CPS216: Data-Intensive Computing Systems

Query Execution (Sort and Join operators)

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Roadmap

- A simple operator: Nested Loop Join
- Preliminaries
  - Cost model
  - Clustering
  - Operator classes
- Operator implementation (with examples from joins)
  - Scan-based
  - Sort-based
  - Using existing indexes
  - Hash-based
- Buffer Management
- Parallel Processing

Nested Loop Join (NLJ)

R1

B	C
a	10
a	20
b	10
d	30

$\bowtie$

C	D
10	cat
40	dog
15	bat
20	rat

R2

- NLJ (conceptually)

```
for each $r \in R1$ do
    for each $s \in R2$ do
        if $r.C = s.C$ then output r,s pair
```

Nested Loop Join (contd.)

- Tuple-based
- Block-based
- Asymmetric

Implementing Operators

- Basic algorithm
  - Scan-based (e.g., NLJ)
  - Sort-based
  - Using existing indexes
  - Hash-based (building an index on the fly)
- Memory management
  - Tradeoff between memory and #IOs
- Parallel processing

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Operator Cost Model

- Simplest: Count # of disk blocks read and written during operator execution
- Extends to query plans
  - Cost of query plan = Sum of operator costs
- Caution: Ignoring CPU costs

Assumptions

- Single-processor-single-disk machine
  - Will consider parallelism later
- Ignore cost of writing out result
  - Output size is independent of operator implementation
- Ignore # accesses to index blocks

Parameters used in Cost Model

B(R) = # blocks storing R tuples

T(R) = # tuples in R

V(R,A) = # distinct values of attr A in R

M   = # memory blocks available

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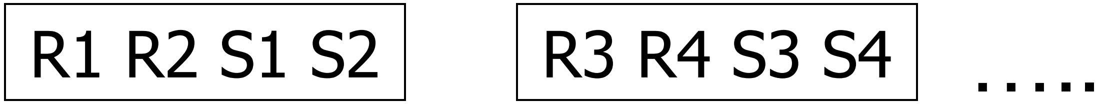
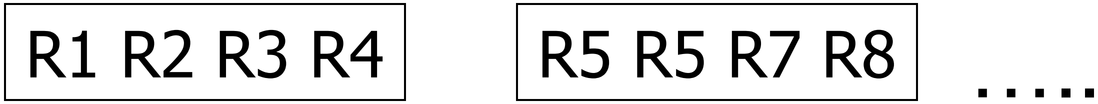
Notions of clustering

- Clustered file organization



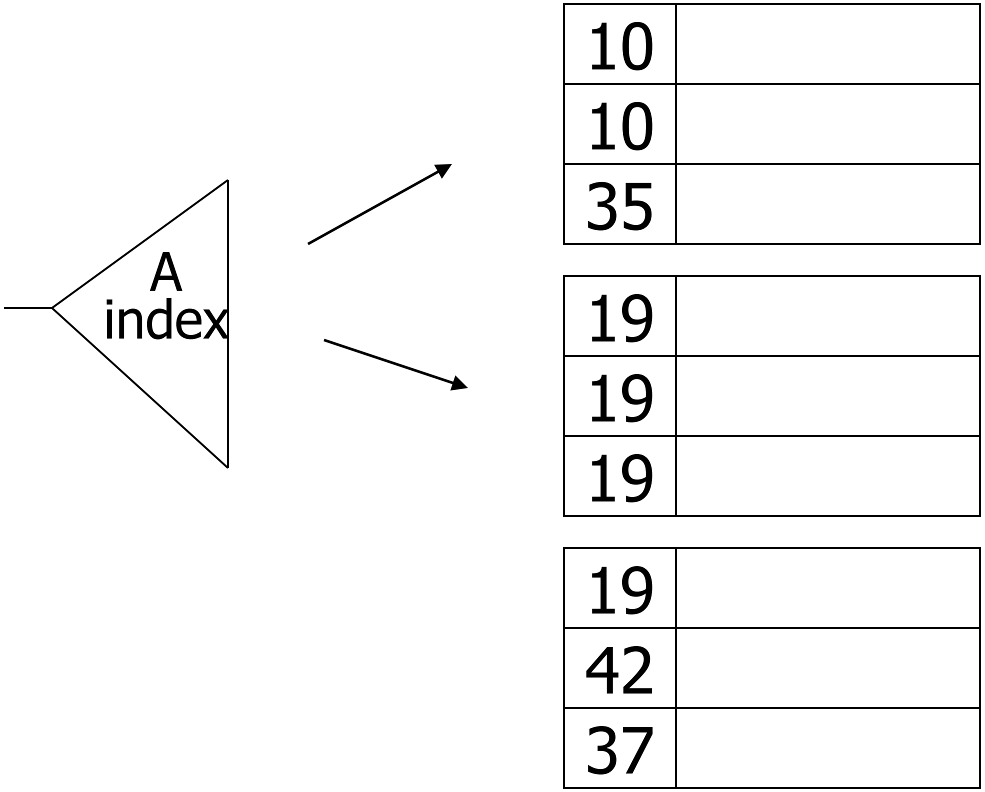
- Clustered relation



- Clustering index

Clustering Index

Tuples with a given value of the search key packed in as few blocks as possible



10	
10	
35	

19	
19	
19	

19	
42	
37	

Examples

T(R) = 10,000

B(R) = 200

If R is clustered, then # R tuples per block = 10,000/200 = 50

Let V(R,A) = 40

➔If I is a clustering index on R.A, then # IOs to access $\sigma_{R.A = \text{“a”}}(R) = 250/50 = 5$

➔ If I is a non-clustering index on R.A, then # IOs to access $\sigma_{R.A = \text{“a”}}(R) = 250$ (> B(R))

Operator Classes

	Tuple-at-a-time	Full-relation
Unary	Select	Sort
Binary		Difference

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Implementing Tuple-at-a-time Operators

- One pass algorithm:
  - Scan
  - Process tuples one by one
  - Write output
- Cost = B(R)
  - Remember: Cost = # IOs, and we ignore the cost to write output

Implementing a Full-Relation Operator, Ex: Sort

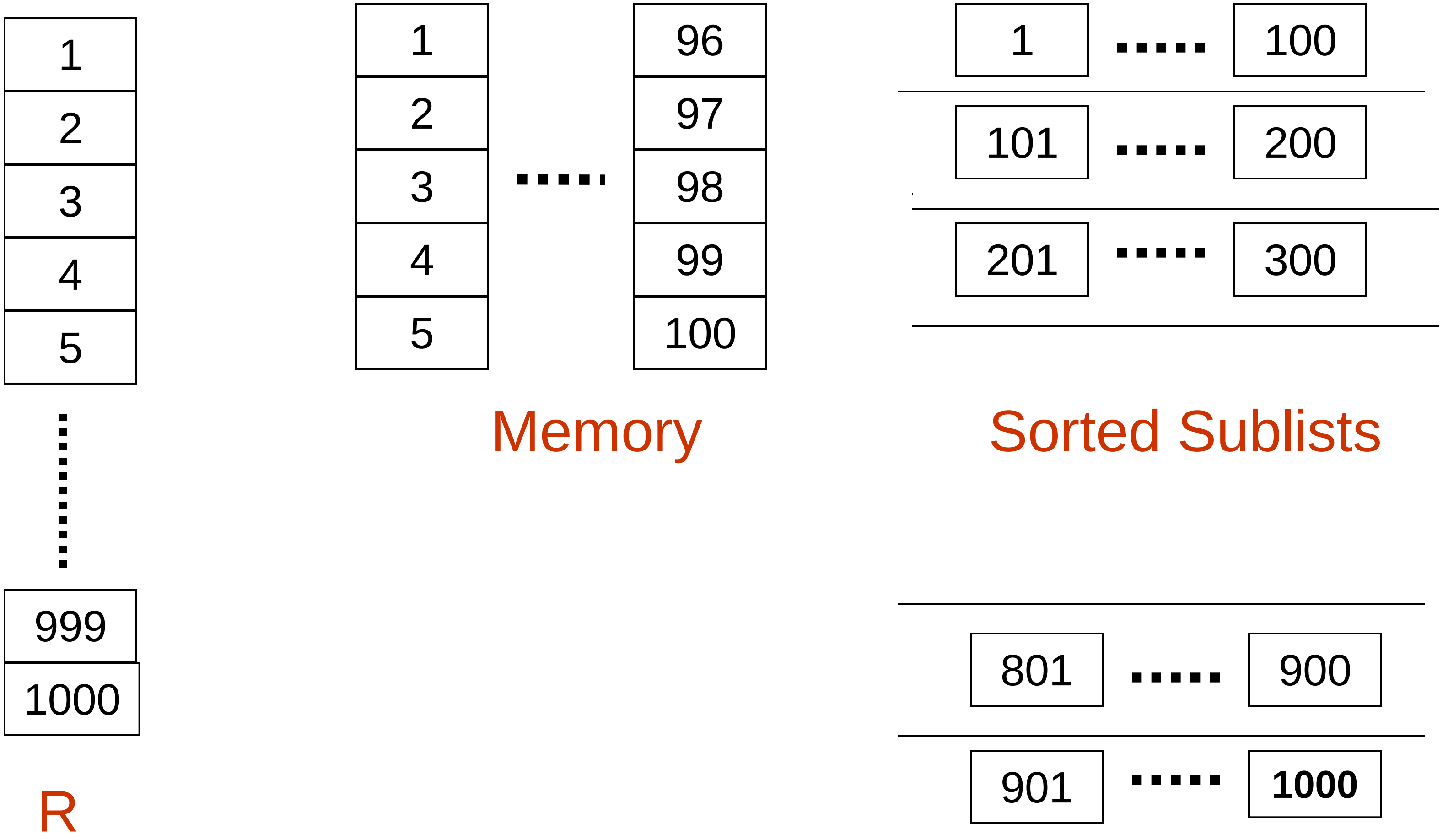
- Suppose T(R) x tupleSize(R) <= M x |B(R)|
- Read R completely into memory
- Sort
- Write output
- Cost = B(R)

