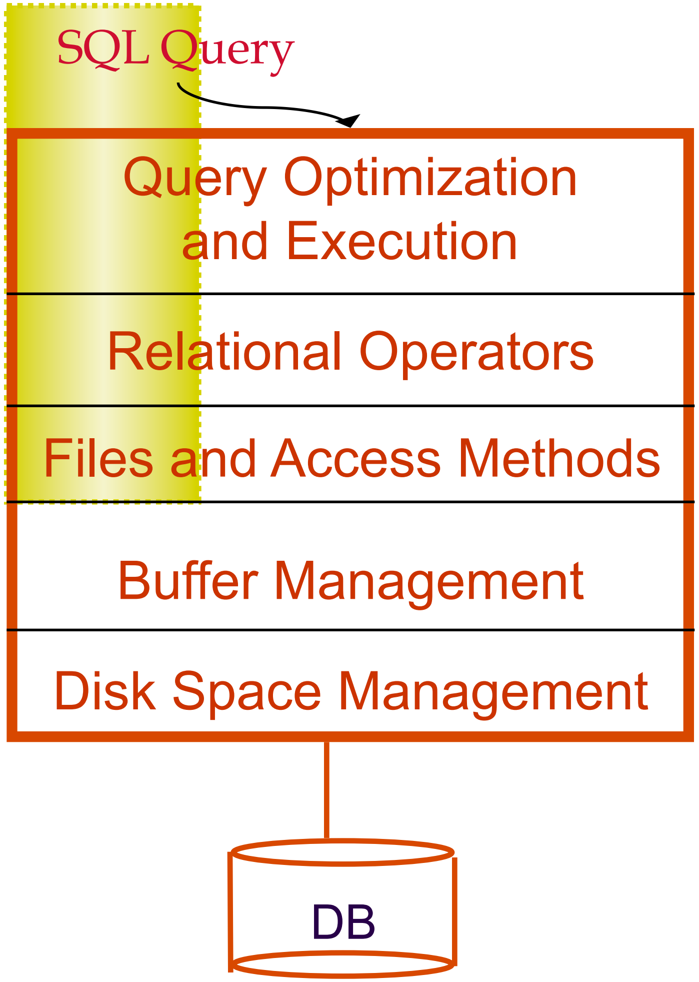
CAS CS 460/660
Introduction to Database Systems

Query Evaluation I

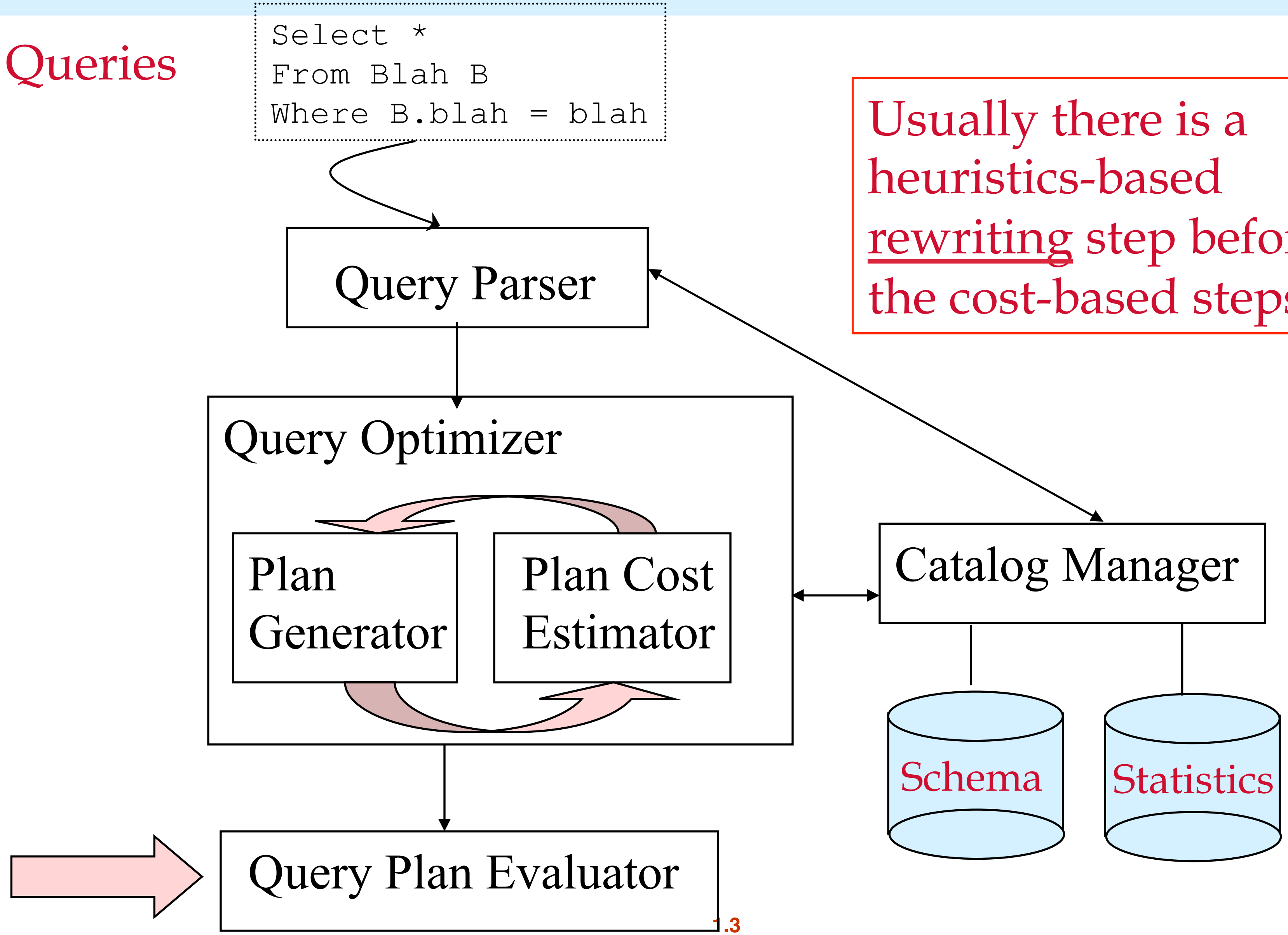
Slides from UC Berkeley

Introduction

- We' ve covered the basic underlying storage, buffering, and indexing technology.
  - Now we can move on to query processing.
- Some database operations are EXPENSIVE
- Can greatly improve performance by being "smart"
  - e.g., can speed up 1,000x over naïve approach
- Main weapons are:
  1. clever implementation techniques for operators
  2. exploiting "equivalencies" of relational operators
  3. using statistics and cost models to choose among these.



