DB 2

12 – Joins

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1 ¦ Q_{11}: One-to-Many Joins

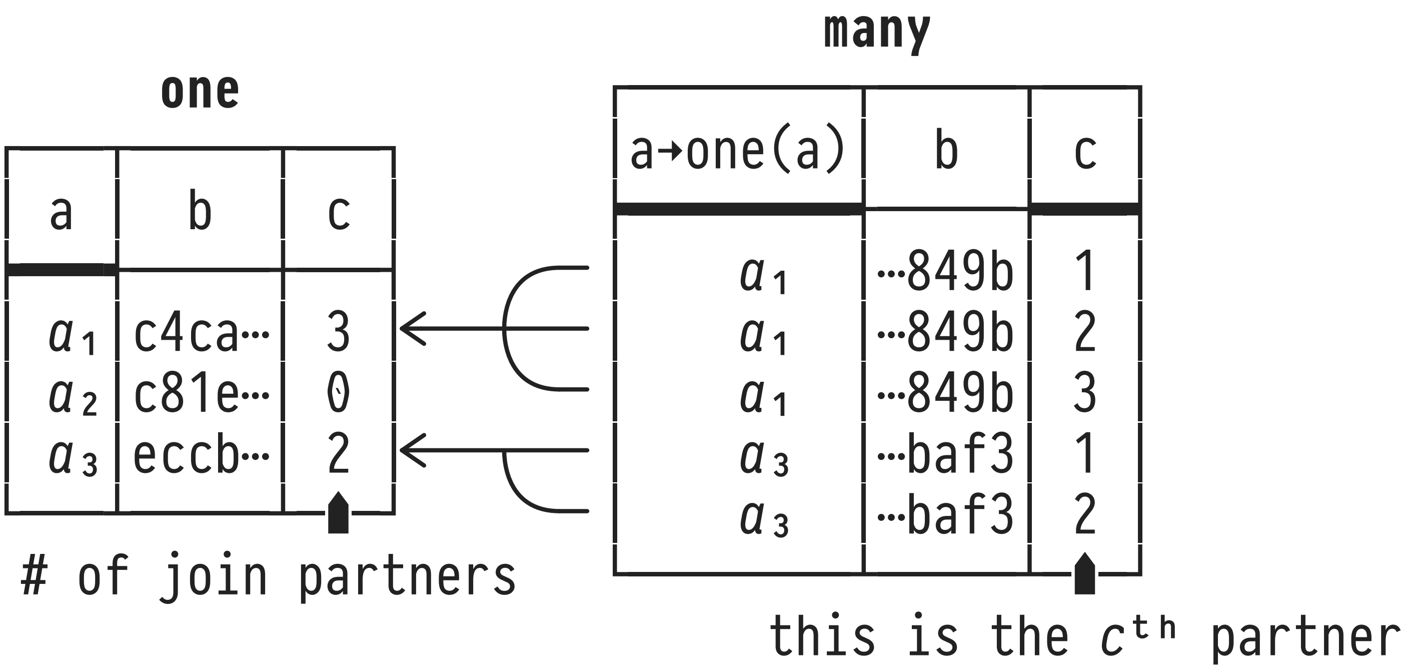
Join (⋈) is a core operation in query processing: given two tables,[1] form all pairs of related rows.

```
SELECT o.a, o.b AS b1, m.b AS b2, m.c
FROM   one AS o,                   -- one o may relate to many m:
       many AS m                   -- [one]─(0,*)─⟨R⟩─(1,1)─[many]
WHERE  o.a = m.a
```

- A one row relates to $0 \ldots n$ rows of many: *1:n relationship*.
    - ⇒ Join size $\in \{0,\ldots,n \times |\text{one}|\}$ rows. Largest possible result if $n = |\text{many}|$ (Cartesian product).

[1] Note: the left and right tables may indeed be the *same* table. This is then coined a **self-join**.

A Sample One-to-Many Relationship



one

a	b	c
a_1	c4ca…	3
a_2	c81e…	0
a_3	eccb…	2

# of join partners

many

a→one(a)	b	c
a_1	…849b	1
a_1	…849b	2
a_1	…849b	3
a_3	…baf3	1
a_3	…baf3	2

this is the c^{th} partner

- Join predicates:
  1. one.a = many.a (index-supported)
  2. md5(one.a) = one.b || many.b (||: string concat)

PostgreSQL: Join Algorithms

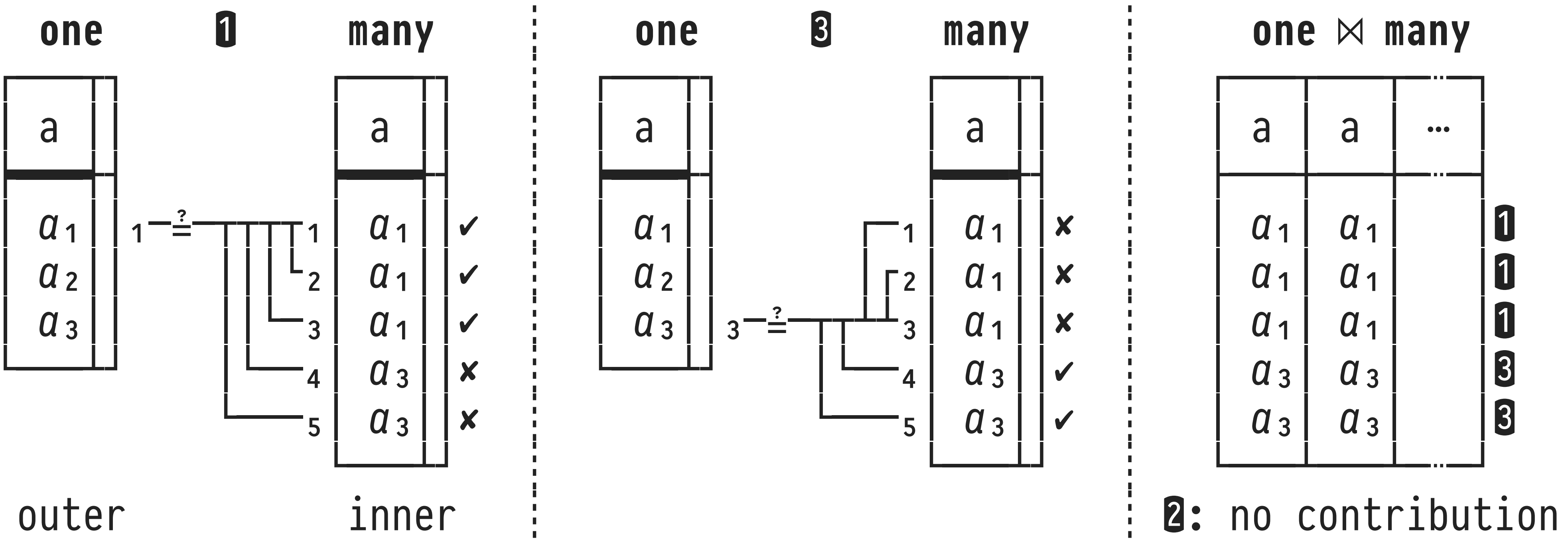
RDBMSs choose between several **join algorithms** based on