Implementing a Full-Relation Operator, Ex: Sort

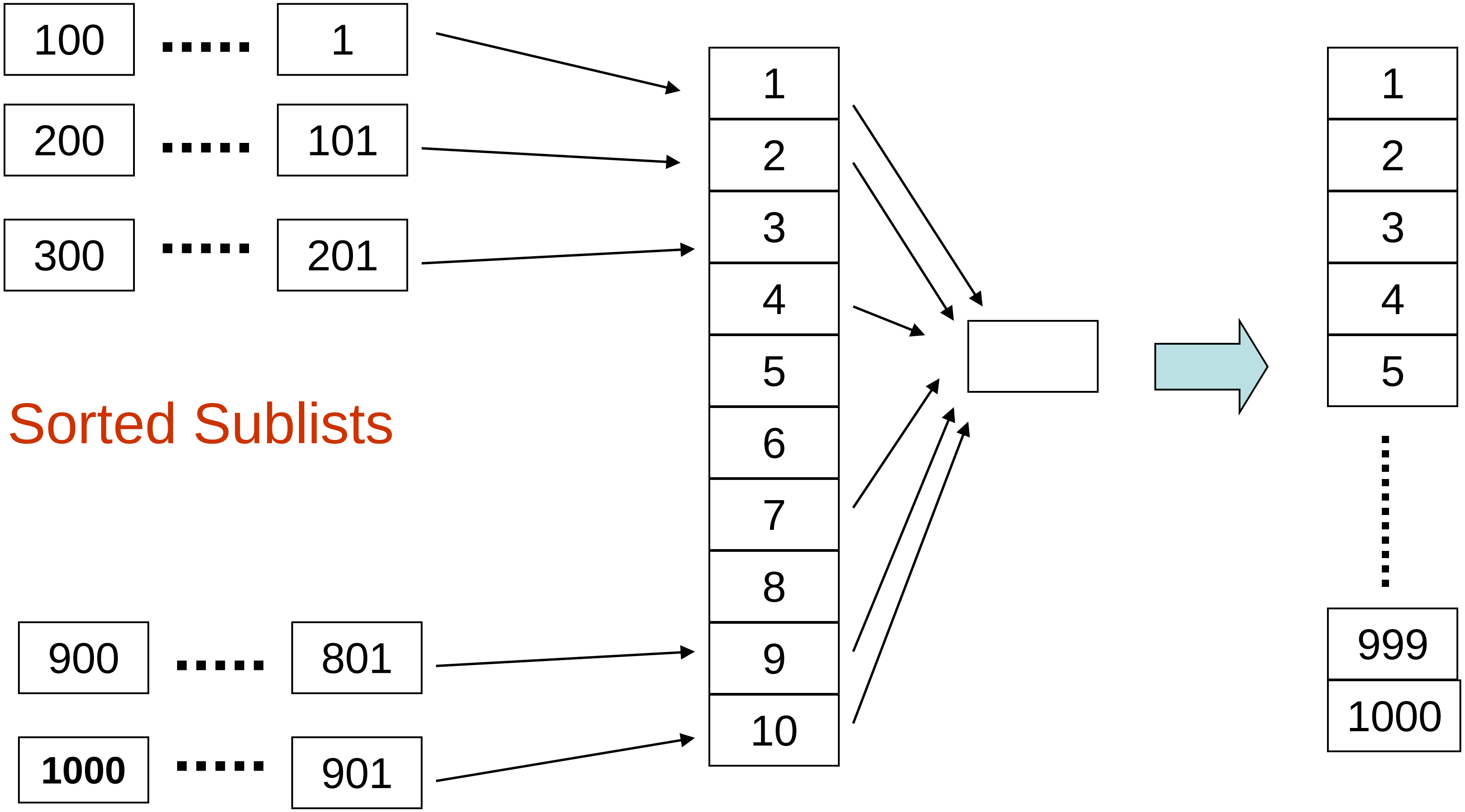
- Suppose R won’t fit within M blocks
- Consider a two-pass algorithm for Sort; generalizes to a multi-pass algorithm
- Read R into memory in M-sized chunks
- Sort each chunk in memory and write out to disk as a sorted sublist
- Merge all sorted sublists
- Write output

Two-phase Sort: Phase 1

Suppose B(R) = 1000, R is clustered, and M = 100



Two-phase Sort: Phase 2



Memory

Sorted R

Analysis of Two-Phase Sort

- Cost = 3xB(R) if R is clustered,
  = B(R) + 2B(R’) otherwise
- Memory requirement M >= $B(R)^{1/2}$

Duplicate Elimination

- Suppose B(R) <= M and R is clustered
- Use an in-memory index structure
- Cost = B(R)
- Can we do with less memory?
  - $B(\delta(R)) <= M$
  - Aggregation is similar to duplicate elimination

Duplicate Elimination Based on Sorting

- Sort, then eliminate duplicates
- Cost = Cost of sorting + B(R)
- Can we reduce cost?
  - Eliminate duplicates during the merge phase

Back to Nested Loop Join (NLJ)

R

B	C
a	10
a	20
b	10
d	30

$\bowtie$

C	D
10	cat
40	dog
15	bat
20	rat

S

- NLJ (conceptually)

```
for each r $\in$ R do
    for each s $\in$ S do
        if r.C = s.C then output r,s pair
```

Analysis of Tuple-based NLJ

- Cost with R as outer = T(R) + T(R) x T(S)
- Cost with S as outer = T(S) + T(R) x T(S)
- M >= 2

Block-based NLJ

- Suppose R is outer
  - Loop: Get the next M-1 R blocks into memory
  - Join these with each block of S
- B(R) + (B(R)/M-1) x B(S)
- What if S is outer?
  - B(S) + (B(S)/M-1) x B(R)

Let us work out an NLJ Example

- Relations are not clustered
- T(R1) = 10,000   T(R2) = 5,000

  10 tuples/block for R1; and for R2

  M = 101 blocks

Tuple-based NLJ Cost: for each R1 tuple:

[Read tuple + Read R2]

Total =10,000 [1+5000]=50,010,000 IOs

Can we do better when R,S are not clustered?

