# 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

| | | |
|---|---|---|
| R1 R2 S1 S2 | R3 R4 S3 S4 | ….. |

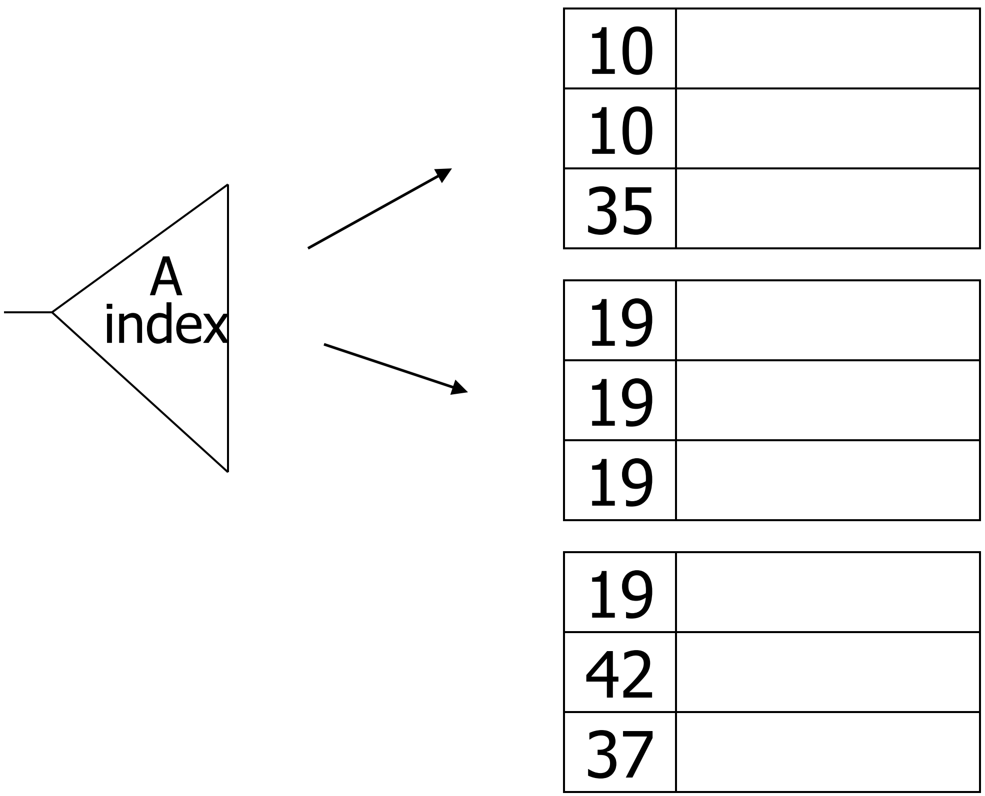
- Clustered relation

| | | |
|---|---|---|
| R1 R2 R3 R4 | R5 R5 R7 R8 | ….. |

- Clustering index

# Clustering Index

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



# 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 |

# Roadmap

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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

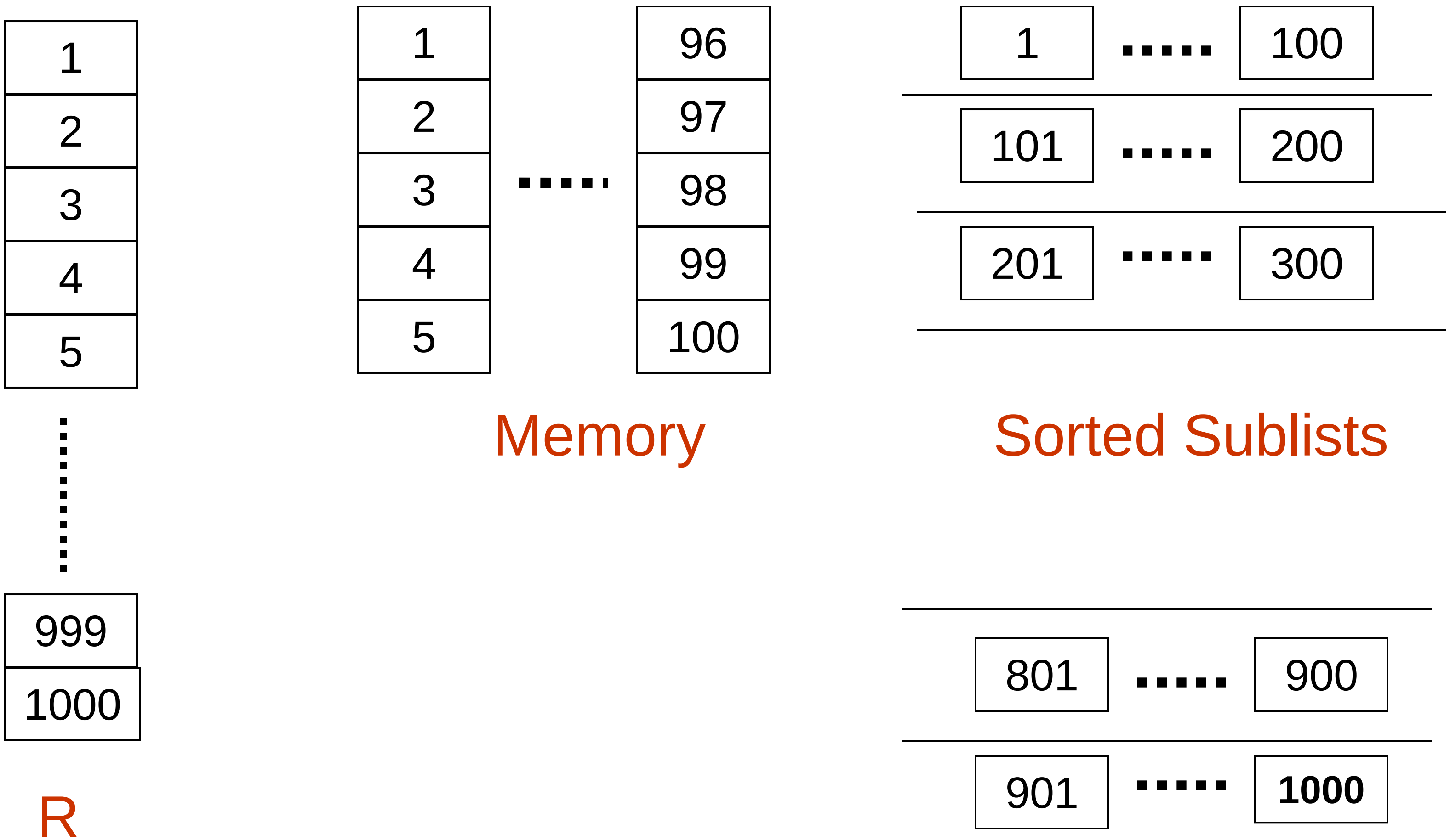
- Suppose T(R) x tupleSize(R) <= M x |B(R)|
- Read R completely into memory
- Sort
- Write output
- Cost = B(R)