- the join **predicate type** (equi-join vs. *θ*-join)
- the existence of **indexes** on the join predicate columns,
- the availability of **working memory**, or
- **interesting sort orders** of join inputs *and* output:

Join Algorithm	Characteristic
Nested Loop Join	processes any *θ*, can benefit from index support
Hash Join	fast equi-joins if plenty working memory available
Merge Join	requires sorted input, produces sorted output

PostgreSQL implements all three kinds of join algorithms.

2 ¦ Nested Loop Join (NLJ, NL⋈)



- Iterate ❶…❸ over rows of **outer table** (here: one) once.
  - For every outer row, iterate over **inner table**.
- Performs |outer| × |inner| join predicate evaluations.

Nested Loop Join (NL⋈) — "The Fallback"

```
NLJ(outer,inner,θ):
 j = ϕ;
 for o ∈ outer
   for i ∈ inner
     if o θ i
       append ⟨o,i⟩ to j;
 return j;
```

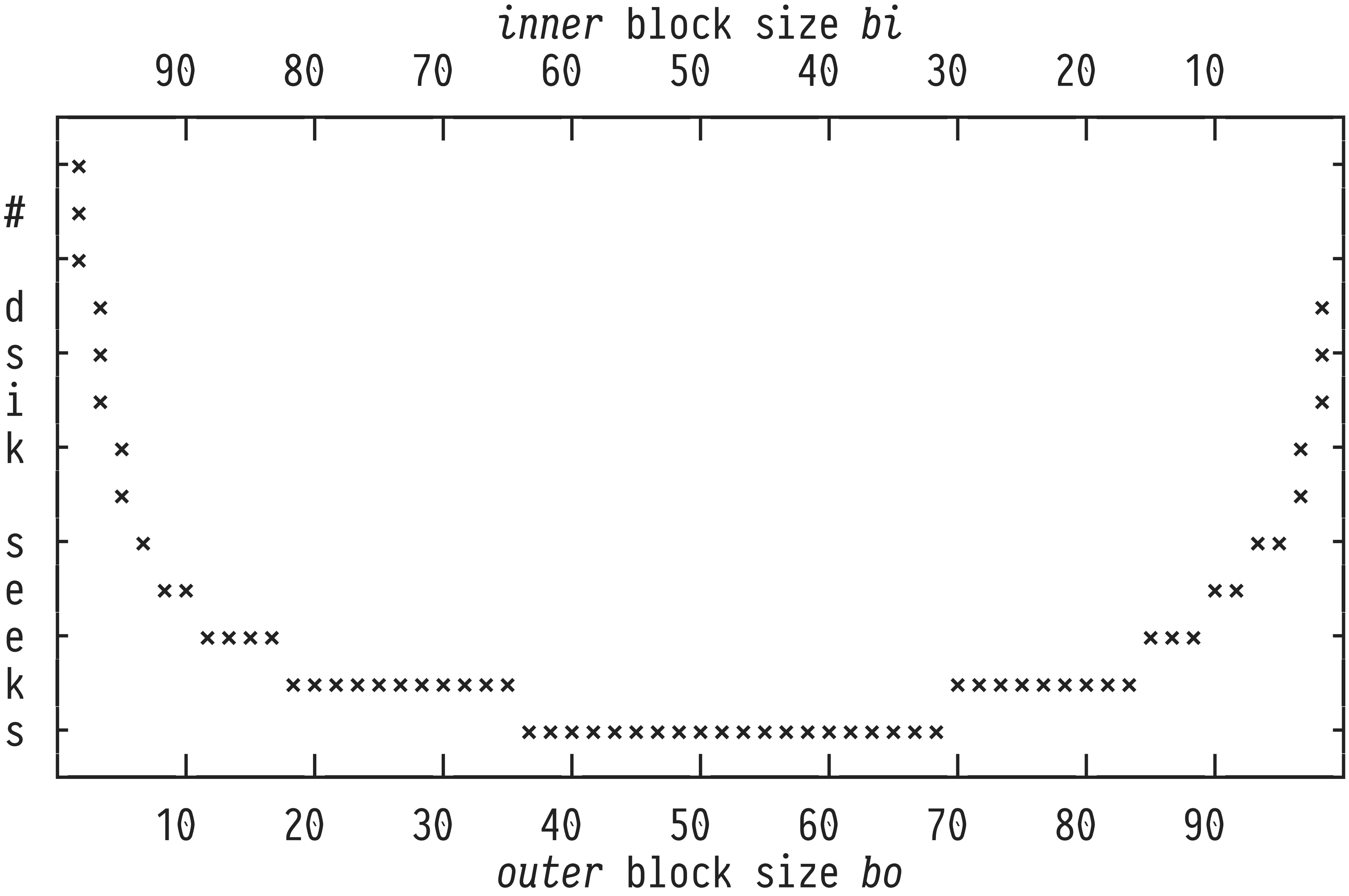
- No restrictions regarding *θ* ∈ {=, <, ⩽, <>, …}. 👍
- No restrictions regarding sort order of *outer*/*inner*. 👍
- Preserves sort order of *outer*. 👍
- Indexes on *outer*/*inner* are ignored. 👎
- Benefits if *inner* can be iterated over quickly (*e.g.*, materialized and/or fits into database buffer).