Use our memory

(1) Read 100 blocks worth of R1 tuples

(2) Read all of R2 (1 block at a time) + join

(3) Repeat until done

Cost: for each R1 chunk:

Read chunk: 1000 IOs

Read R2: 5000 IOs

Total/chunk = 6000

$$\text{Total} = \frac{10,000}{1,000} \text{ x } 6000 = 60,000 \text{ IOs}$$

[Vs. 50,010,000!]

- Can we do better?

☛ Reverse join order: R2 $\bowtie$ R1

Total = $\frac{5000}{1000}$ x (1000 + 10,000) =

5 x 11,000 = 55,000 IOs

[Vs. 60,000]

Example contd. NLJ R2 $\bowtie$ R1

- Now suppose relations are clustered

Cost

For each R2 chunk:

Read chunk: 100 IOs

Read R1: $\underline{1000}$ IOs

Total/chunk = 1,100

Total= 5 chunks x 1,100 = 5,500 IOs

[Vs. 55,000]

Joins with Sorting

- Sort-Merge Join (conceptually)

```
(1) if R1 and R2 not sorted, sort them
(2) $i \leftarrow 1$; $j \leftarrow 1$;
    While $(i \leq T(R1)) \wedge (j \leq T(R2))$ do
        if R1{ i }.C = R2{ j }.C then OutputTuples
        else if R1{ i }.C > R2{ j }.C then $j \leftarrow j+1$
        else if R1{ i }.C < R2{ j }.C then $i \leftarrow i+1$
```

Procedure Output-Tuples

```
While $(R1\{ i \}.C = R2\{ j \}.C) \wedge (i \leq T(R1))$ do
    [$jj \leftarrow j$;
    while $(R1\{ i \}.C = R2\{ jj \}.C) \wedge (jj \leq T(R2))$ do
              [output pair R1{ i }, R2{ jj };
               $jj \leftarrow jj+1$ ]
    $i \leftarrow i+1$ ]
```

Example

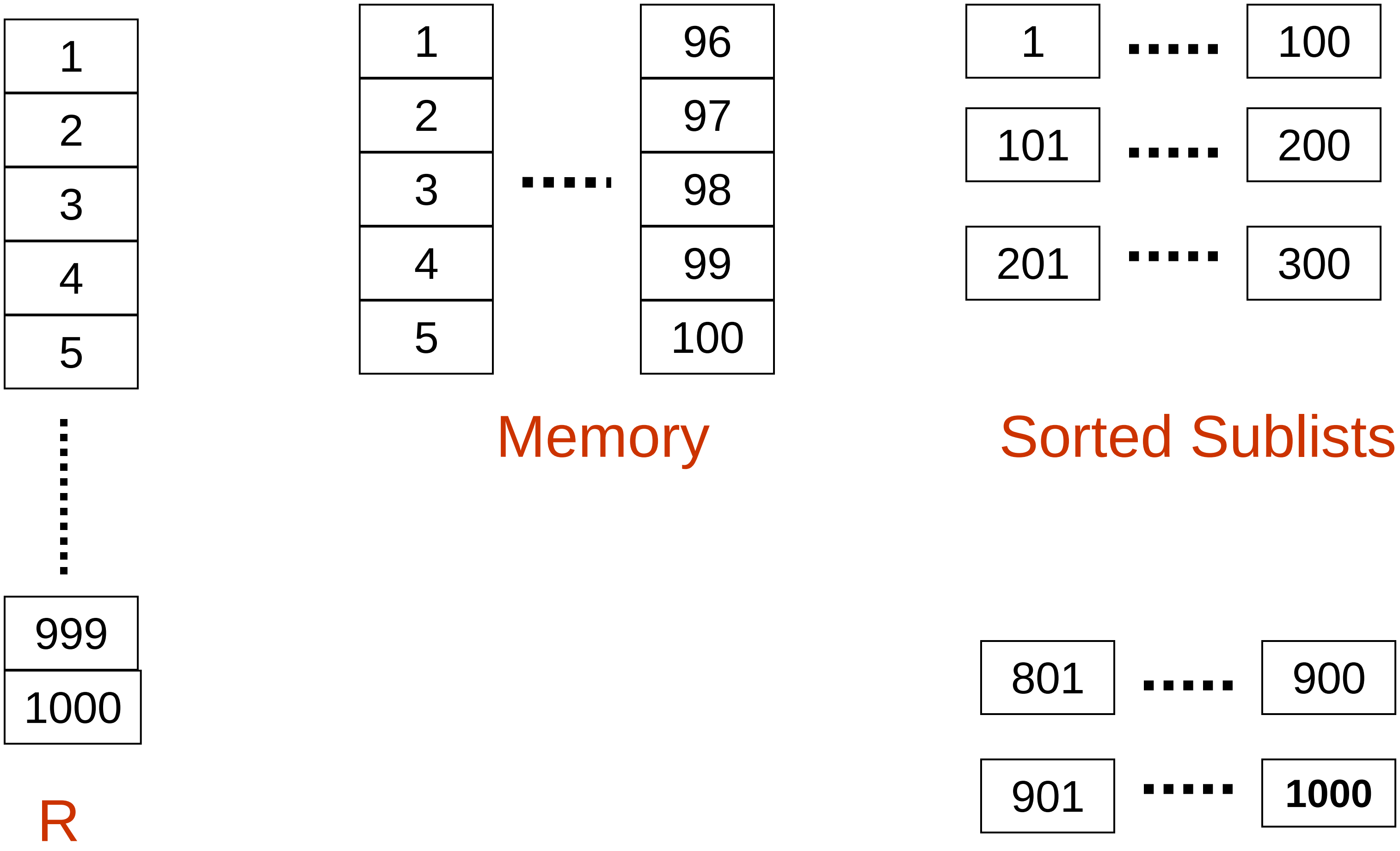
i	R1{i}.C	R2{j}.C	j
1	10	5	1
2	20	20	2
3	20	20	3
4	30	30	4
5	40	30	5
		50	6
		52	7