# Implementing a Full-Relation Operator, Ex: Sort

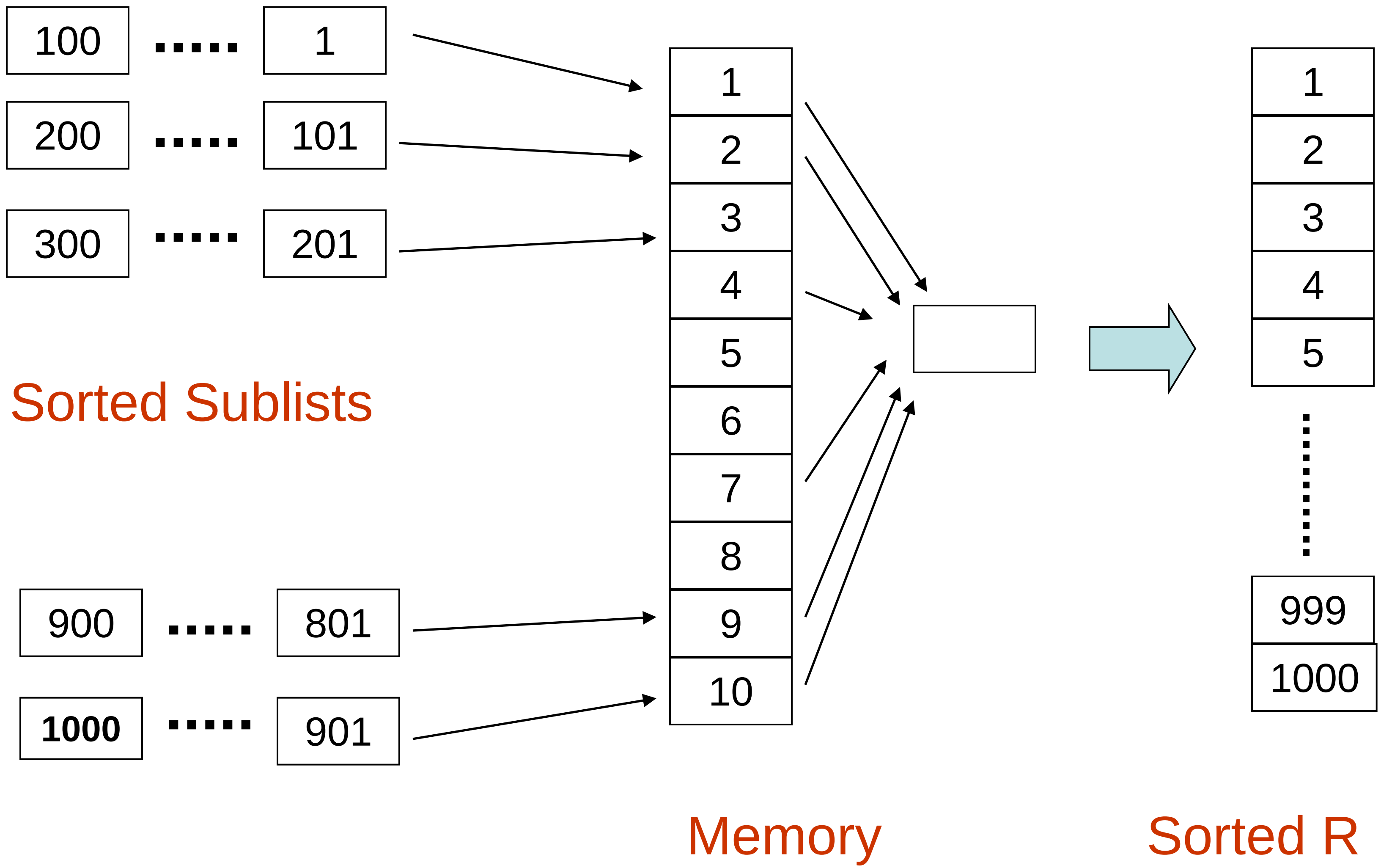
- Suppose R won’t fit within M blocks
- Consider a two-pass algorithm for Sort; generalizes to a multi-pass algorithm
- Read R into memory in M-sized chunks
- Sort each chunk in memory and write out to disk as a sorted sublist
- Merge all sorted sublists
- Write output

# Two-phase Sort: Phase 1

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



# Two-phase Sort: Phase 2



# 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

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

[Vs. 50,010,000!]

- Can we do better?

☛ Reverse join order: $R2 \bowtie R1$

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

$$5 \times 11{,}000 = 55{,}000 \text{ IOs}$$

[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: 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