Block Nested Loop Join (BNL⋈)

```
BlockNLJ(outer,inner,θ):
 j = ϕ;
 foreach block (of size $b_o$) bo ∈ outer
    foreach block (of size $b_i$) bi ∈ inner
       for o ∈ bo                          ⎫
          for i ∈ bi                       ⎬ entirely performed
             if o θ i                      ⎪ inside the buffer
                append ⟨o,i⟩ to j;         ⎭
 return j;
```

- Perform blocked I/O on *outer*/*inner*: less disk seeks. 👍
    - # seeks on *outer*: $\lceil |outer| / bo \rceil$.
    - # seeks on *inner*: $\lceil |outer| / bo \rceil \times \lceil |inner| / bi \rceil$.

Sharing a Buffer of Size B = 100 Slots



NL⋈: Materialization of the Inner Input

The inner NL⋈ input is scanned $\lceil |outer|/b_o \rceil$ times (see PostgreSQL EXPLAIN plans: ⋯ loops=n ⋯).

- 💡 Plan operator Materialize:
  1. **Evaluates its subplan once, saves rows** in working memory or temporary file (“tuple store”).
  2. Can scan tuple store more quickly than regular heap file pages (*e.g.*, no xmin/xmax checking).

```
                        QUERY PLAN
  ⋮
  ->  Materialize  (cost=⋯) (actual time=⋯ loops=n)
        -> ⌜ Subplan (cost=⋯) (actual time=⋯ loops=1) ⌝
           ⌞                                          ⌟
```

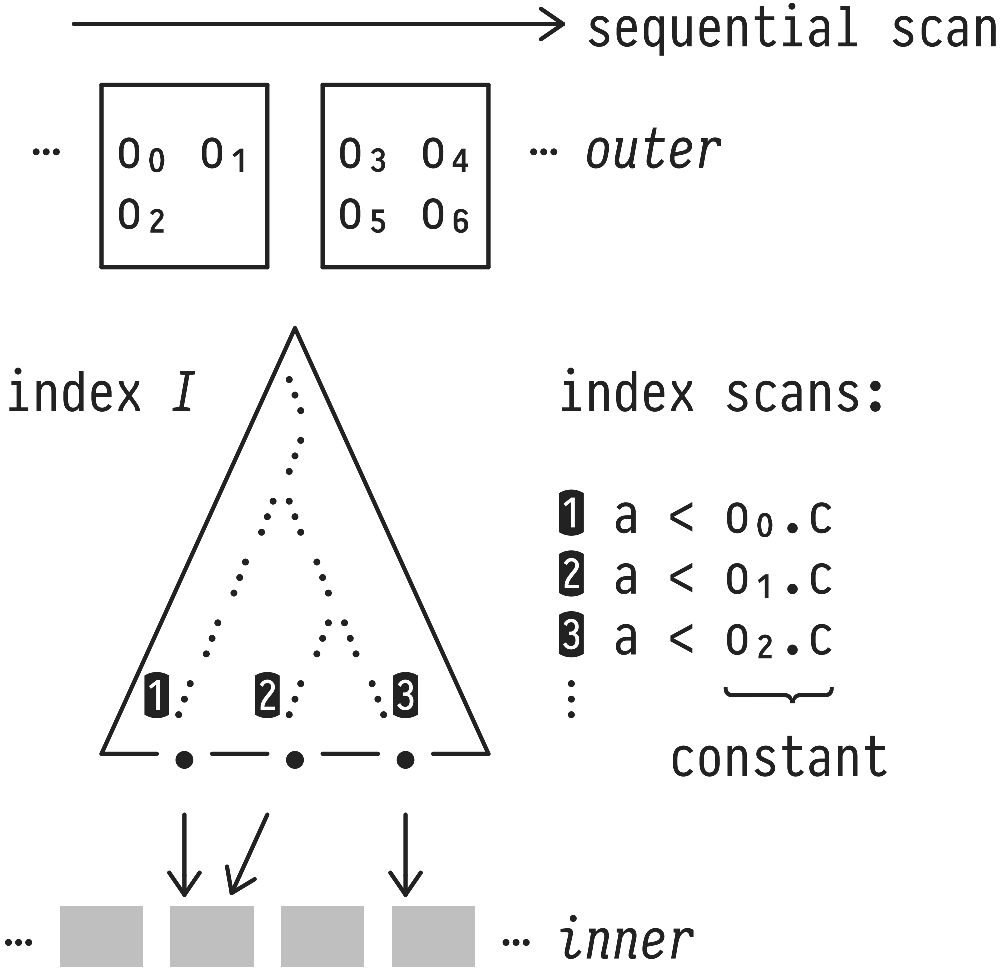
3 ⋮ Index Nested Loop Join (INL⋈)

NL⋈ may be sped up considerably if the $|outer|$ scans of *inner* can be turned into $|outer|$ **index scans on** *inner*:

```
IndexNLJ($outer$,$inner$,$\theta$):
  $j$ = $\phi$;
  for $o \in outer$
  │ for $i \in$ Index[Only]Scan($I$, $\underbrace{o\ \theta\ \square}_{\text{index condition}}$)
  └   └ append ‹$o$,$i$› to $j$;
  return $j$;
```

- *N.B.*: In each of the $|outer|$ invocations of IndexScan, row o essentially is a constant.
  - Index *I* on *inner* must be able to support predicate θ.
- The index scan only delivers actual partners for o. 👍

Index Nested Loop Join (INL⋈)



index scans:

❶ a < o_0.c
❷ a < o_1.c
❸ a < $\underbrace{o_2.c}_{\text{constant}}$
⋮

```
CREATE INDEX I ON many
  USING btree (a);

SELECT *
FROM   one AS o,   -- outer
       many AS m   -- inner
WHERE  m.a < o.c;
```

4 ¦ Merge Join

Join algorithm **Merge Join** supports equality join predicates ("equi-joins") of the form $c_l = c_r$:[2]

1. left input *must* be **sorted** by c_l, right input *must* be **sorted** by c_r,
2. left input scanned once in order, right input scanned once but must support repeated *re-scanning* of rows,
3. the **join output is sorted** by c_l (and thus c_r).

N.B.: Merge Join's guaranteed output order can provide a true benefit during later query processing stages.