Cost-based Query Sub-System



Queries

```
Select *
From Blah B
Where B.blah = blah
```

Usually there is a heuristics-based rewriting step before the cost-based steps.

Query Parser

Query Optimizer

Plan Generator

Plan Cost Estimator

Catalog Manager

Schema

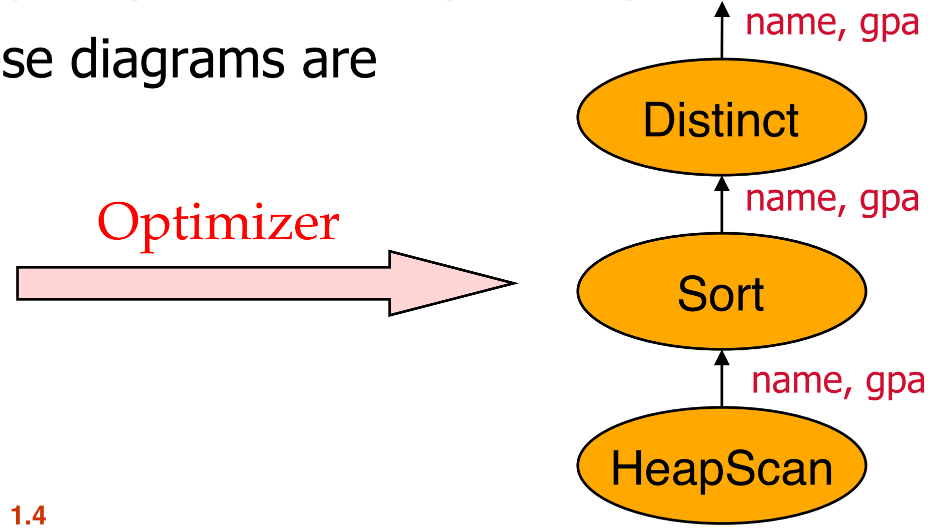
Statistics

Query Plan Evaluator

Query Processing Overview

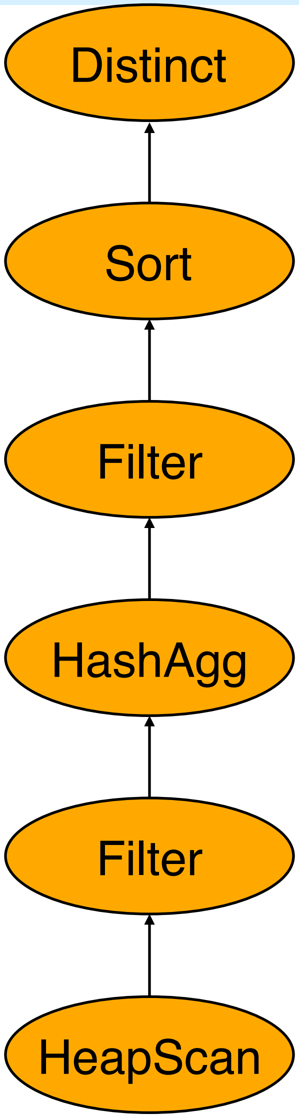
- The *query optimizer* translates SQL to a special internal "language"
  - Query Plans
- The *query executor* is an *interpreter* for query plans
- Think of query plans as "box-and-arrow" *dataflow* diagrams
  - Each box implements a *relational operator*
  - Edges represent a flow of tuples (columns as specified)
  - For single-table queries, these diagrams are straight-line graphs

```
SELECT DISTINCT name, gpa
  FROM Students
```



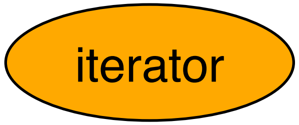
Query Optimization

- A deep subject, focuses on multi-table queries
  - We will only need a cookbook version for now.
- Build the dataflow bottom up:
  - Choose an Access Method (HeapScan or IndexScan)
    - Non-trivial, we'll learn about this later!
  - Next apply any WHERE clause filters
  - Next apply GROUP BY and aggregation
    - Can choose between sorting and hashing!
  - Next apply any HAVING clause filters
  - Next Sort to help with ORDER BY and DISTINCT
    - In absence of ORDER BY, can do DISTINCT via hashing!



Iterators

- The relational operators are all subclasses of the class `iterator`:



```
class iterator {
   void init();
   tuple next();
   void close();
   iterator inputs[];
   // additional state goes here
}
```

- Note:
  - Edges in the graph are specified by inputs (max 2, usually 1)
  - Encapsulation: any iterator can be input to any other!
  - When subclassing, different iterators will keep different kinds of state information

Example: Scan

```
class Scan extends iterator {
   void init();
   tuple next();
   void close();
   iterator inputs[1];
   bool_expr filter_expr;
   proj_attr_list proj_list;
}
```

- `init()`:
  - Set up internal state
  - call init() on child – often a file open
- `next()`:
  - call next() on child until qualifying tuple found or EOF
  - keep only those fields in “proj_list”
  - return tuple (or EOF -- “End of File” -- if no tuples remain)
- `close()`:
  - call close() on child
  - clean up internal state

Note: Scan also applies “selection” filters and “projections”
(without duplicate elimination)