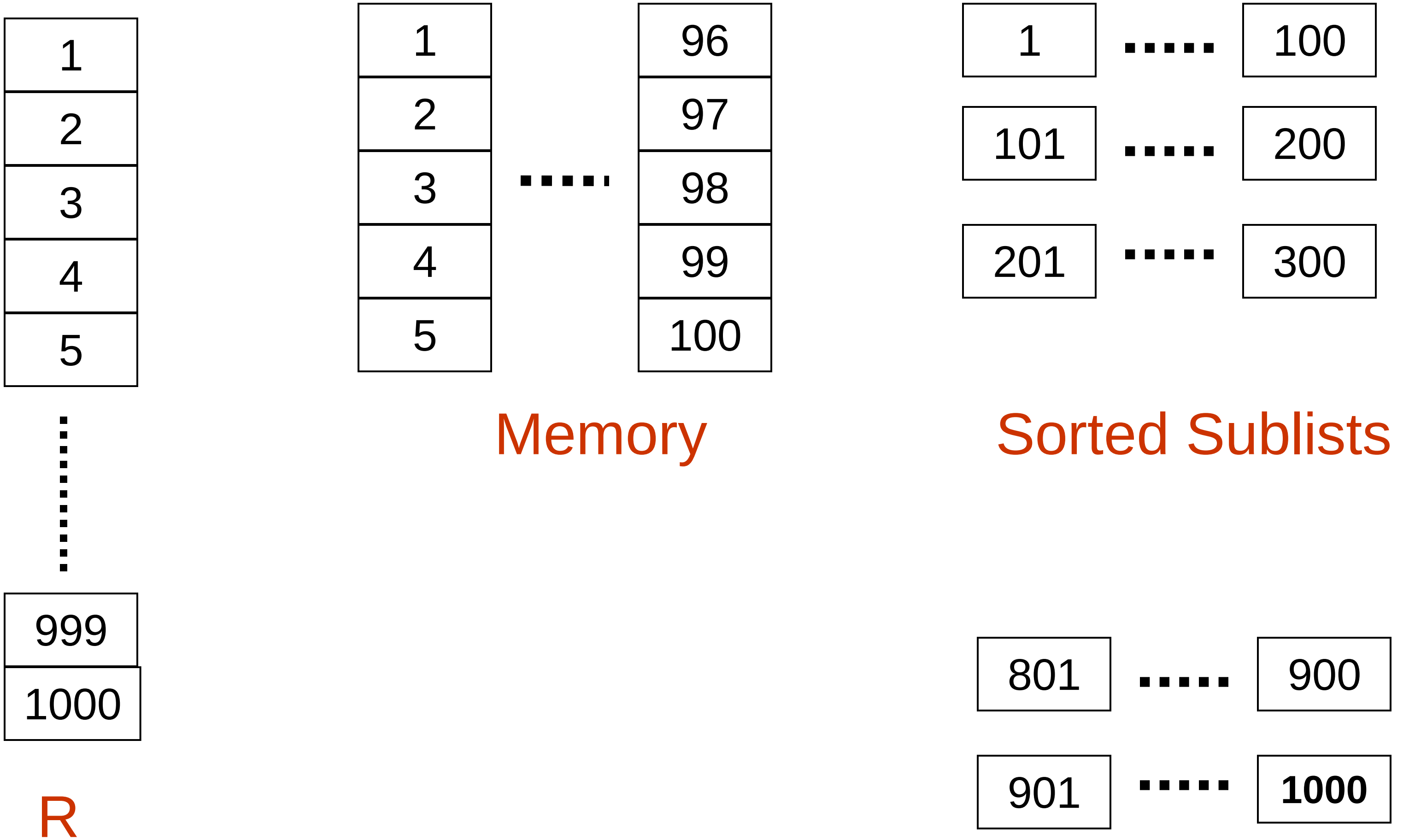
| i | R1{i}.C | R2{j}.C | j |
|---|---|---|---|
| 1 | 10 | 5 | 1 |
| 2 | 20 | 20 | 2 |
| 3 | 20 | 20 | 3 |
| 4 | 30 | 30 | 4 |
| 5 | 40 | 30 | 5 |
| | | 50 | 6 |
| | | 52 | 7 |