[2] Generalizations to predicates $c_l\ \theta\ c_r$ with $\theta \in \{<, \leqslant, \ldots\}$ have been defined but are seldomly found implemented in actual RDBMSs.

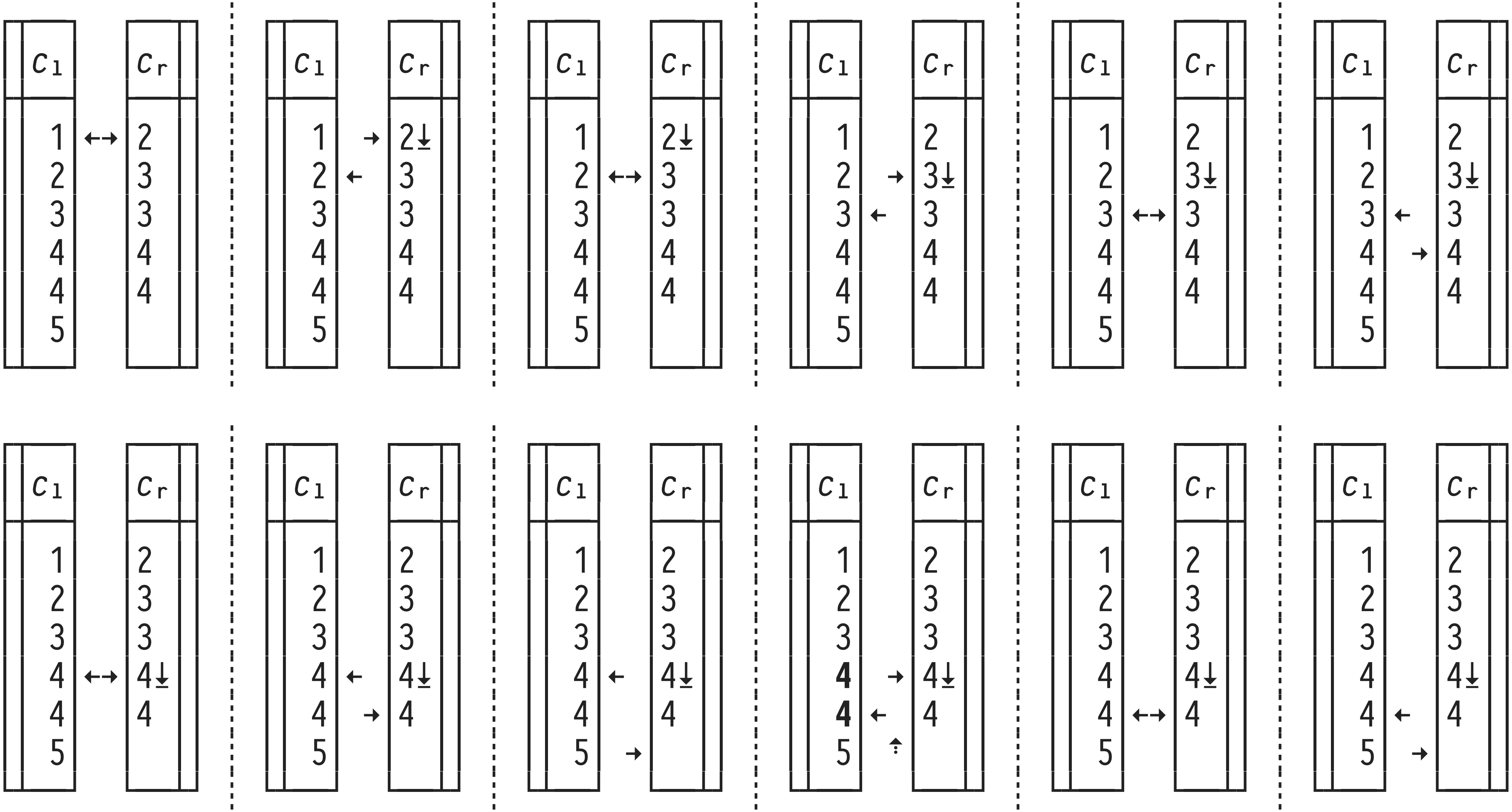
Merge Join Ingredients

Merge Join performs synchronized forward (≡ sorted) scans:[3]

- Maintain row pointers into left/right inputs (←/→).
- Iterate:
  - Move row pointers forward in lock step:
    - If $c_l < c_r$, advance ←. If $c_l > c_r$, advance →.
    - If $c_l = c_r$, emit joined row.
  - If required, save current position (⤓) of → so that we can reset (⇡) the scan of the right input back to ⤓.
    - This resetting may lead to (limited) re-scanning of the right input.

[3] Arrow symbols ←, →, ⤓, ⇡ refer to the illustration on the next slide. Only the join columns c_l, c_r (of type int) are shown.

Merge Join: Synchronized Scan Pointers



Merge Join: Pseudo Code

```
MergeJoin(left,right,$c_l$,$c_r$):
 $j \leftarrow \emptyset$;
 while left ≠ ␄ ∧ right ≠ ␄                 } reached end-of-table?
    while left.$c_l$ < right.$c_r$             ⎫
       advance left;                         ⎬ move scans forward
    while left.$c_l$ > right.$c_r$             ⎪ in lock step
       advance right;                        ⎭
    ⤓ ← right;                               } save current right pos
    while left.$c_l$ = ⤓.$c_r$                 } scan repeating left group
       right ← ⤓;                            } reset right scan
       while left.$c_l$ = right.$c_r$
          append ‹left,right› to j;
          advance right;
       advance left;
 return j;
```

Merge Join: Sorted Inputs

Merge Join requires inputs sorted on c_l/c_r. Options:

1. Introduce **explicit** **Sort** plan operator below Merge Join.
2. Input is **Index Scan** with key column prefix c_l/c_r.[4]
3. Input table is (perfectly) **clustered** on c_l/c_r.
4. **Subplan** below Merge Join delivers rows in c_l/c_r **order**.

```
                       QUERY PLAN
Merge Join (cost=…) (actual time=… loops=n)
  -> ⌜ Subplan left (cost=…) (actual time=… loops=1)  ⌝

     ⌞                                                ⌟
  -> ⌜ Subplan right (cost=…) (actual time=… loops=1) ⌝

     ⌞                                                ⌟
```

[4] **Q:** Will Bitmap Index/Heap Scan also fit the bill here?