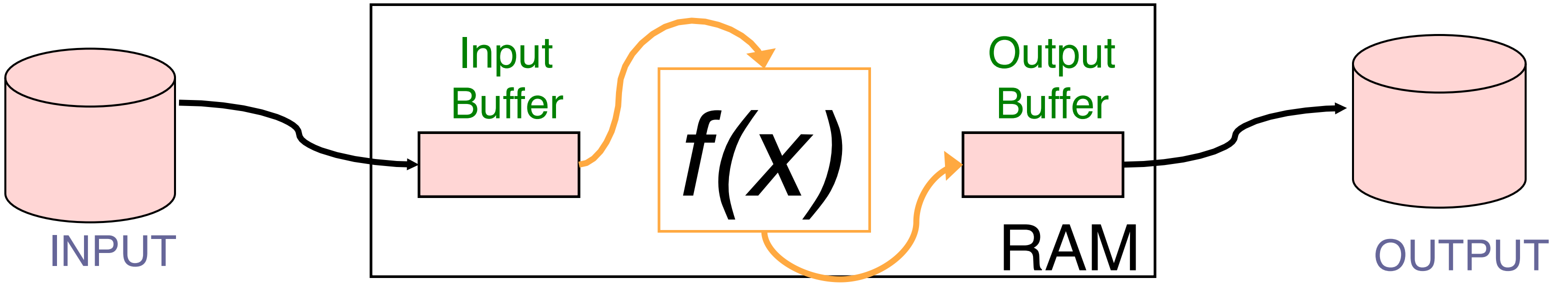
Example: Sort

```
class Sort extends iterator {
   void init();
   tuple next();
   void close();
   iterator inputs[1];
   int numberOfRuns;
   DiskBlock runs[];
   RID nextRID[];
}
```

- `init()`:
  - generate the sorted runs on disk
  - Allocate `runs[]` array and fill in with disk pointers.
  - Initialize numberOfRuns
  - Allocate nextRID array and initialize to NULLs
- `next()`:
  - nextRID array tells us where we’re “up to” in each run
  - find the next tuple to return based on nextRID array
  - advance the corresponding nextRID entry
  - return tuple (or EOF -- “End of File” -- if no tuples remain)
- `close()`:
  - deallocate the runs and nextRID arrays

Streaming through RAM

- Simple case: “Map”. (assume many records per disk page)
  - Goal: Compute *f(x)* for each record, write out the result
  - Challenge: minimize RAM, call read/write rarely
- Approach
  - Read a chunk from INPUT to an *Input Buffer*
  - Write *f(x)* for each item to an *Output Buffer*
  - When Input Buffer is consumed, read another chunk
  - When Output Buffer fills, write it to OUTPUT
- Reads and Writes are *not* coordinated (i.e., not in lockstep)
  - E.g., if f() is Compress(), you read many chunks per write.
  - E.g., if f() is DeCompress(), you write many chunks per read.



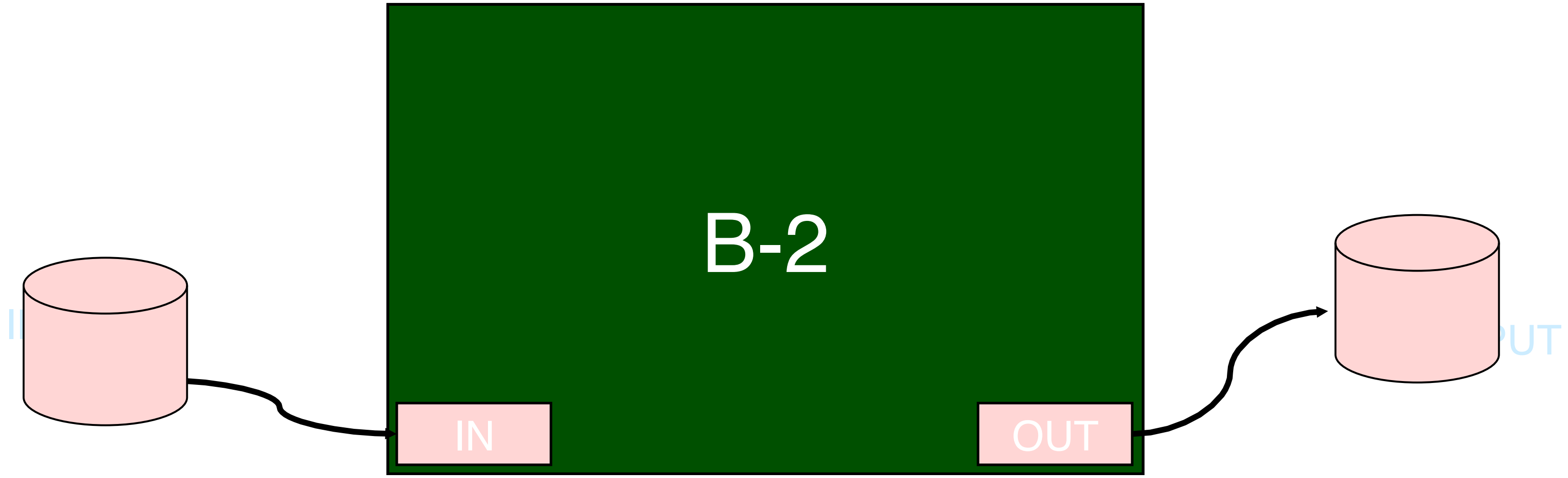
Rendezvous

- Streaming: one chunk at a time. Easy.
- But some algorithms need certain items to be co-resident in memory
  - not guaranteed to appear in the same input chunk

- *Time-space Rendezvous*
  - in the same place (RAM) at the same time
- There may be many combos of such items