# Block-based Sort-Merge Join

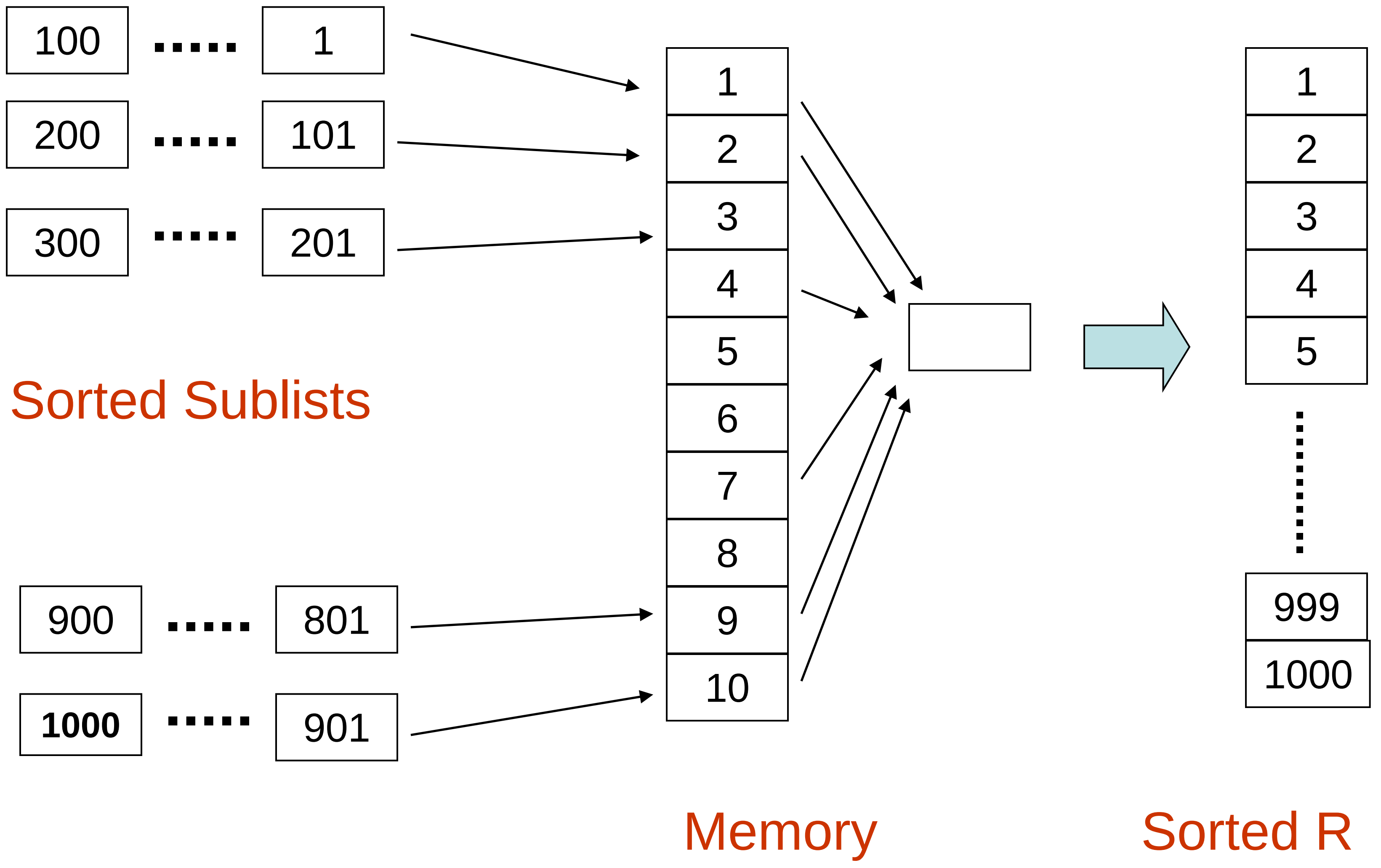
- Block-based sort
- Block-based merge

# Two-phase Sort: Phase 1

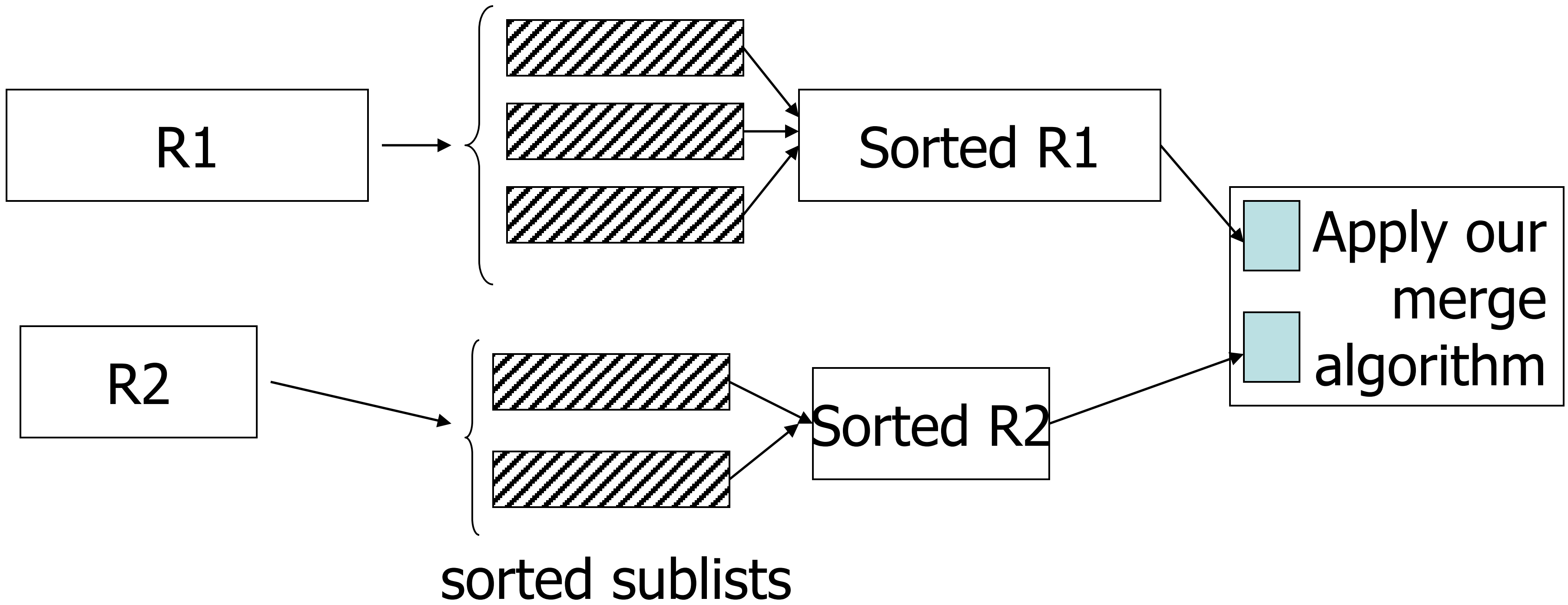
Suppose B(R) = 1000 and M = 100



# Two-phase Sort: Phase 2



# Sort-Merge Join



# 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

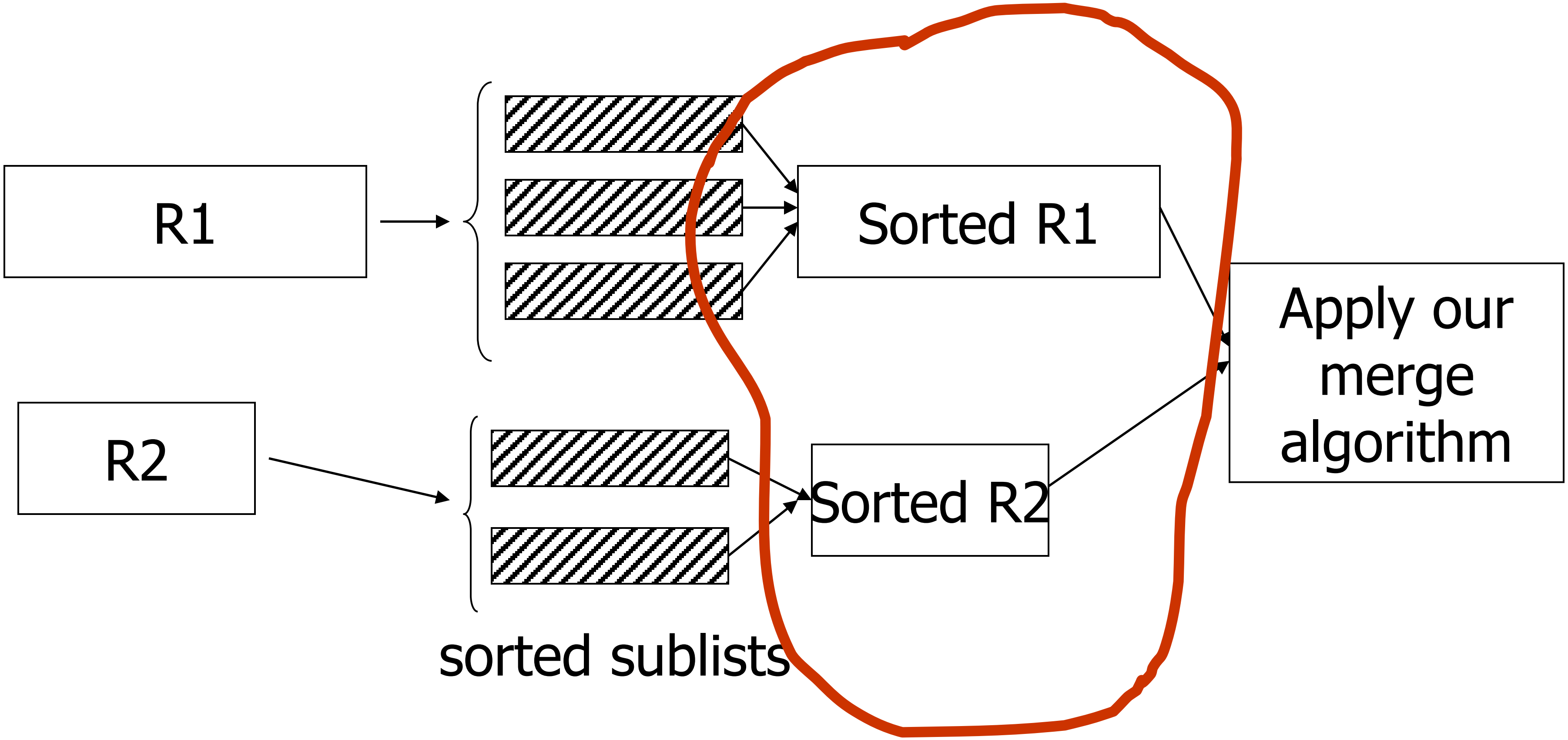
<u>But:</u> NLJ cost = 5,500

So merge join does not pay off!