Merge Join: Re-Scanning the Right Input

Since Merge Join may need to reset the pointer in *right*, its subplan is required to support re-scanning of rows:

- Supported by Index Scan and in-memory buffers, but may be impossible and/or costly for complex subplans.
- 💡 Place Materialize above *right* to support re-scan:

```
                          QUERY PLAN
Merge Join (cost=…) (actual time=… loops=…)
  -> ⌜ Subplan left (cost=…) (actual time=… loops=1)   ⌝
     ⌞                                                 ⌟
  -> Materialize (cost=…) (actual time=… loops=1)
       -> ⌜ Subplan right (cost=…) (actual time=… loops=1) ⌝
          ⌞                                                ⌟
```

Interesting Orders

If a subplan *delivers* rows in a well-defined **interesting order**, the *upstream* query plan may

- save an explicit Sort operator—*e.g.*, to implement ORDER BY or GROUP BY—that now becomes obsolete,
- employ order-dependent operators at no extra cost.

May reduce overall plan cost, even if the subplan itself does not benefit: sorting effort will only pay off later.

- Nested Loop Join and Merge Join can deliver rows in such interesting orders.

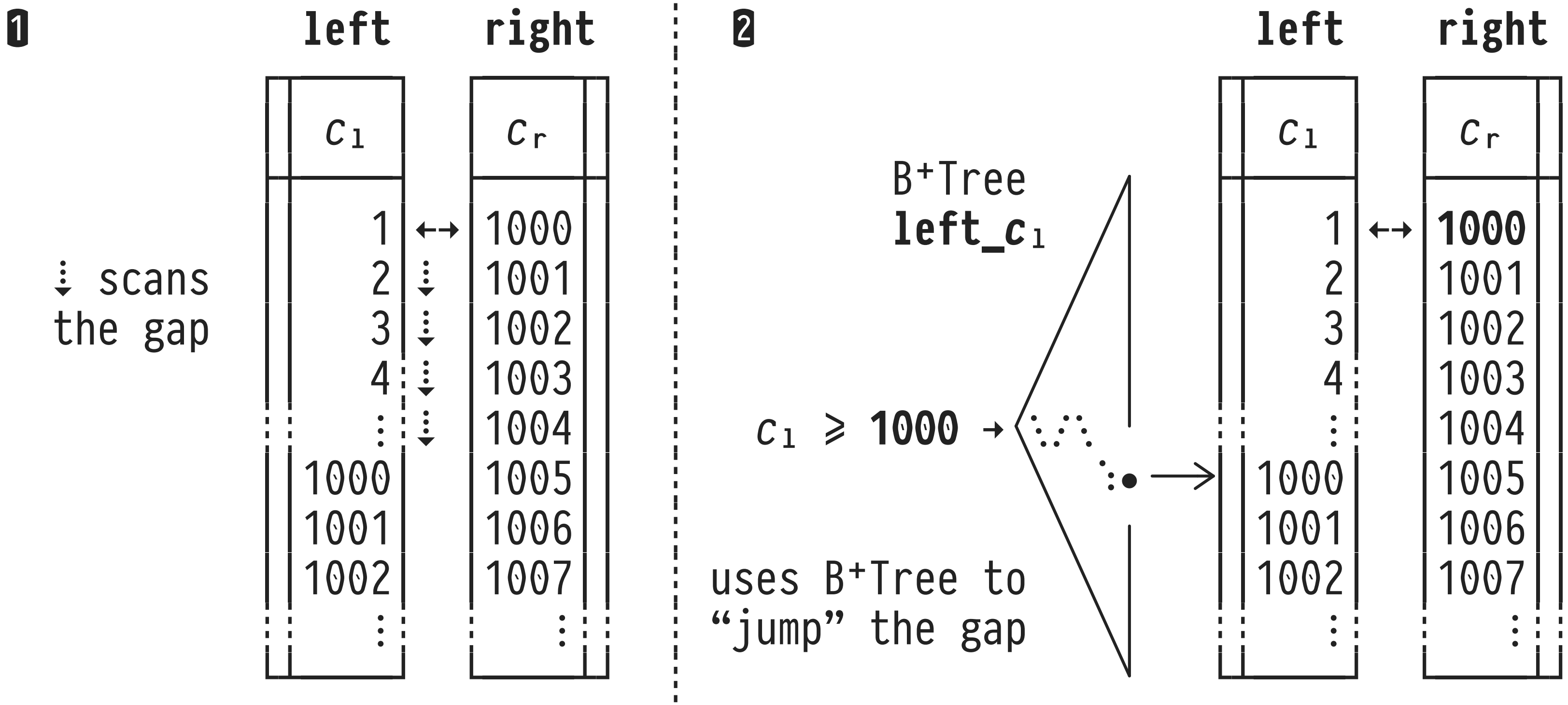
Merge Join: Low Memory Requirements

Hash Join (see below) is the go-to equi-join algorithm in modern RDBMSs including PostgreSQL. If **memory is tight**, however, Merge Join may be superior:

- If inputs are sorted, the actual *merging* requires as few as 3 buffer pages (2×input + 1×output).
  - Requirement: *right* needs no re-scanning, *e.g.*, if *right*.c_r is unique.
  - See Merge Join plan property: Inner Unique: true.
  - Algorithm MergeJoinUnique(*left*,*right*,c_l,c_r) requires no management of ↓ at all. **Q:** Simplified code?