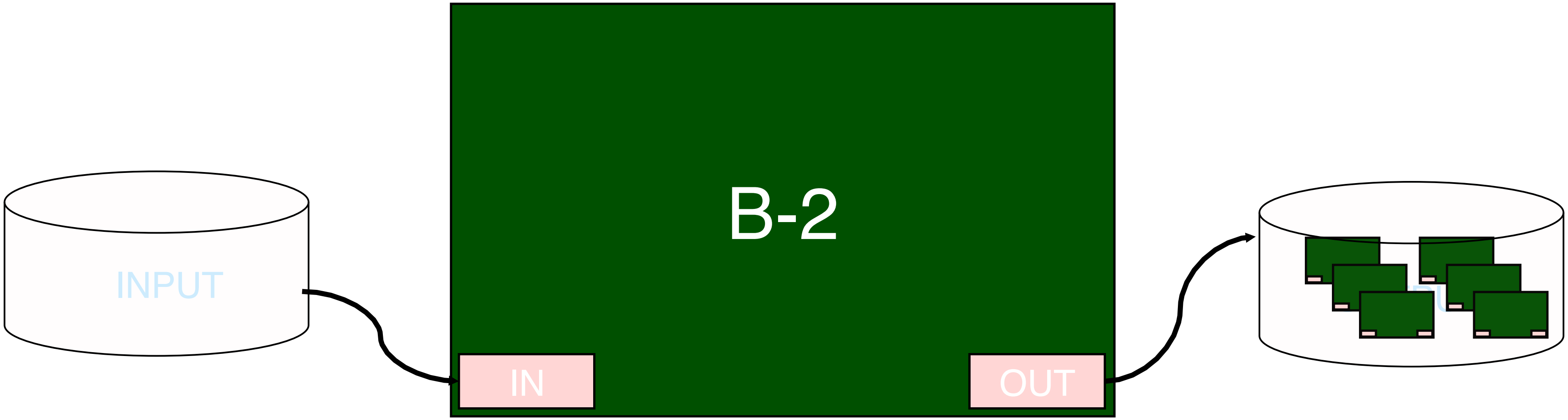
Divide and Conquer

- *Out-of-core* algorithms orchestrate rendezvous.
- Typical RAM Allocation:
    - Assume B pages worth of RAM available
    - Use 1 page of RAM to read into
    - Use 1 page of RAM to write into
    - B-2 pages of RAM as workspace



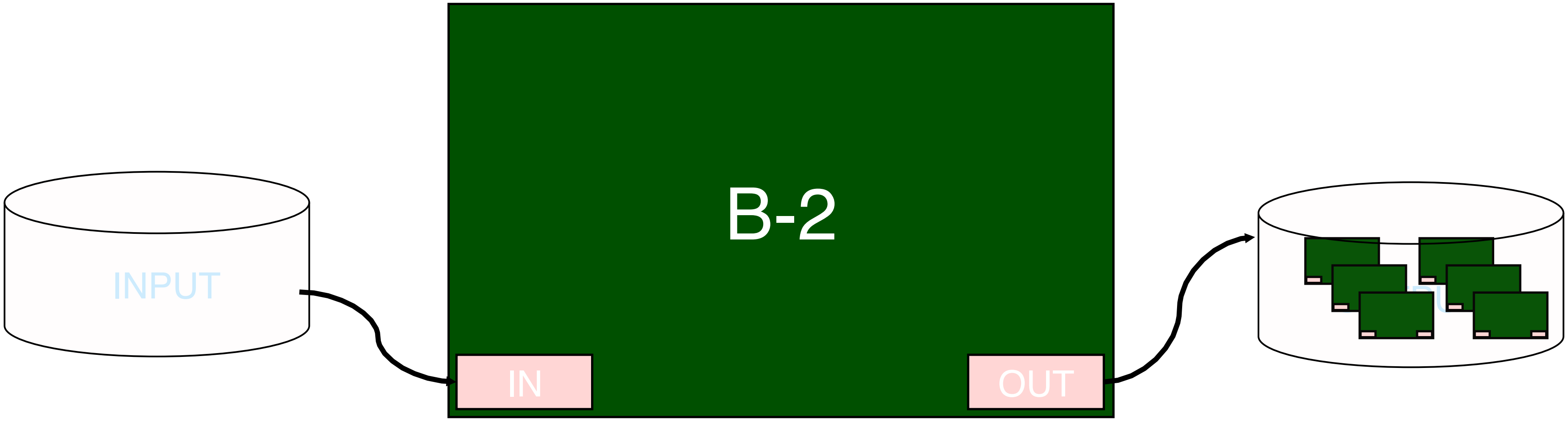
Divide and Conquer

- Phase 1
  - “streamwise” *divide* into N/(B-2) megachunks
  - output (write) to disk one megachunk at a time



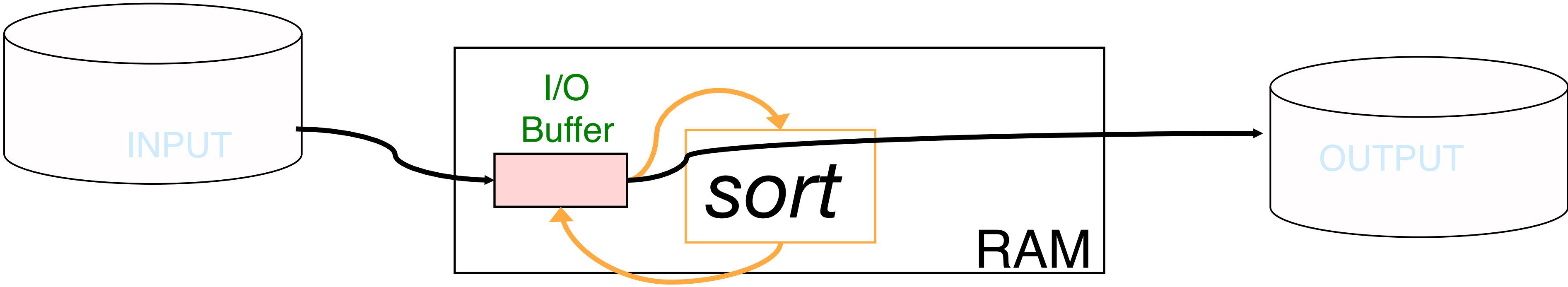
Divide and Conquer

- Phase 2
  - Now megachunks will be the input
  - process each *megachunk* individually.