# However …

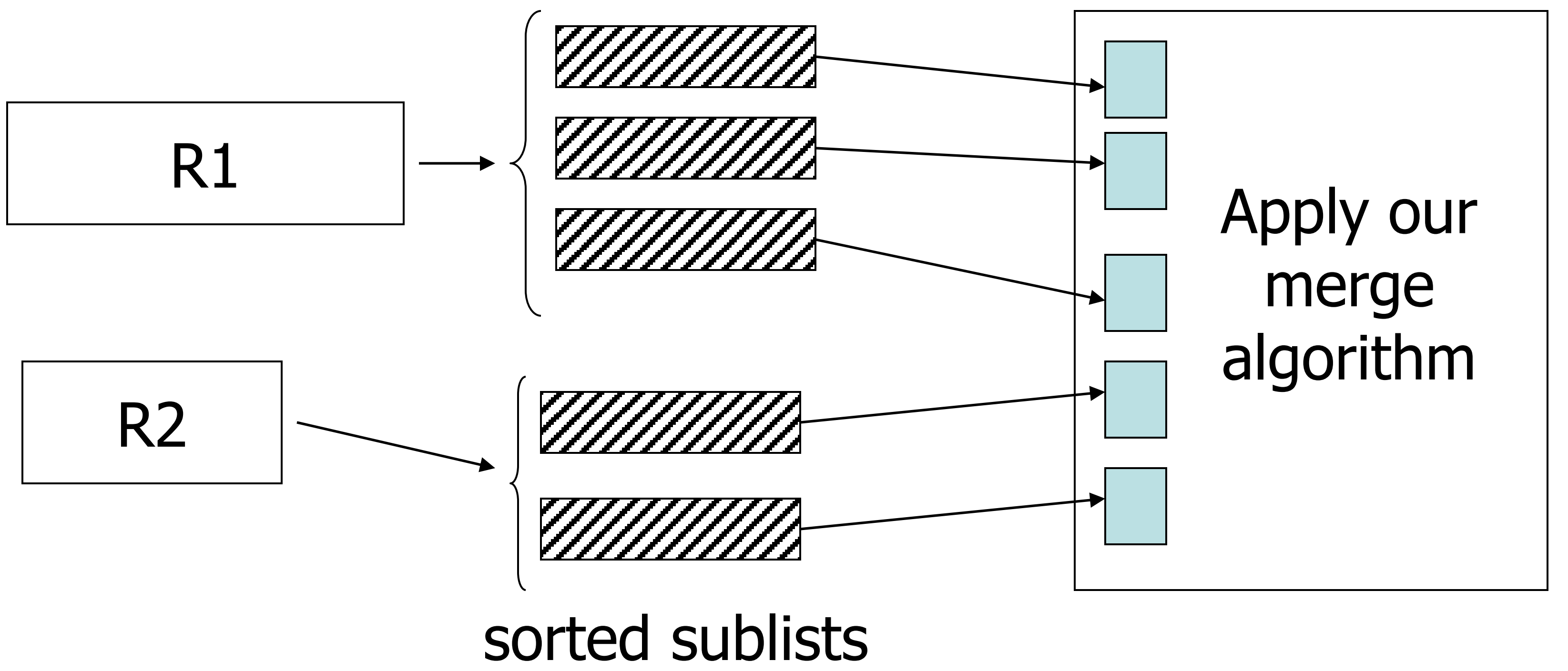
- NLJ cost = B(R) + B(R)B(S)/M-1 = O(B(R)B(S))   [Quadratic]
- Sort-merge join cost = 5 x (B(R) + B(S)) = O(B(R) + B(S)) [Linear]

# 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

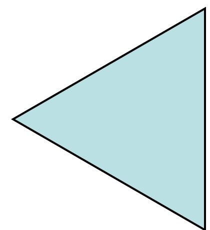
# Joins Using Existing Indexes

R

| B | C |
|---|---|
| a | 10 |
| a | 20 |
| b | 10 |
| d | 30 |

$\bowtie$

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)