Challenges for Merge Join

- Large groups of repeating values in *right* input (*i.e.*, positions of ⇣ and → diverge). **Q:** Worst case?
- Large *left*.c_l ↔ *right*.c_r gaps. Consider ❶:



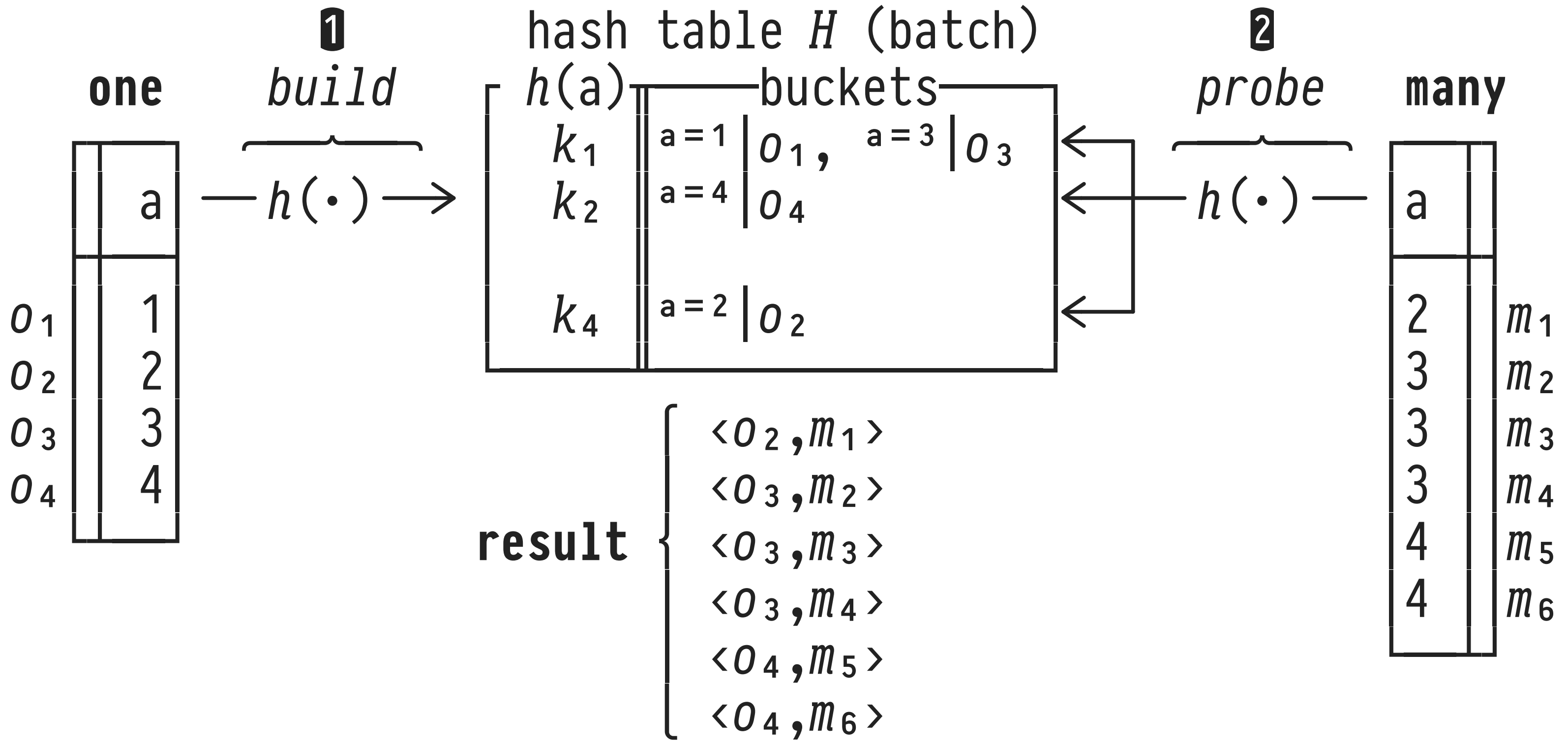
Equi-joins—*e.g.*, foreign-key joins—are arguably the most prominent kinds of relational join. Merge Join relies on *sorting* while **Hash Join** uses *hashing* to perform equi-joins:

1. **Build:** Read and hash the rows of one input table to populate a **hash table** H. Requires memory to store H.
2. **Probe:** Iterate over and hash rows of other input table. Find potential join partner rows in hash bucket of H.

- If $|H|$ > working memory, partition build/probe tables, iterate phases (**Hybrid Hash Join**).
- Hash Join does not require input order and does not guarantee output order.

Hash Join: ··· FROM one AS o, many AS m WHERE o.a = m.a

- **Build + Probe:** Apply hash function $h(\cdot)$.
- **Probe:** Evaluate join predicate o.a = m.a for entries in hash bucket with key $k_i = h(\text{m.a})$ only.



one

	a
o_1	1
o_2	2
o_3	3
o_4	4

❶ *build* $h(\cdot)$

hash table H (batch)

$h(\text{a})$	buckets
k_1	a = 1 | o_1, a = 3 | o_3
k_2	a = 4 | o_4
k_4	a = 2 | o_2

❷ *probe* $h(\cdot)$

many

a	
2	m_1
3	m_2
3	m_3
3	m_4
4	m_5
4	m_6

result

$\langle o_2, m_1 \rangle$
$\langle o_3, m_2 \rangle$
$\langle o_3, m_3 \rangle$
$\langle o_3, m_4 \rangle$
$\langle o_4, m_5 \rangle$
$\langle o_4, m_6 \rangle$

Hash Join: Pseudo Code

```
HashJoin($build$,$probe$,$c_l$,$c_r$):
  $j \leftarrow \phi$;
  $H \leftarrow [\,]$;                                } empty hash table

  for $b \in build$                                   } ❶ build
    insert $b$ into bucket $H[h(b.c_l)]$;                  phase

  for $p \in probe$                                   } ❷ probe
    for $b \in H[h(p.c_r)]$                                 phase
      if $b.c_l = p.c_r$
        append $\langle b,p \rangle$ to $j$;

  return $j$;
```

Hash Join: Execution Plan

```
                          QUERY PLAN
Hash Join (cost=…) (actual time=… loops=…)
  Hash Cond: (… = …)
  -> ⌜ Subplan probe (cost=…) (actual time=… loops=1)  ⌝

     ⌞                                                ⌟
  -> Hash (cost=…) (actual time=… loops=1)
      -> ⌜ Subplan build (cost=…) (actual time=… loops=1) ⌝

         ⌞                                                ⌟
```

- Use smaller join input for *build* phase (reduces $|H|$).
- ⚠️ Indexes on *build* and *probe* inputs remain unused, even if defined on join predicate columns.