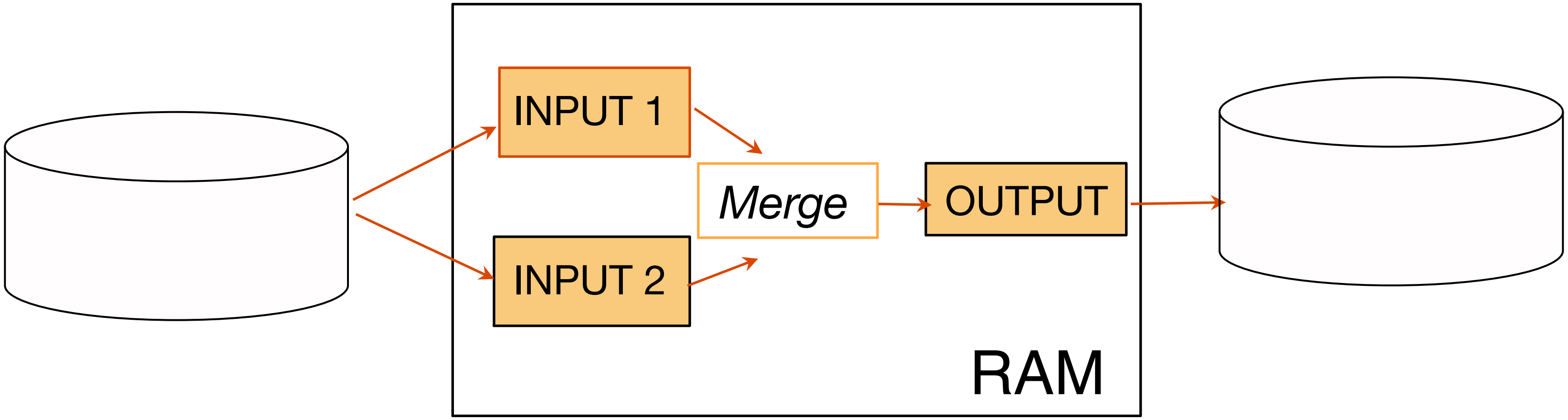
Sorting: 2-Way

- Pass 0:
  - read a page, sort it, write it.
  - only one buffer page is used
  - a repeated "batch job"



Sorting: 2-Way (cont.)

- Pass 1, 2, 3, …, etc. (merge):
  - requires **3 buffer pages**
    - note: this has nothing to do with double buffering!
  - *merge pairs* of runs into runs twice as long
  - a streaming algorithm, as in the previous slide!



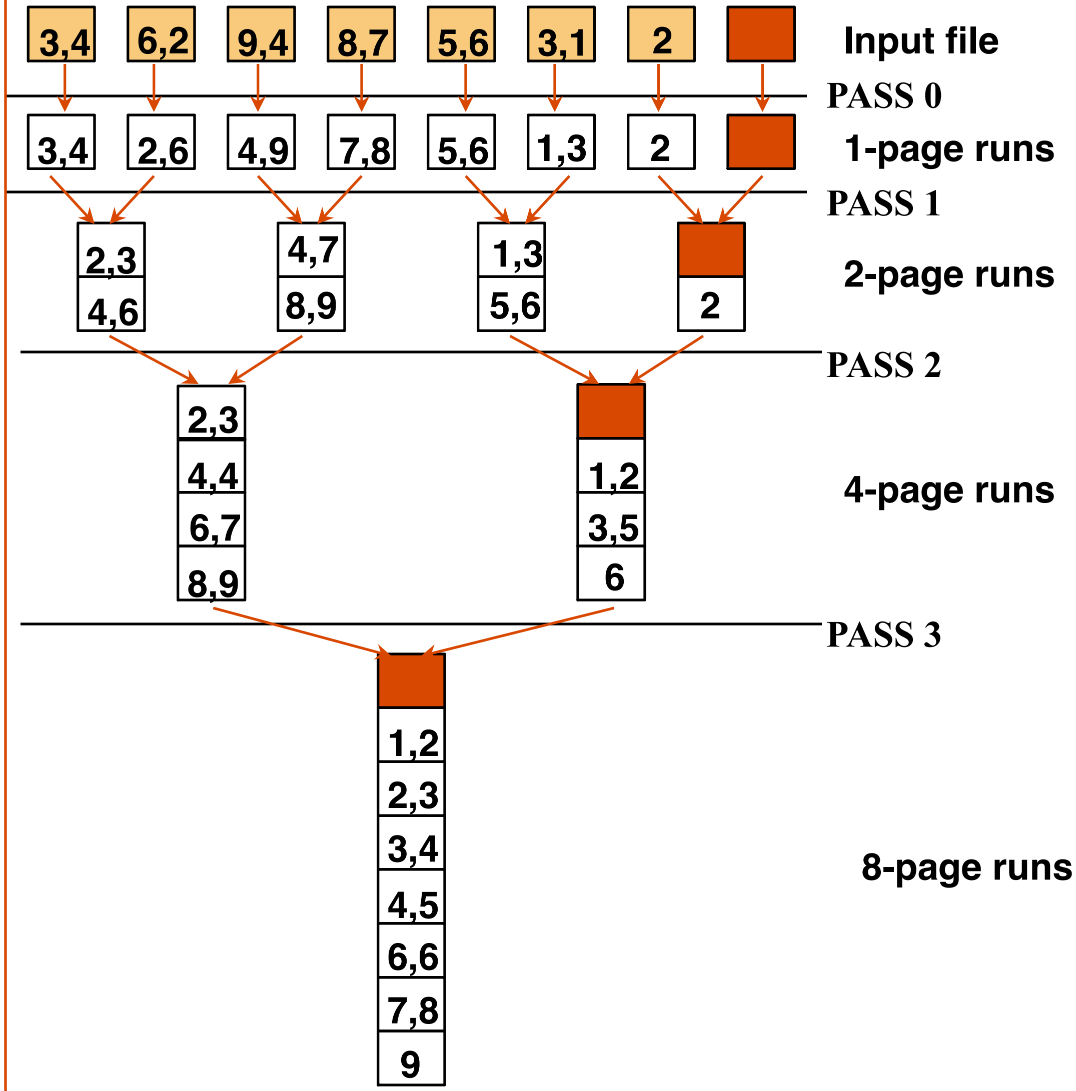
Two-Way External Merge Sort

- ***Sort subfiles and Merge***
- How many passes?
- N pages in the file
  => the number of passes =