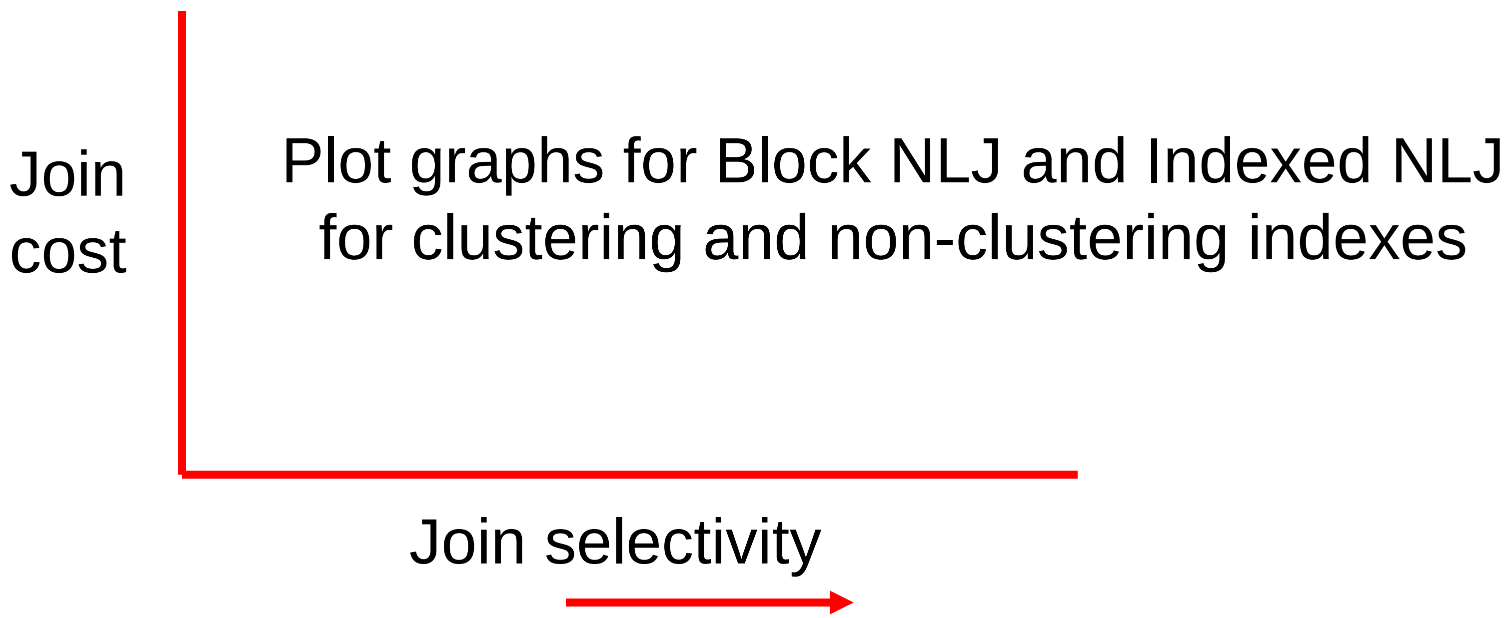
For Case (c):

$= 500+5000[0.5 \times 1 + (1/100) \times 1]$

= 500+2500+50 = 3050 IOs

# Block-Based NLJ Vs. Indexed NLJ

- Wrt #joining records
- Wrt index clustering



# 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 $\rightarrow$ 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 $\rightarrow$ 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