Block-based Sort-Merge Join

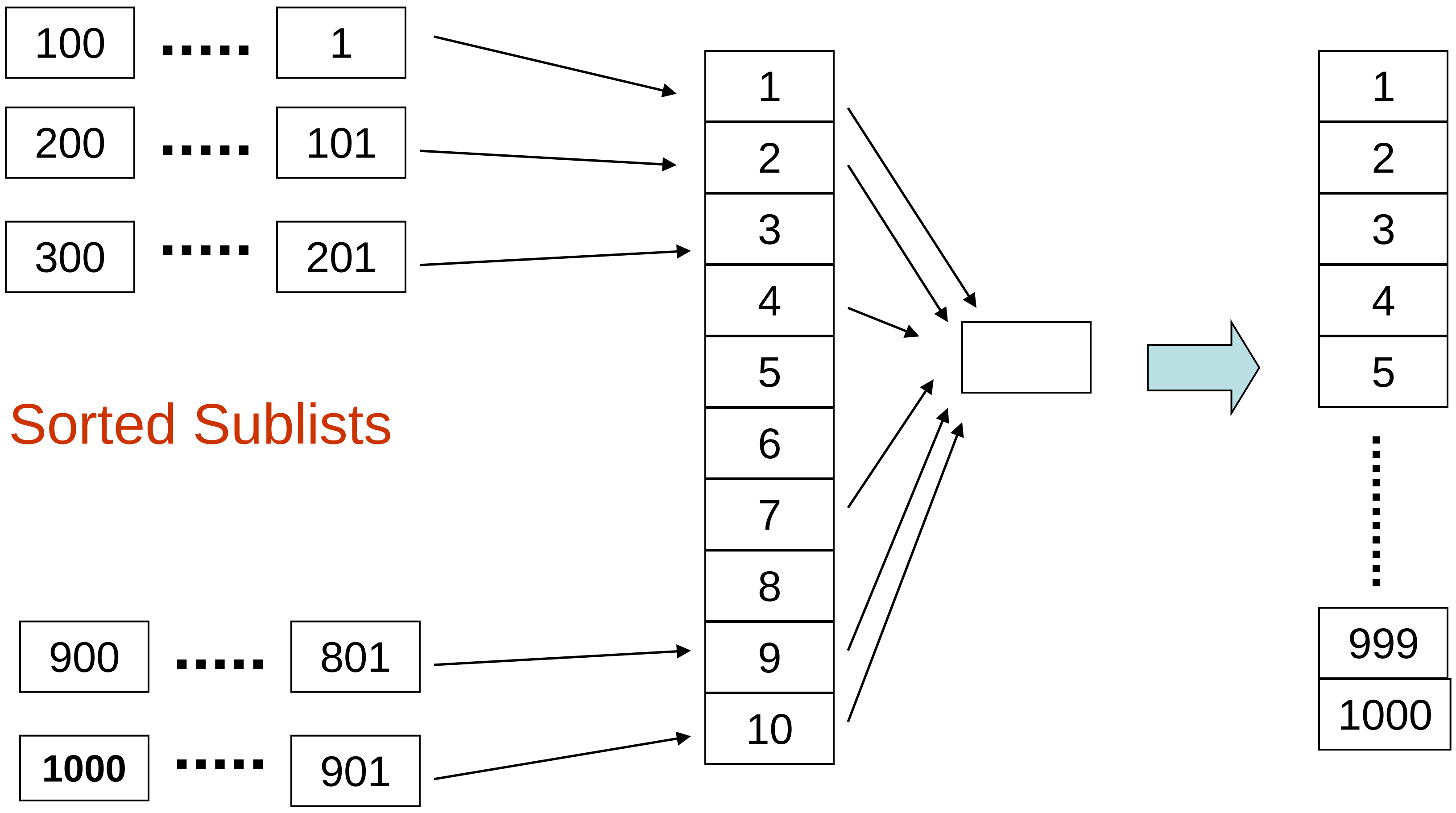
- Block-based sort
- Block-based merge

Two-phase Sort: Phase 1

Suppose B(R) = 1000 and M = 100



Two-phase Sort: Phase 2

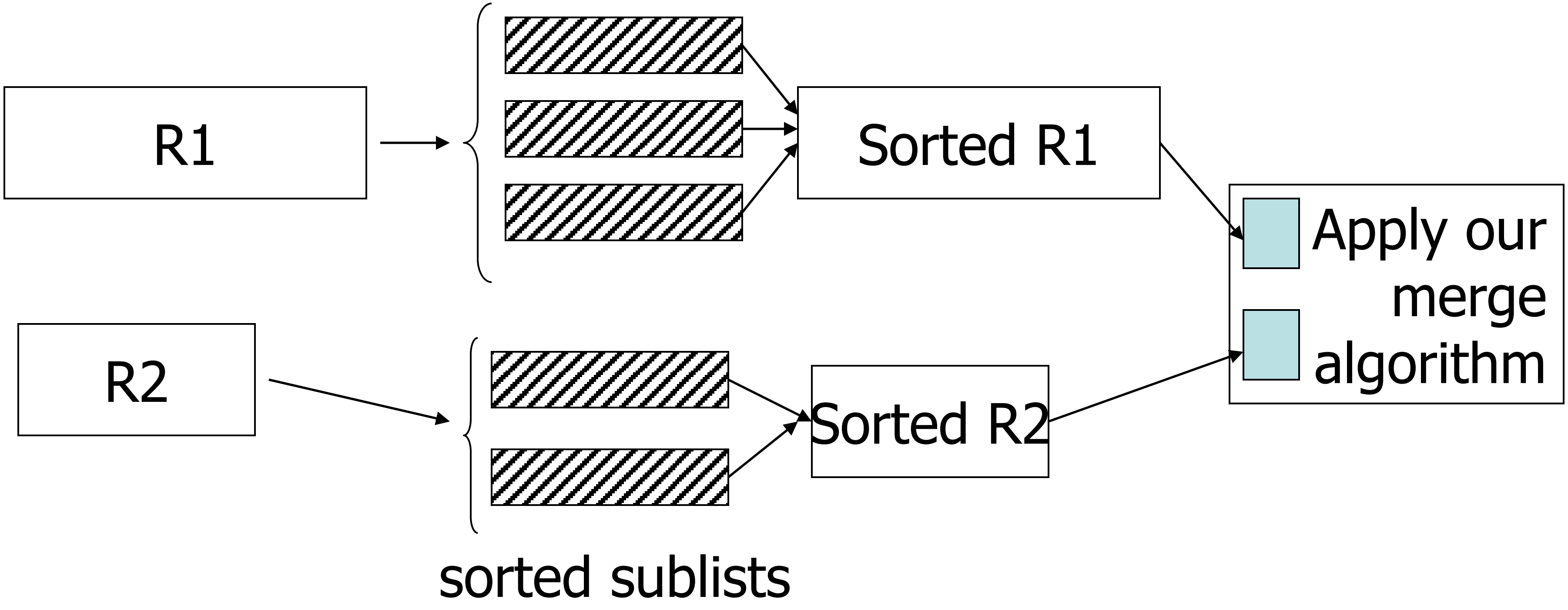


Sorted Sublists

Memory

Sorted R

Sort-Merge Join



R1

R2

Sorted R1

Sorted R2

Apply our merge algorithm

sorted sublists

Analysis of Sort-Merge Join

- Cost = 5 x (B(R) + B(S))
- Memory requirement:

$$M >= (\max(B(R), B(S)))^{1/2}$$

Continuing with our Example

R1,R2 clustered, but unordered

Total cost = sort cost + join cost

= 6,000 + 1,500 = 7,500 IOs

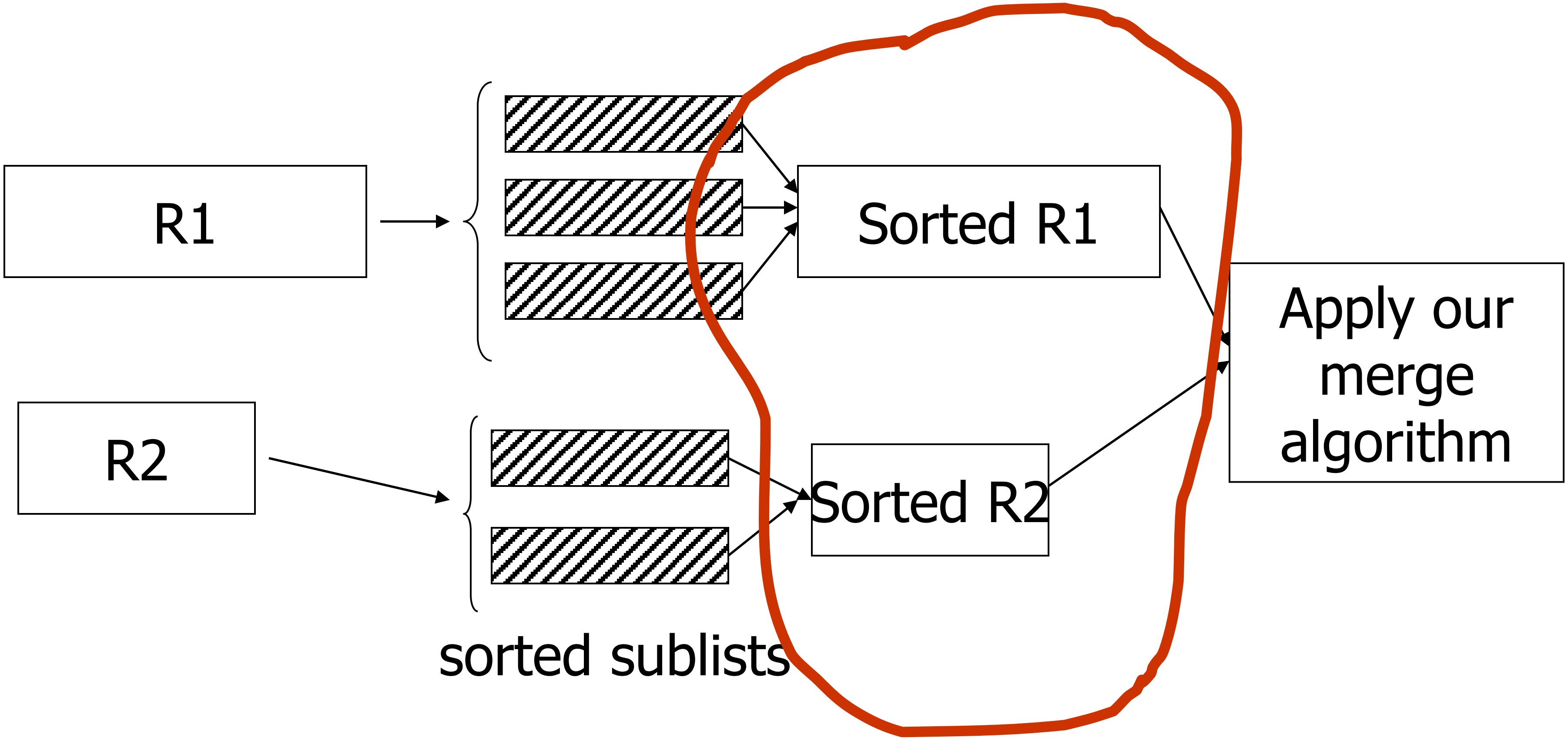
But: NLJ cost = 5,500

So merge join does not pay off!