$$\lceil \log_2 N \rceil + 1$$

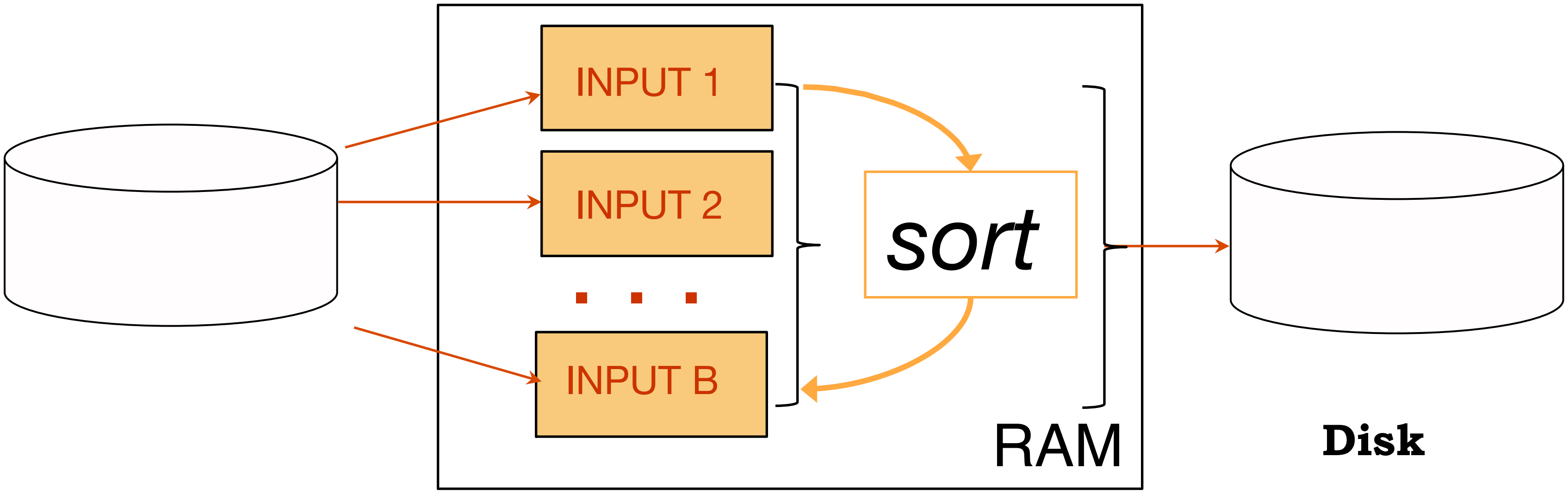
- Total I/O cost? (reads + writes)
- Each pass we read + write each page in file. So total cost is:

$$2N\left(\lceil \log_2 N \rceil + 1\right)$$



General External Merge Sort

- More than 3 buffer pages. How can we utilize them?
- To sort a file with N pages using B buffer pages:
  - Pass 0: use B buffer pages. Produce $\lceil N / B \rceil$ sorted runs of B pages each.

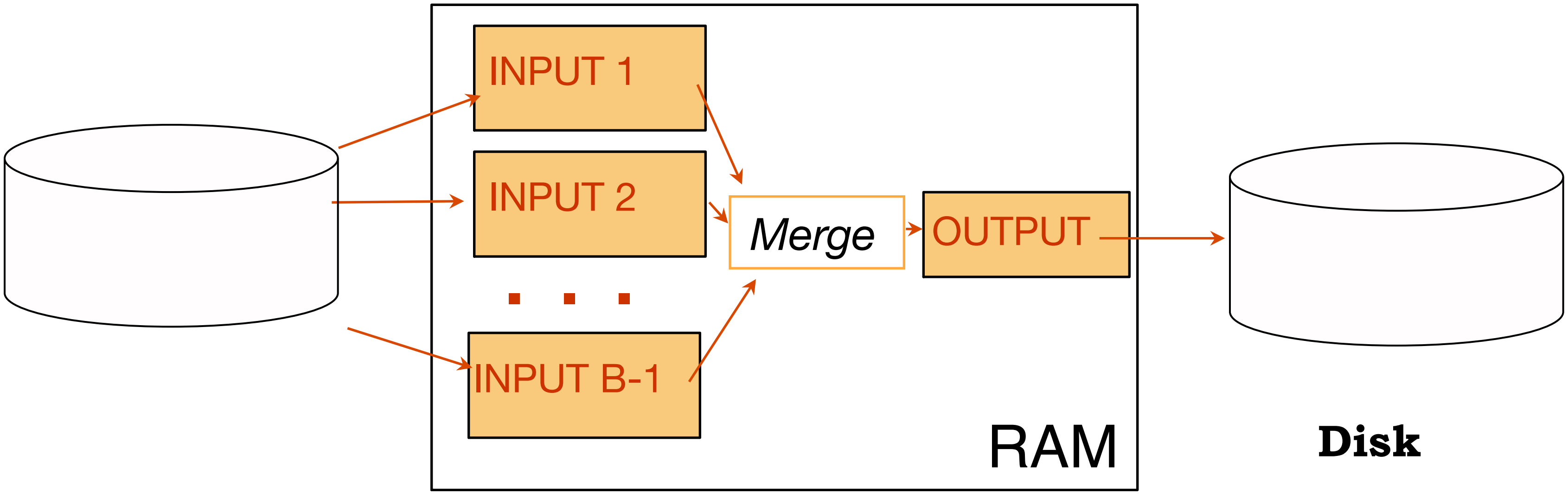


Pass 0 – Create Sorted Runs

General External Merge Sort

Pass 1, 2, …, etc.: merge B-1 runs.

Creates runs of (B-1) * size of runs from previous pass.