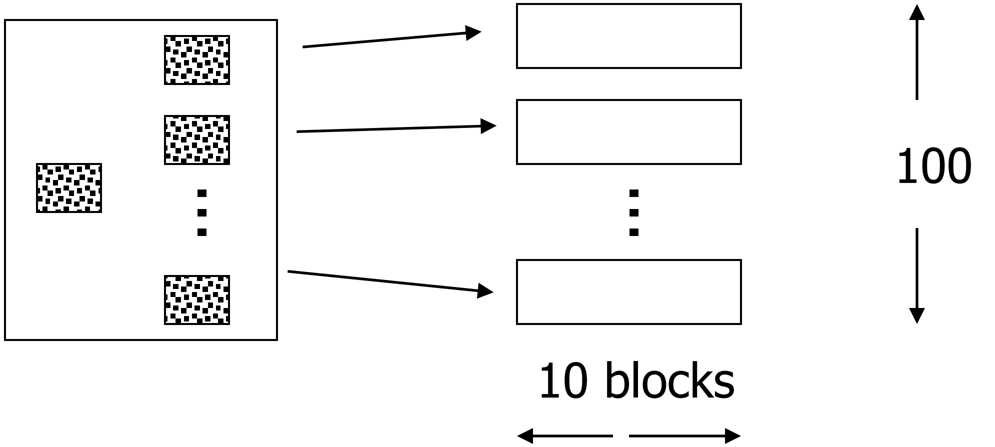
# Example Continued: Hash Join

- R1, R2 contiguous

$\rightarrow$ Use 100 buckets

$\rightarrow$ Read R1, hash, + write buckets

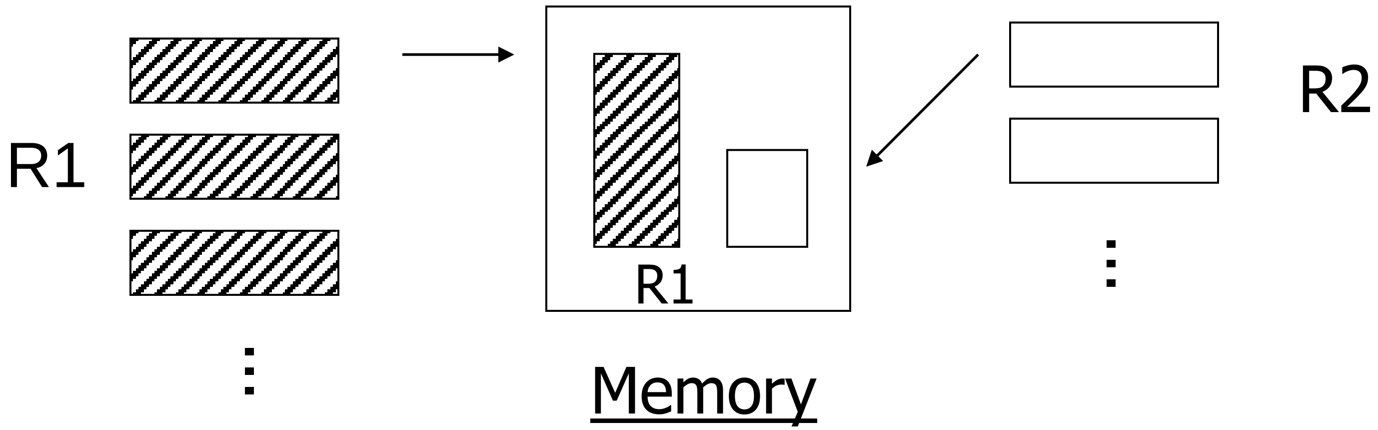
R1 $\rightarrow$



-> 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

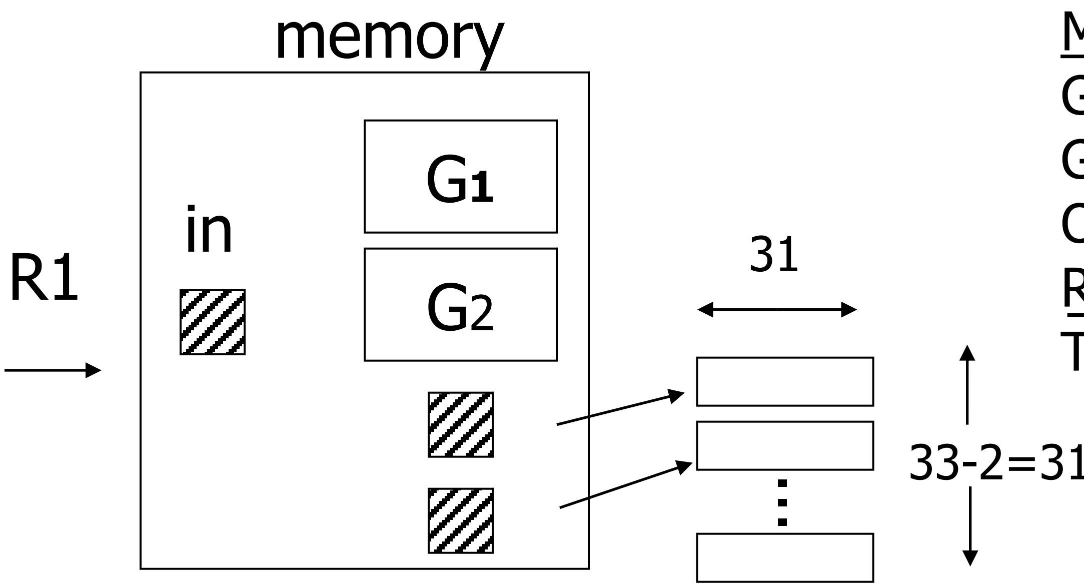
So...  (x/k) <= k $\Rightarrow$ k >= $\sqrt{x}$ $\Rightarrow$ M > $\sqrt{x}$

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 |

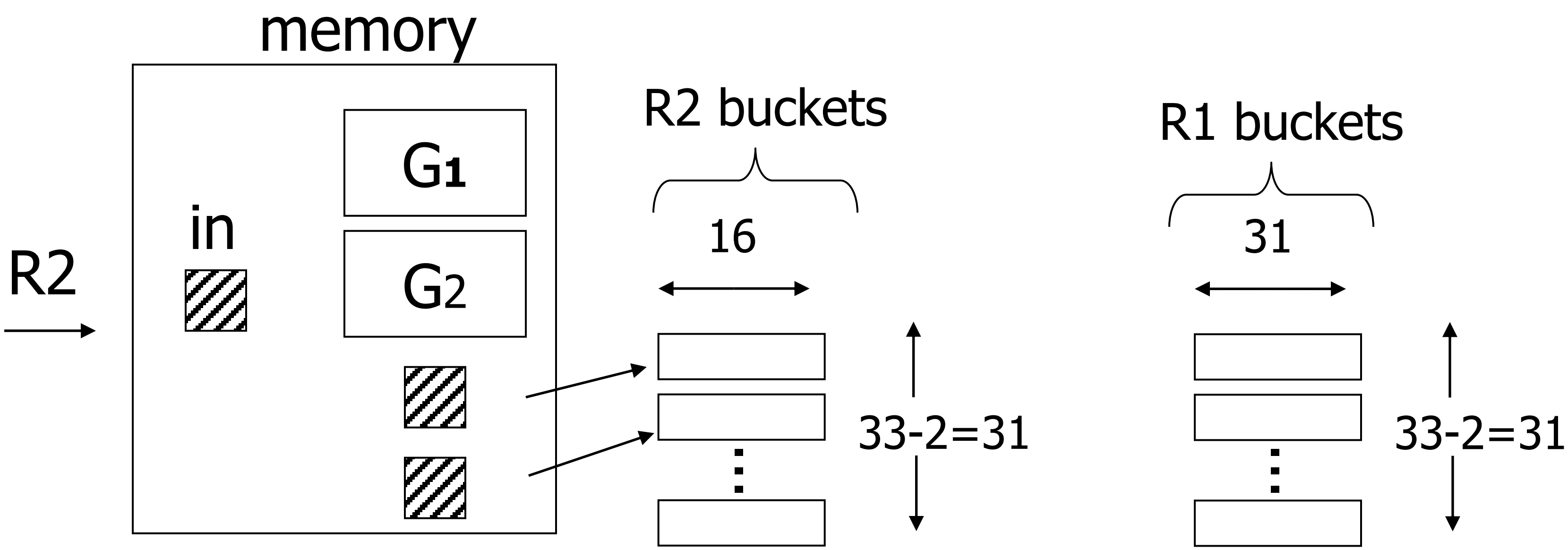
6 buffers to spare!!