However …

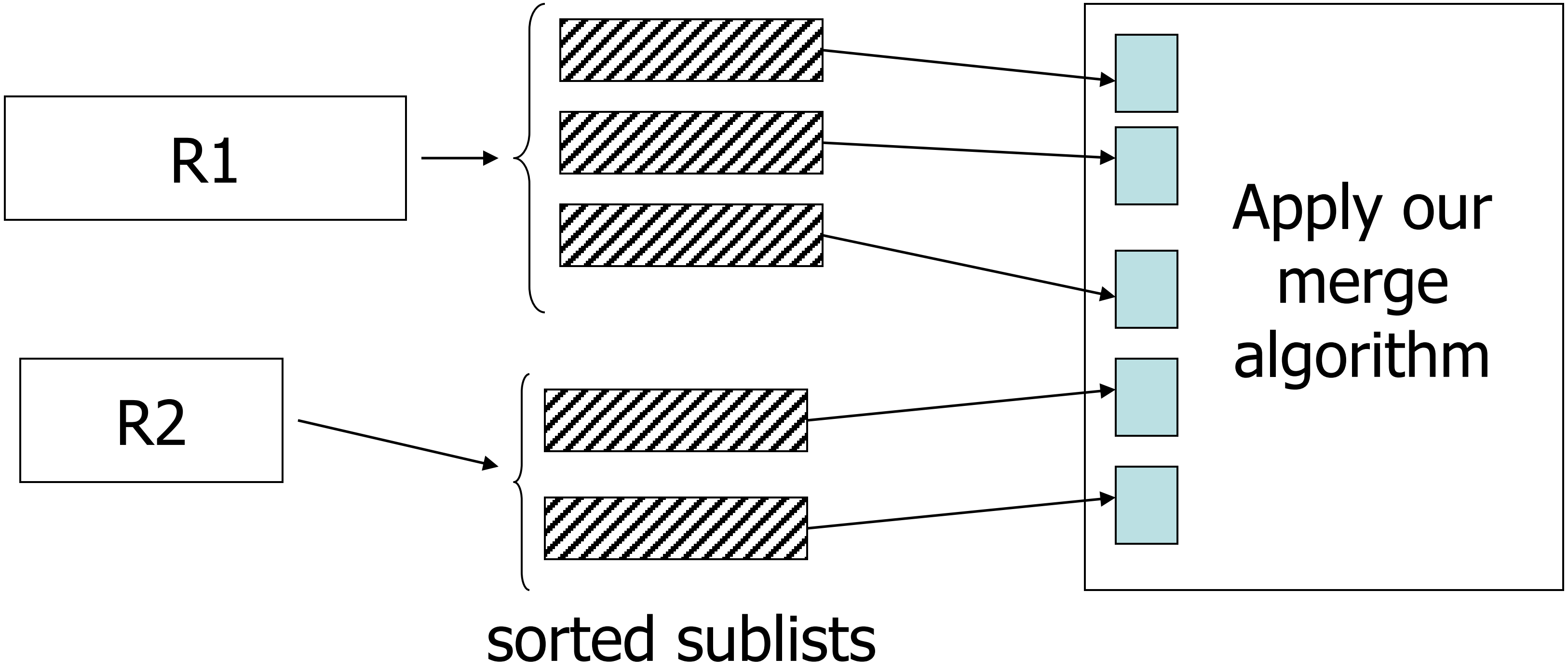
- NLJ cost = B(R) + B(R)B(S)/M-1 = O(B(R)B(S))   [Quadratic]
- Sort-merge join cost = 5 x (B(R) + B(S)) = O(B(R) + B(S)) [Linear]

Can we Improve Sort-Merge Join?



Do we need to create the sorted R1, R2?

A more “Efficient” Sort-Merge Join



Analysis of the “Efficient” Sort-Merge Join

- Cost = 3 x (B(R) + B(S))

  [Vs. 5 x (B(R) + B(S))]

- Memory requirement:

  $M >= (B(R) + B(S))^{1/2}$

  [Vs. $M >= (\max(B(R), B(S)))^{1/2}$

Another catch with the more “Efficient” version: Higher chances of thrashing!

Cost of “Efficient” Sort-Merge join:

Cost = Read R1 + Write R1 into sublists

+ Read R2 + Write R2 into sublists

+ Read R1 and R2 sublists for Join

= 2000 + 1000 + 1500 = 4500

[Vs. 7500]

Memory requirements in our Example

B(R1) = 1000 blocks, $1000^{1/2} = 31.62$

B(R2) = 500 blocks, $500^{1/2} = 22.36$

B(R1) + B(R2) = 1500, $1500^{1/2} = 38.7$

M > 32 buffers for simple sort-merge join

M > 39 buffers for efficient sort-merge join

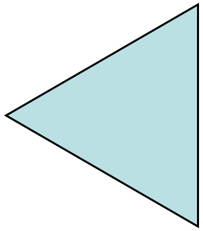
Joins Using Existing Indexes

R

B	C
a	10
a	20
b	10
d	30

⋈

Index I on S.C



C	D
10	cat
40	dog
15	bat
20	rat

S

- Indexed NLJ (conceptually)

```
for each r ∈ R do
    for each s ∈ S that matches probe(I,r.C) do
        output r,s pair
```

Continuing with our Running Example

- Assume R1.C index exists; 2 levels
- Assume R2 clustered, unordered

- Assume R1.C index fits in memory

Cost: R2 Reads: 500 IOs

```
for each R2 tuple:
    - probe index - free
    - if match, read R1 tuple
```

➔# R1 Reads depends on:

- # matching tuples
- clustering index or not

What is expected # of matching tuples?

(a) say R1.C is key, R2.C is foreign key

then expected = 1 tuple

(b) say V(R1,C) = 5000, T(R1) = 10,000

with uniform assumption

expect = 10,000/5,000   = 2

What is expected # of matching tuples?

(c) Say DOM(R1, C) = 1,000,000

T(R1) = 10,000

with assumption of uniform distribution in domain

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

Total cost with Index Join with a Non-Clustering Index

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

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

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

Will any of these change if we have a clustering index?

What if index does not fit in memory?