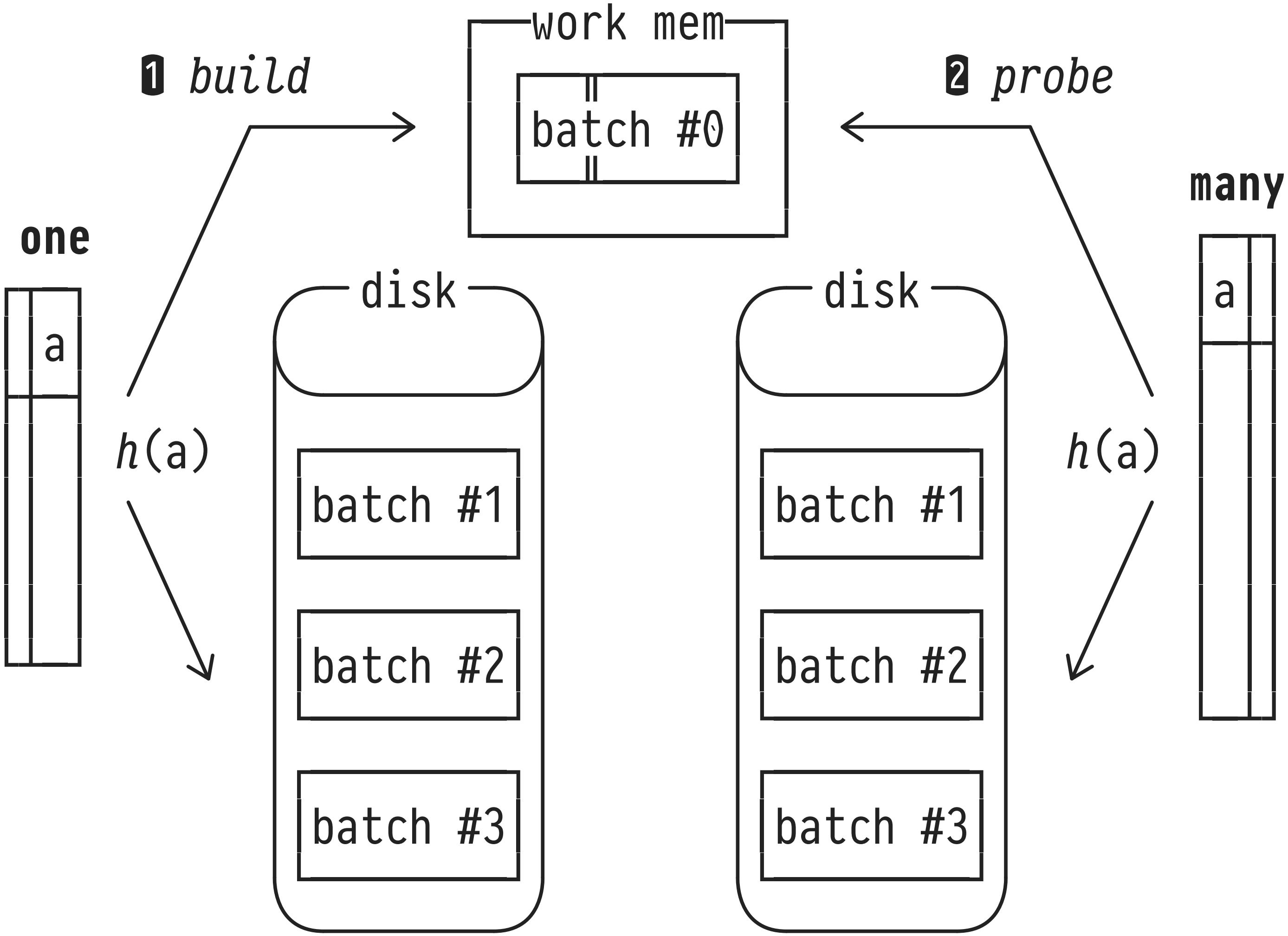
Multiple Rounds: Hybrid Hash Join

- Input in round 0: tables **one** and **many**.

- Input in round $i \geqslant 1$: batches #i read from temp files.

- Prepare 2^n batches, first n bits of h(a) determine batch #:

  batches #0: 00…
  #1: 01…
  #2: 10…
  #3: 11…



Hybrid Hash Join (With Skew)

- If working memory cannot hold entire hash table H, use hash key $h(\cdot)$ to split *build* input into 2^n batches.
  - *Probe* input hashed into batch #0 is joined as usual (**round 0**).
  - All other batches processed in subsequent **2^n-1 rounds.**

- 💡 Allocate additional **skew batch** in working memory:

$$\text{Place row } t \text{ in } \begin{cases} \text{skew batch, if } t.\text{a among } \textbf{most common} \\ \qquad\qquad\qquad\; \textbf{a-values} \text{ in } \textit{probe} \text{ input,} \\ \text{batch } \#i\text{ , based on } h(t.\text{a}),\text{ otherwise.} \end{cases}$$