called Hybrid Hash-Join

# Next: Bucketize R2

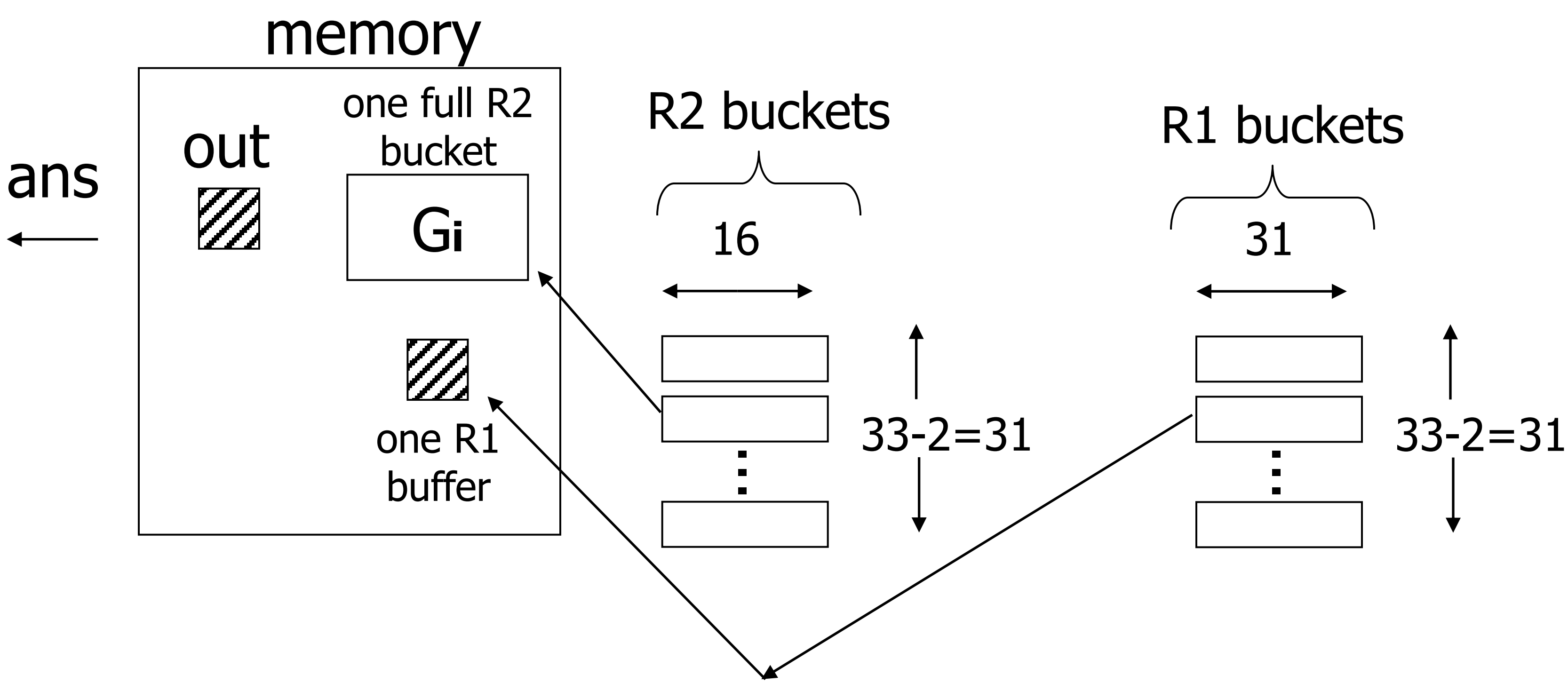
– R2 buckets =500/33= 16 blocks

– 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

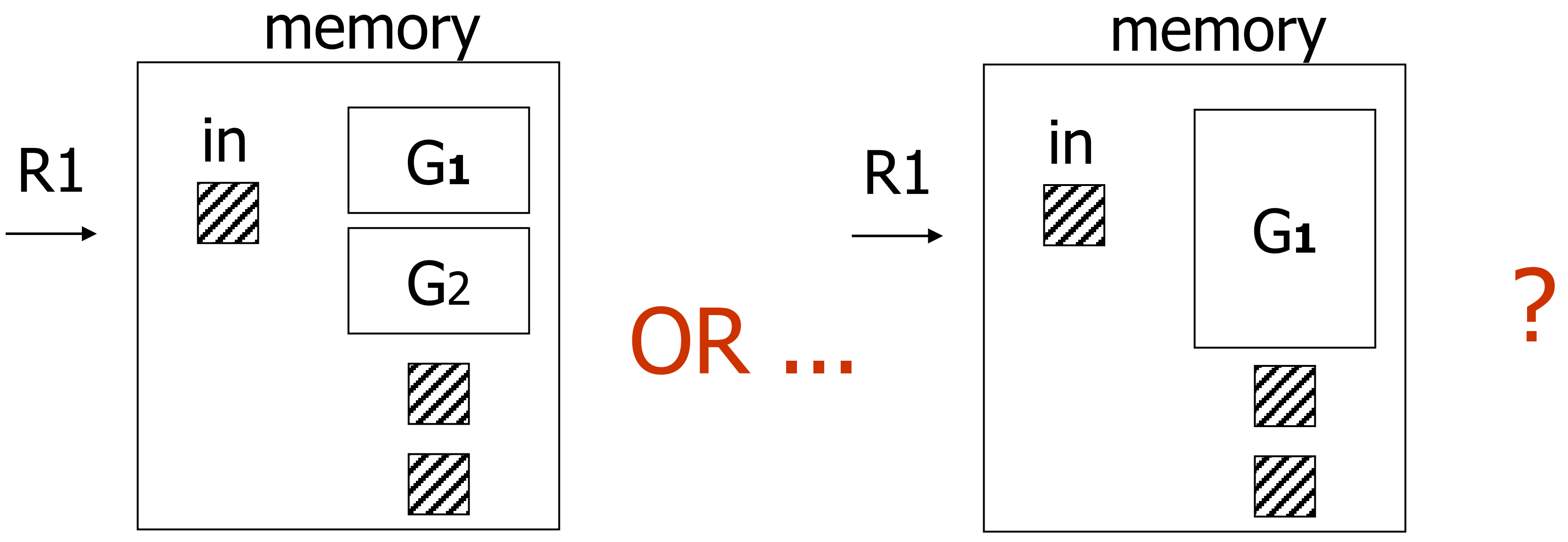


## Cost

- Bucketize R1 = $1000+31\times31=1961$
- To bucketize R2, only write 31 buckets:
  so, cost = $500+31\times16=996$
- To compare join (2 buckets already done)
  read $31\times31+31\times16=1457$

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

# How many Buckets in Memory?




- See Garcia-Molina, Ullman, Widom book 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 $\rightarrow$ 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 $\rightarrow$ 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

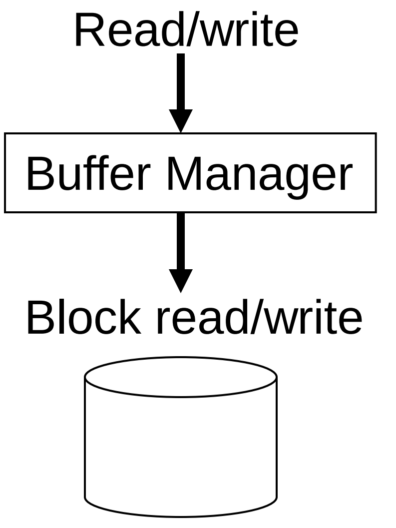
- NLJ ok for “small” relations (relative to memory size)
- For equi-join, where relations not sorted and no indexes exist, Hybrid Hash Join usually best

# 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

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