Example: say R1.C index is 201 blocks

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

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

Total cost (including Index Probes)

= 500+5000 [Probe + Get Records]

= 500+5000 [0.5+2]

= 500+12,500 = 13,000 (Case b)

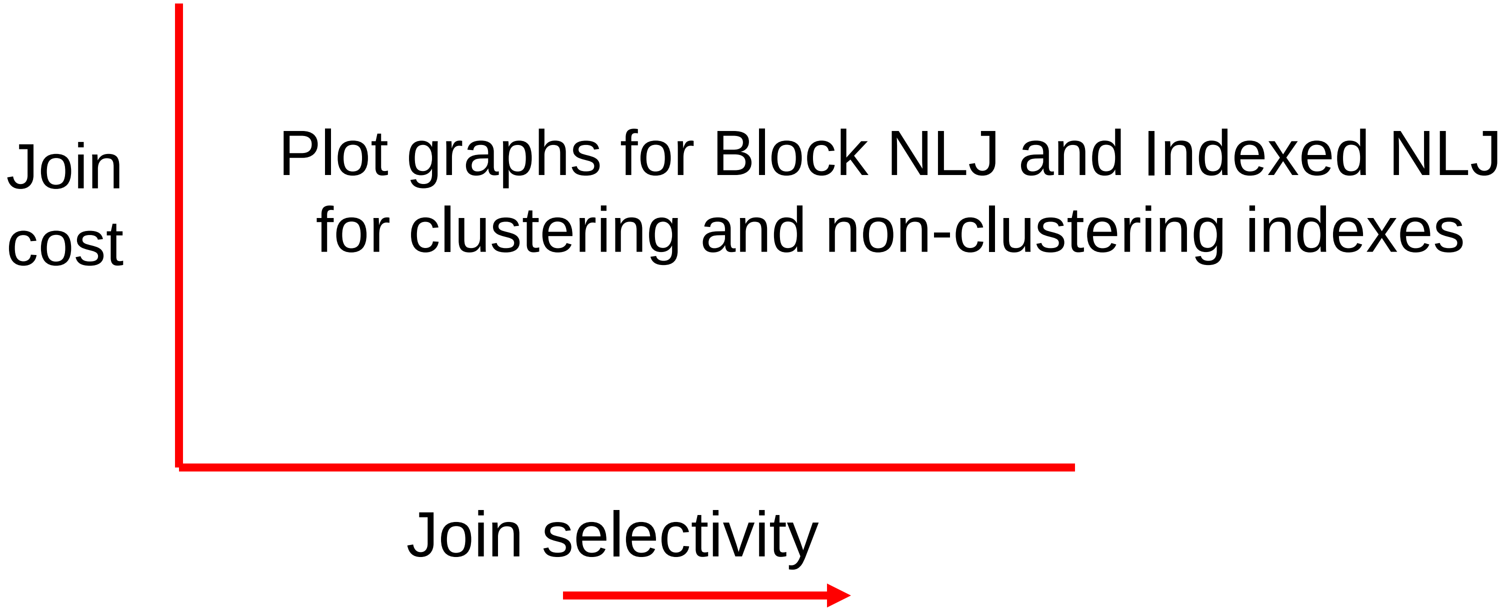
For Case (c):

= 500+5000[0.5 × 1 + (1/100) × 1]

= 500+2500+50 = 3050 IOs

Block-Based NLJ Vs. Indexed NLJ

- Wrt #joining records
- Wrt index clustering



Plot graphs for Block NLJ and Indexed NLJ
for clustering and non-clustering indexes

Sort-Merge Join with Indexes

- Can avoid sorting
- Zig-zag join

So far

not clustered	NLJ R2 $\bowtie$ R1	55,000 (best)
	Merge Join	________
	Sort+ Merge Join	________
	R1.C Index	________
	R2.C Index	________
clustered	NLJ R2 $\bowtie$ R1	5500
	Merge join	1500
	Sort+Merge Join	7500 → 4500
	R1.C Index	5500, 3050, 550
	R2.C Index	________

Building Indexes on the fly for Joins

- Hash join (conceptual)
  - Hash function h, range 1 → k
  - Buckets for R1: G1, G2, ... Gk
  - Buckets for R2: H1, H2, ... Hk

Algorithm

```
(1) Hash R1 tuples into G1--Gk
(2) Hash R2 tuples into H1--Hk
(3) For i = 1 to k do
        Match tuples in Gi, Hi buckets
```

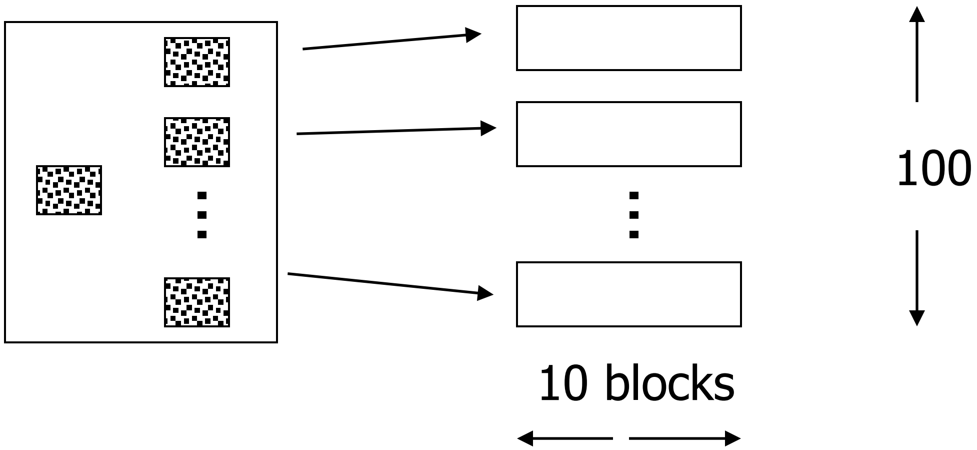
Example Continued: Hash Join

- R1, R2 contiguous

→ Use 100 buckets

→ Read R1, hash, + write buckets

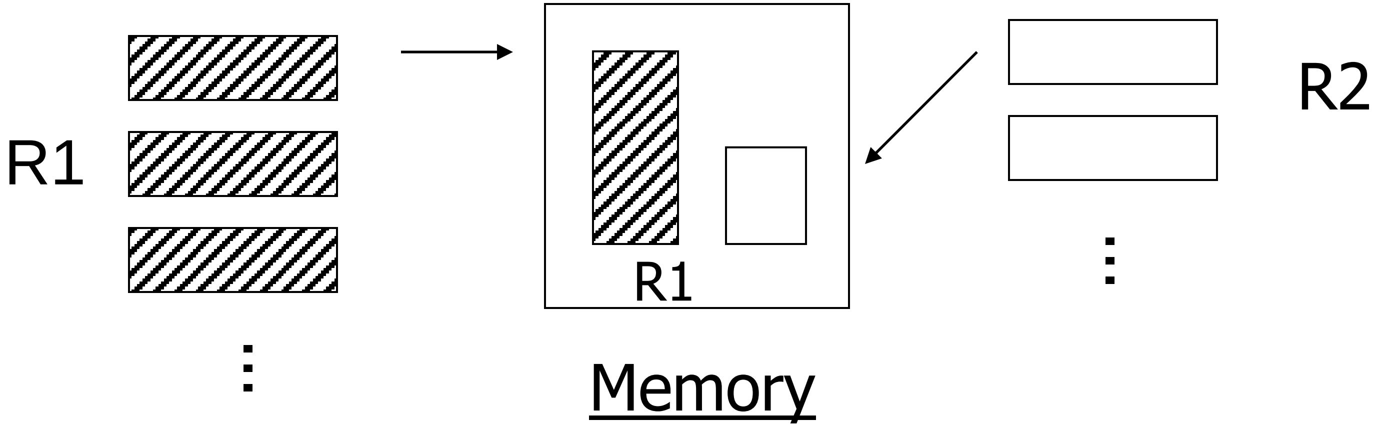
R1 →



-> Same for R2

-> Read one R1 bucket; build memory hash table
[R1 is called the build relation of the hash join]

-> Read corresponding R2 bucket + hash probe
[R2 is called the probe relation of the hash join]



Then repeat for all buckets

Cost:

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

Total cost = 3 x [1000+500] = 4500

Minimum Memory Requirements

Size of R1 bucket = (x/k)

k = number of buckets (k = M-1)

x = number of R1 blocks

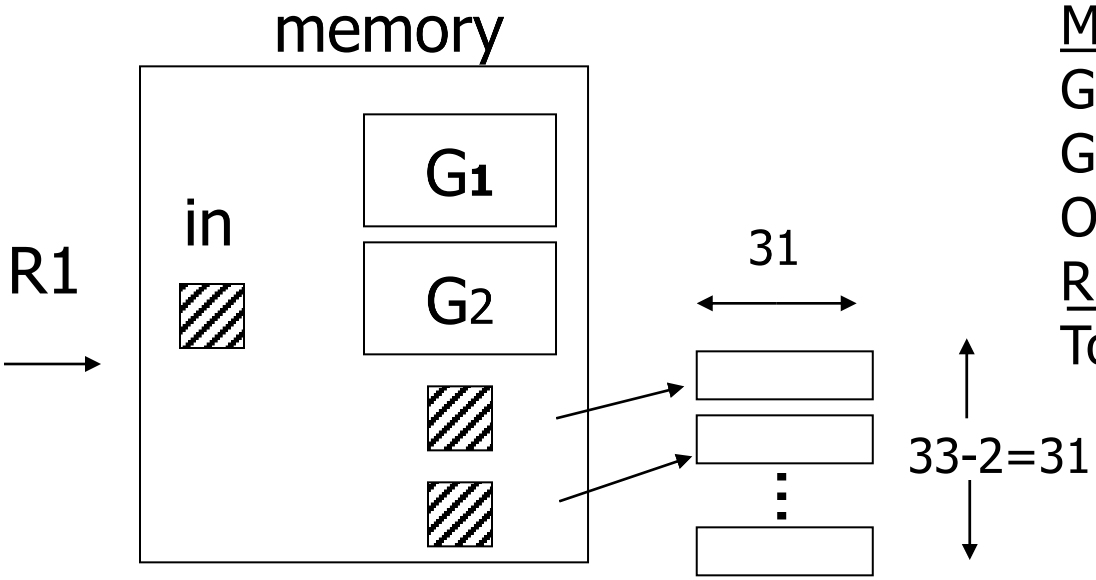
So... $(x/k) <= k$ → $k >= \sqrt{x}$ → $M > \sqrt{x}$

Actually, $M > \sqrt{\min(B(R),B(S))}$

[Vs. $M > \sqrt{B(R)+B(S)}$ for Sort-Merge Join]

Trick: keep some buckets in memory

E.g., k'=33 R1 buckets = 31 blocks
keep 2 in memory



Memory use:

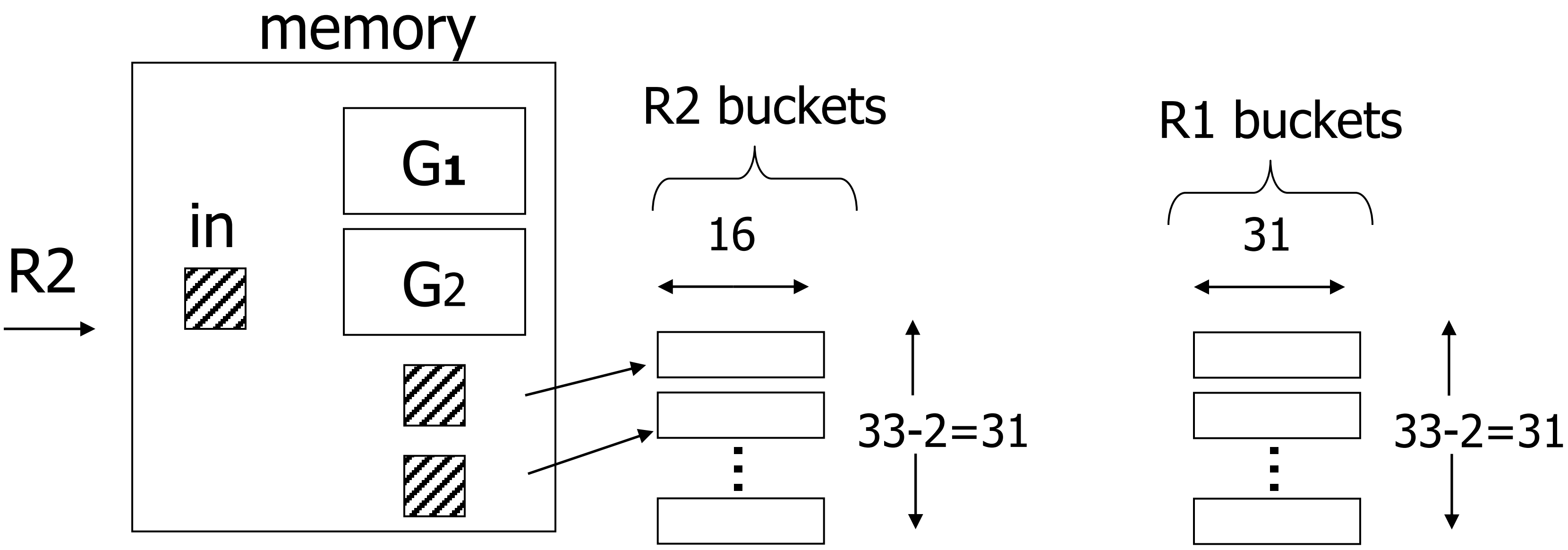
G1	31 buffers
G2	31 buffers
Output	33-2 buffers
R1 input	1
Total	94 buffers

6 buffers to spare!!

called Hybrid Hash-Join

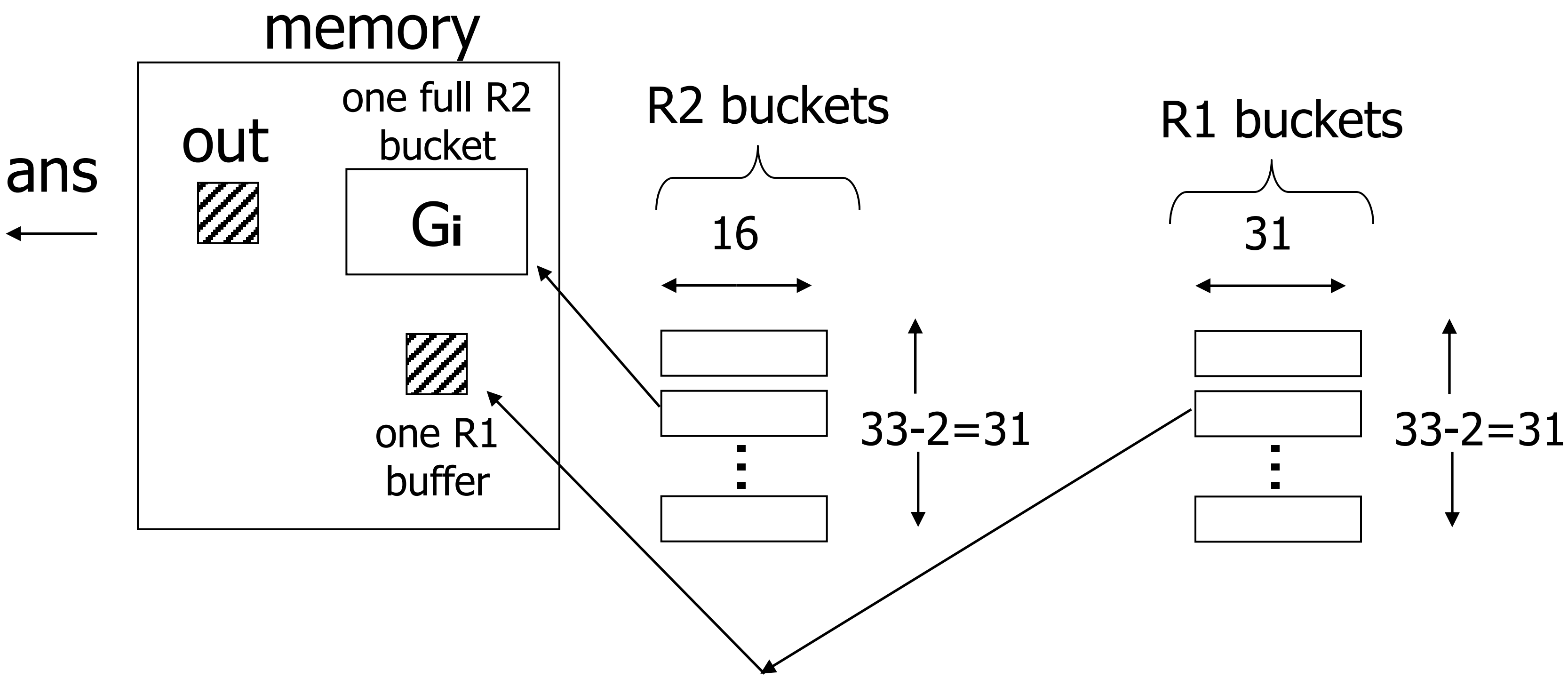
Next: Bucketize R2

- R2 buckets =500/33= 16 blocks
- Two of the R2 buckets joined immediately with G1,G2