Merging Runs

Cost of External Merge Sort

- Number of passes: $1 + \lceil \log_{B-1} \lceil N / B \rceil \rceil$
- Cost = 2N * (# of passes)
- E.g., with 5 buffer pages, to sort 108 page file:
    - Pass 0: $\lceil 108 / 5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
    - Pass 1: $\lceil 22 / 4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
    - Pass 2: 2 sorted runs, 80 pages and 28 pages
    - Pass 3: Sorted file of 108 pages

Formula check: $1 + \lceil \log_4 22 \rceil = 1+3$ → <u>4 passes</u> √

of Passes of External Sort

(I/O cost is 2N times number of passes)

N	B=3	B=5	B=9	B=17	B=129	B=257
100	7	4	3	2	1	1
1,000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

Memory Requirement for External Sorting

- How big of a table can we sort in two passes?
  - Each "sorted run" after Phase 0 is of size B
  - Can merge up to B-1 sorted runs in Phase 1
- Answer: B(B-1).
  - Sort N pages of data in about $\sqrt{N}$ space

Alternative: Hashing

- Idea:
  - Many times we don’t require order
  - E.g.: removing duplicates
  - E.g.: forming groups
- Often just need to *rendezvous* matches
- Hashing does this
  - And may be cheaper than sorting! (Hmmm…!)
  - But how to do it out-of-core??

Divide

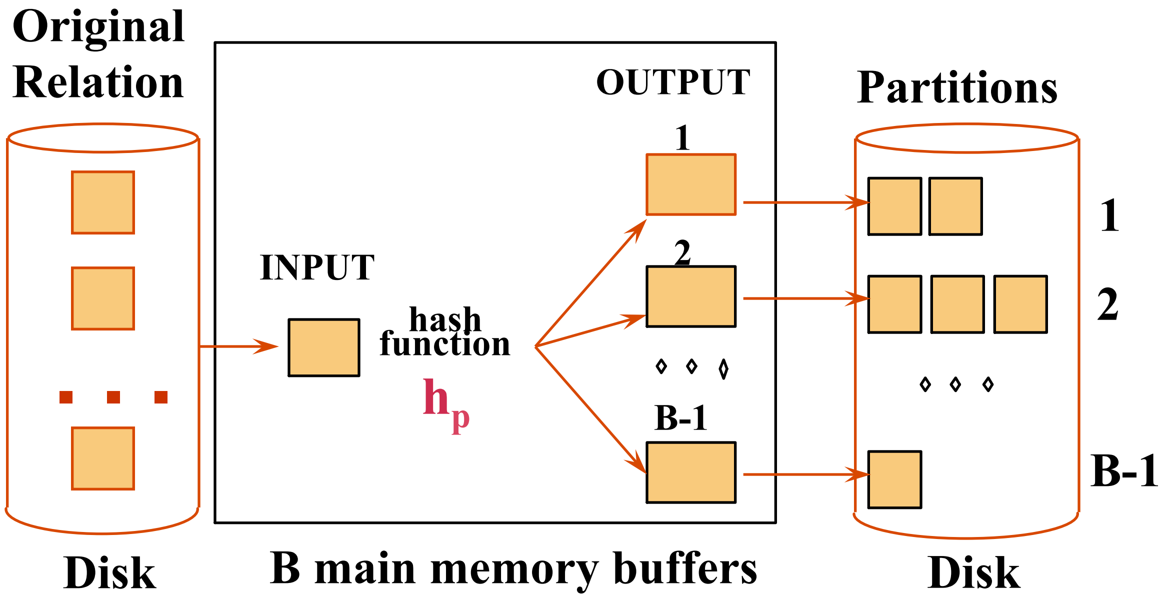
- Streaming Partition (divide):
  Use a hash f'n h_p to stream records to disk partitions
  - All matches rendezvous in the same partition.
  - *Streaming* alg to create partitions on disk:
    - "Spill" partitions to disk via output buffers

Divide & Conquer

- Streaming Partition (divide):
  Use a hash function h_p to stream records to disk-based partitions
  - All matches rendezvous in the same partition.
  - *Streaming* alg to create partitions on disk:
    - "Spill" partitions to disk via output buffers
- ReHash (conquer):
  Read partitions into RAM-based hash table one at a time, using hash function h_r
  - Then go through each bucket of this hash table to achieve rendezvous in RAM
- Note: Two different hash functions
  - h_p is coarser-grained than h_r

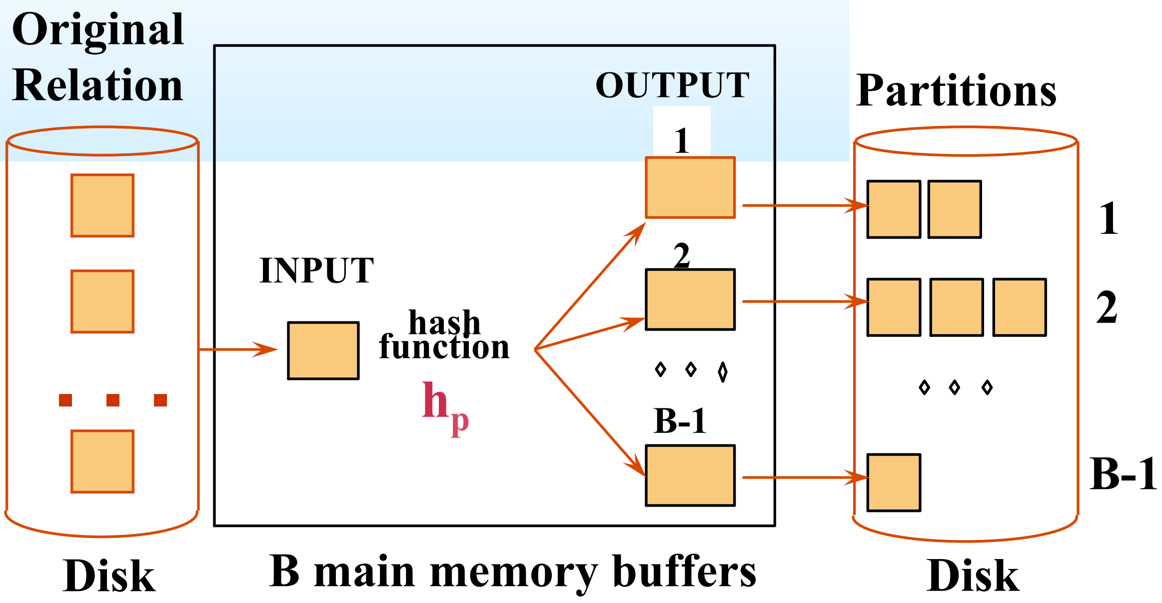
Two Phases

- Partition:

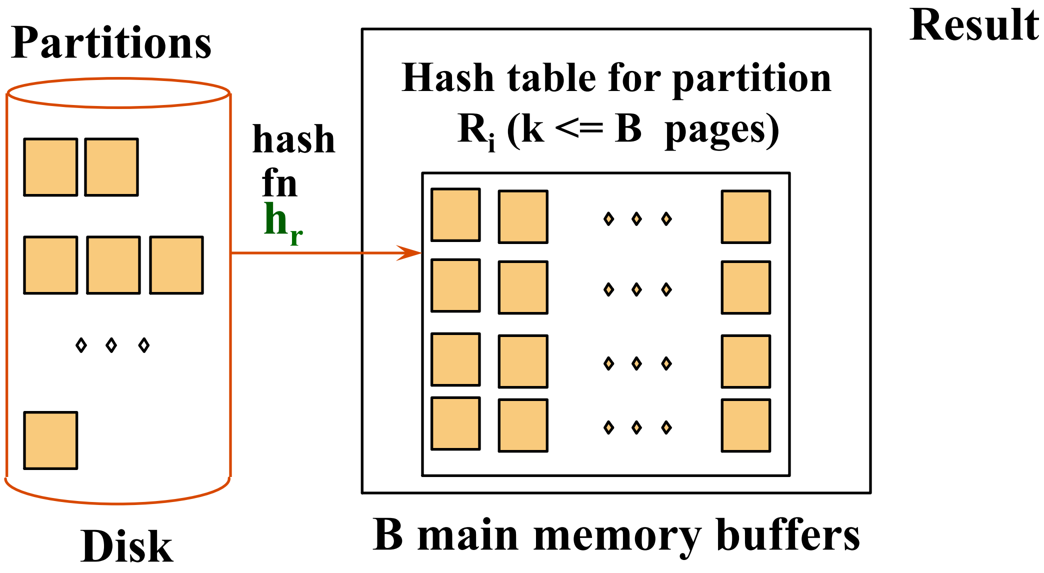


Two Phases

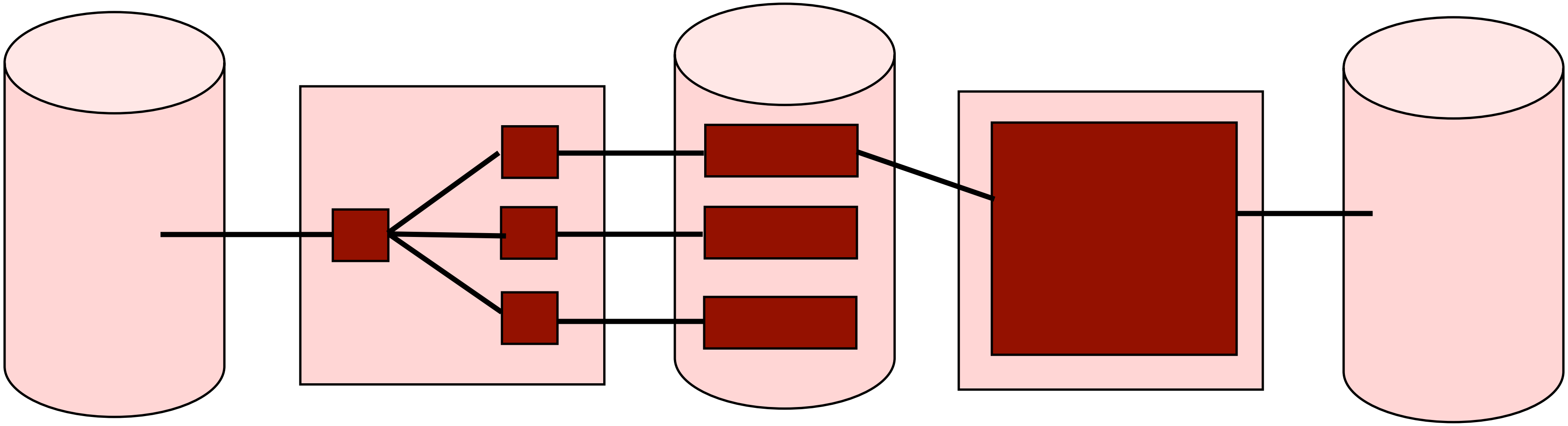
- Partition:



- Rehash:



Cost of External Hashing



cost = 4*N IO’s

Memory Requirement

- How big of a table can we hash in two passes?
  - B-1 “partitions” result from Phase 0
  - Each should be no more than B pages in size
  - Answer: B(B-1).
    - We can hash a table of size N pages in about $\sqrt{N}$ space
  - Note: assumes hash function distributes records evenly!
- Have a bigger table? Recursive partitioning!
  - How many times?
    - Until every partition fits in memory !! (<=B)

How does this compare with external sorting?

So which is better ??

- Simplest analysis:
  - Same memory requirement for 2 passes
  - Same I/O cost
  - But we can dig a bit deeper…
- Sorting pros:
  - Great if input already sorted (or almost sorted) w/heapsort
  - Great if need output to be sorted anyway
  - Not sensitive to “data skew” or “bad” hash functions
- Hashing pros:
  - For duplicate elimination, scales with # of values
    - Not # of items! We’ll see this again.
  - Can exploit extra memory to reduce # IOs (stay tuned…)

Summing Up 1

- Unordered collection model
- Read in chunks to avoid fixed I/O costs

- Patterns for Big Data
  - Streaming
  - Divide & Conquer
  - also Parallelism (but we didn’t cover this here)

Summary Part 2

- Sort/Hash Duality
  - Sorting is Conquer & Merge
  - Hashing is Divide & Conquer
- Sorting is overkill for rendezvous
  - But sometimes a win anyhow
- Sorting sensitive to internal sort alg
  - Quicksort vs. HeapSort
  - In practice, QuickSort tends to be used
- Don’t forget double buffering (with threads)