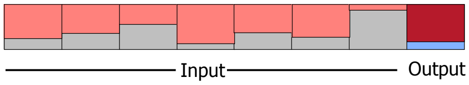

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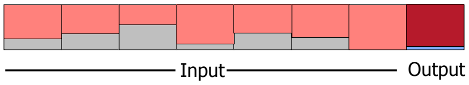

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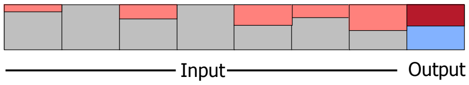

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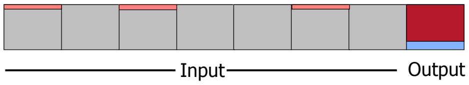

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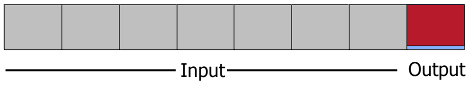


What did that cost us?

- P pages in file, B buffer pages in RAM
- P/B runs of size B
- Each pass: read and write P pages
- How many passes?
  - $\lceil Log_{B-1} \lceil P/B \rceil \rceil + 1$
- Total cost: $2P * \lceil Log_{B-1} \lceil P/B \rceil \rceil + 1$

Example

- 1,000,000 records in 12,500 pages
- Use 10 buffer pages in memory
- 4 passes
- 100,000 disk I/Os
  - 17 minutes versus 1 hour for 2-way sort

Can I do two passes?

- Pass 0: sort runs
- Pass 1: merge runs
- Given B buffers
- Need:
  - No more than B-1 runs
  - Each run no longer than B pages
- Can do two passes if $P \leq B * (B-1)$
- Question: what's the largest file we can sort in three passes? N passes?

Make I/Os faster

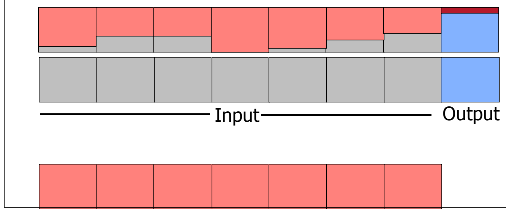
- Cost = I/Os is a simplification
  - Sequential I/Os are cheaper than random I/Os
- Read blocks of pages at a time
  - X = Blocking factor
  - B = buffer pages
  - (B/X – X) input "buffer blocks", one output "buffer block"
- Result
  - Fewer runs merged per pass = more passes
  - Less time per I/O = quicker passes
  - Tradeoff!
    - Maximize total sort time by choosing X given B, P and I/O latencies

Overlap computation and I/O

- Problem: CPU must wait for I/O
  - Suppose I need to read a new block
    - Stop merging
    - Initiate I/O
    - Wait
    - Complete I/O
    - Resume merging

Solution: double buffering

- Keep a second set of buffers
  - Process one set while waiting for disk I/O to fill the other set



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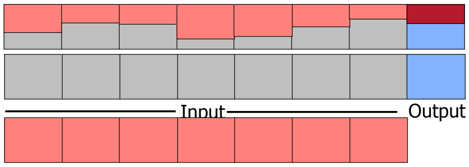

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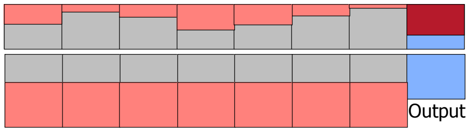

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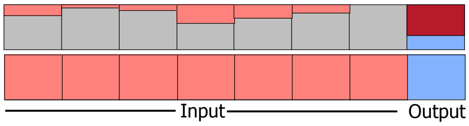

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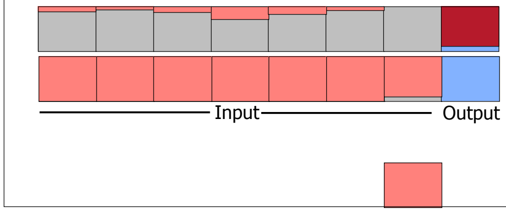

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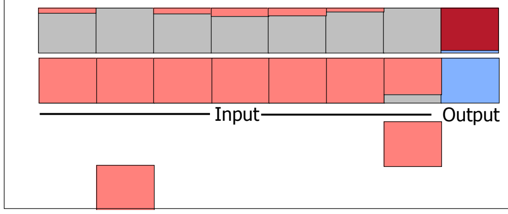
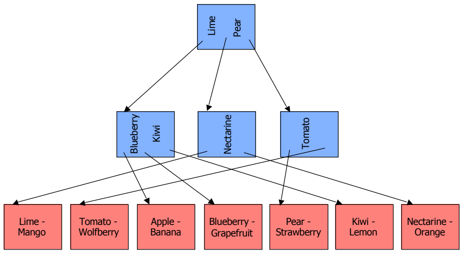


What if the data is already sorted?

- Yay!
- Often this happens because of a B+ tree index
  - Leaf level of a B+ tree has all records in sorted order
  - Two possibilities: B+ tree is clustered or unclustered

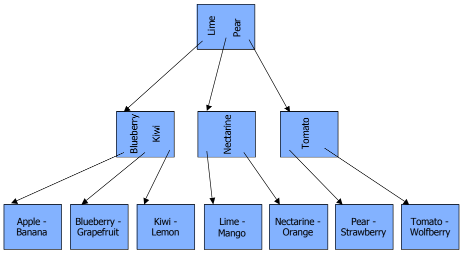
Clustered B+ tree

Sweep through leaf layer, reading data blocks in order



Clustered B+ tree

Sweep through leaf layer, reading leaf blocks in order



What did that cost us?

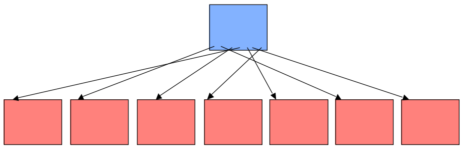
- Traverse B+ tree to left-most leaf page
- Read all leaf pages
  - For each leaf page, read data pages
- Data not in B+ tree:
  - Height + Width + Data pages
- Data in B+ tree:
  - Height + Width

Example

- 1,000,000 records, 12,500 data pages
- Assume keys are 10 bytes, disk pointers are 8 bytes
  - So ≈ 300 entries per 8 KB B+ tree page (if two-thirds full)
- Data not in B+ tree
  - 12,500 entries needed = 42 leaf pages
  - Two level B+tree
  - Total cost: 1 + 42 + 12,500 = 12,543 I/Os
  - 2 minutes versus 17 minutes for external merge sort
- Data in B+ tree
  - Three level B+ tree, 12,500 leaf pages
  - Total cost: 2 + 12,500 = 12,502 I/Os
  - Also about 2 minutes

What if the B+ tree is unclustered?

- We know the proper sort order of the data
- But retrieving the data is hard!



What if the B+ tree is unclustered?

- Result is that in the worst case, may need one disk I/O per record
  - Even though we know the sort order!
- Usually external merge sort is better in these cases
  - Unless all you need is the set of keys

Summary

- Sorting is very important
- Basic algorithms not sufficient
  - Assume memory access free, CPU is costly
  - In databases, memory (e.g. disk) access is costly, CPU is (almost free)
- Try to minimize disk accesses
  - 2-way sort: read and write records in blocks
  - External merge sort: fill up as much memory as possible
  - Blocked I/O: try to do sequential I/O
  - Double buffering: read and compute at the same time
  - Clustering B+ tree: the data is already sorted. Hooray!
  - Unclusered B+ tree: no help at all