Finally: Join remaining buckets

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

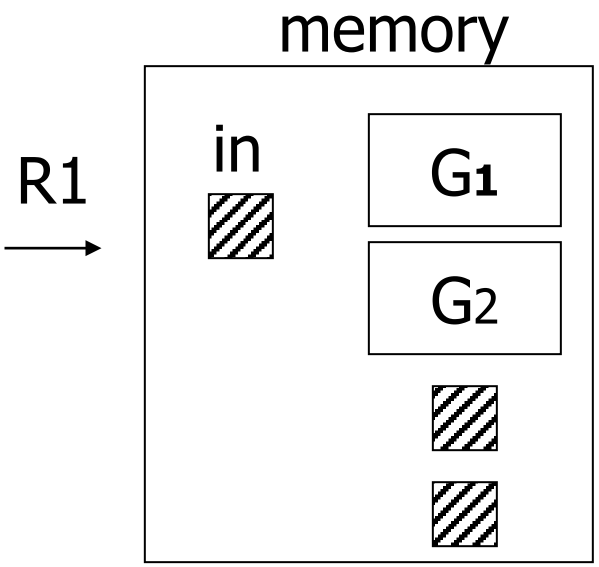


Cost

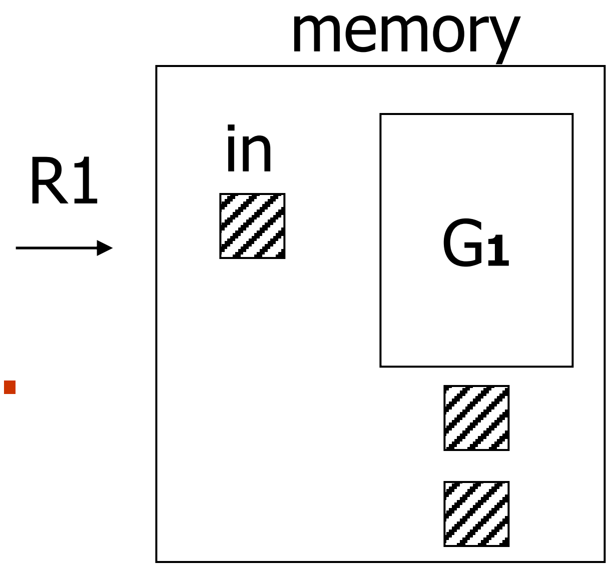
- Bucketize R1 = 1000+31×31=1961
- To bucketize R2, only write 31 buckets:
  so, cost = 500+31×16=996
- To compare join (2 buckets already done)
  read 31×31+31×16=1457

Total cost = 1961+996+1457 = 4414

How many Buckets in Memory?



OR ...



?

- See textbook for an interesting answer ...

Another hash join trick:

- Only write into buckets
  <val,ptr> 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
- Build hash table for R2 in memory

  5000 tuples → 5000/100 = 50 blocks
- Read R1 and match
- Read ~ 100 R2 tuples

Total cost =	Read R2:	500
	Read R1:	1000
	Get tuples:	100
		1600

So far:

clustered

NLJ	5500
Merge join	1500
Sort+merge joint	7500
R1.C index	5500 → 550
R2.C index	______
Build R.C index	______
Build S.C index	______
Hash join	4500
with trick,R1 first	4414
with trick,R2 first	______
Hash join, pointers	1600

Hash-based Vs. Sort-based Joins

- Some similarities (see textbook), some dissimilarities
- Non-equi joins
- Memory requirement
- Sort order may be useful later

Summary

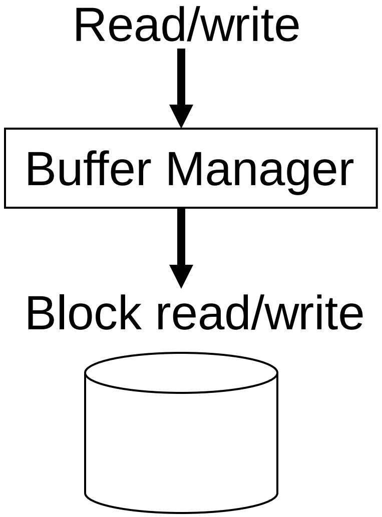
- NLJ ok for “small” relations (relative to memory size)
- For equi-join, where relations not sorted and no indexes exist, Hybrid Hash Join usually best

Summary (contd.)

- Sort-Merge Join good for
  non-equi-join (e.g., R1.C > R2.C)
- If relations already sorted, use
  Merge Join
- If index exists, it could be useful
  - Depends on expected result size and index clustering
- Join techniques apply to Union, Intersection, Difference

Buffer Management

- DBMS Buffer Manager



- May control memory directly (i.e., does not allocate from virtual memory controlled by OS)

Buffer Replacement Policies

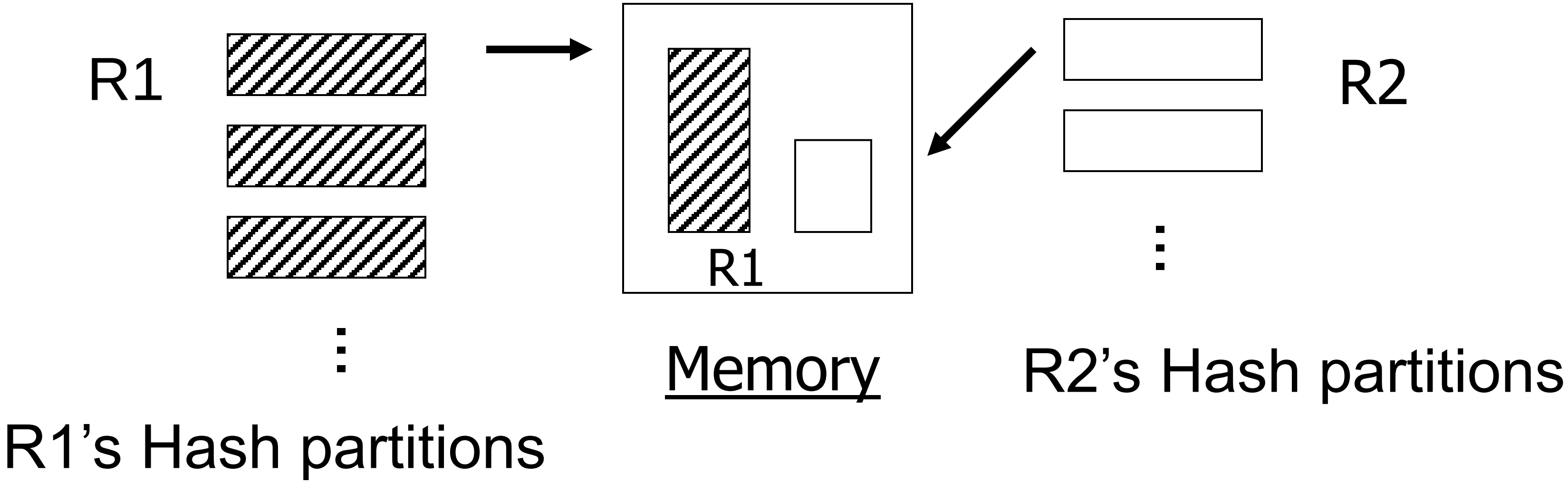
- Least Recently Used (LRU)
- Second-chance
- Most Recently Used (MRU)
- FIFO

Interaction between Operators and Buffer Management

- Memory (our M parameter) may change while an operator is running
- Some operators can take advantage of specific buffer replacement policies
  - E.g., Rocking for Block-based NLJ

Join Strategies for Parallel Processors

- May cover later if time permits
- We will see one example: Hash Join



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  - Operator classes
- Operator implementation (with examples from joins)
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