6 ¦ Q_{11}: Equi-Joins in MonetDB

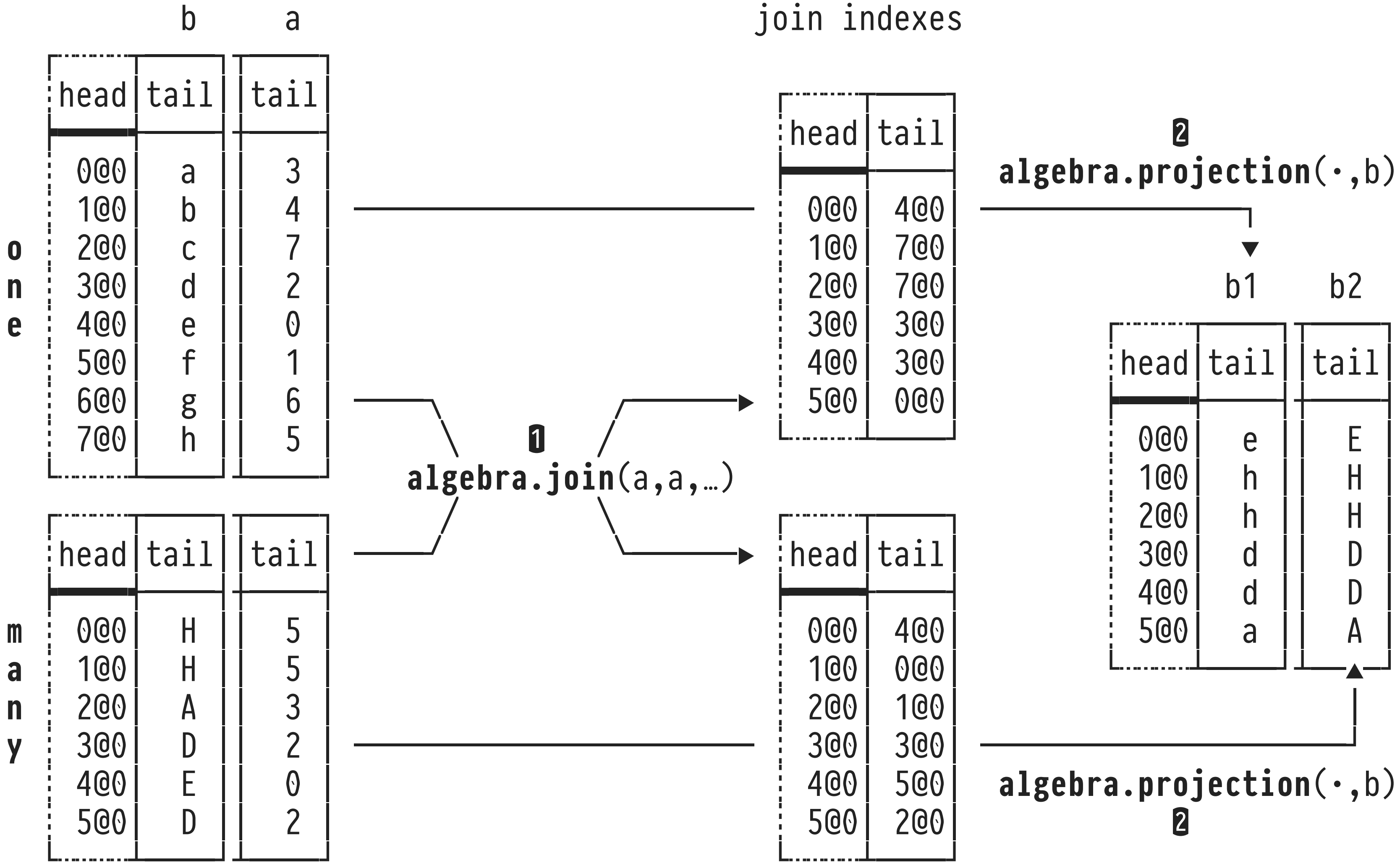
```
SELECT o.b AS b1, m.b AS b2
FROM   one AS o,
       many AS m
WHERE  o.a = m.a
```

Since database instances reside on hosts with plenty of RAM, **Hash Join** is the go-to join method for MMDBMS.

In MonetDB, a join computes **join index** BATs[5] to identify rows in one, many that find a join partner.

[5] Much like filtering is implemented in terms of **selection vectors.**

Equi-Joins and Join Indexes in MonetDB



one

	b	a
head	tail	tail
0@0	a	3
1@0	b	4
2@0	c	7
3@0	d	2
4@0	e	0
5@0	f	1
6@0	g	6
7@0	h	5

many

head	tail	tail
0@0	H	5
1@0	H	5
2@0	A	3
3@0	D	2
4@0	E	0
5@0	D	2

❶ **algebra.join**(a,a,…)

join indexes

head	tail
0@0	4@0
1@0	7@0
2@0	7@0
3@0	3@0
4@0	3@0
5@0	0@0

head	tail
0@0	4@0
1@0	0@0
2@0	1@0
3@0	3@0
4@0	5@0
5@0	2@0

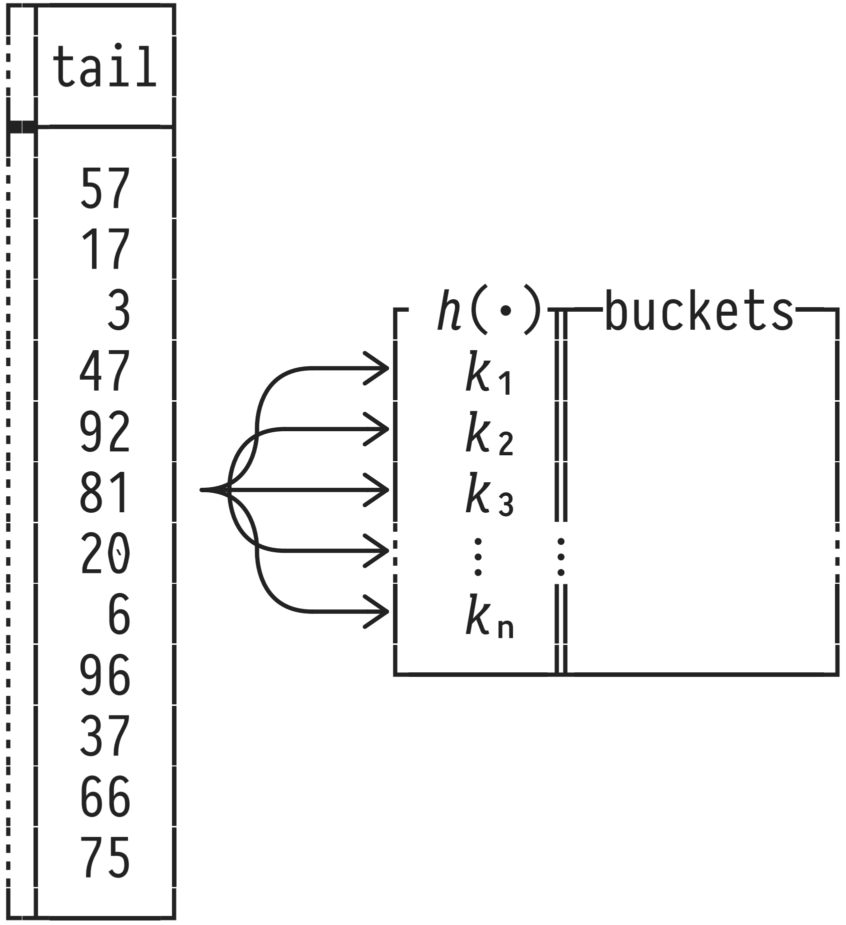
❷ **algebra.projection**(·,b)

	b1	b2
head	tail	tail
0@0	e	E
1@0	h	H
2@0	h	H
3@0	d	D
4@0	d	D
5@0	a	A

algebra.projection(·,b)
❷

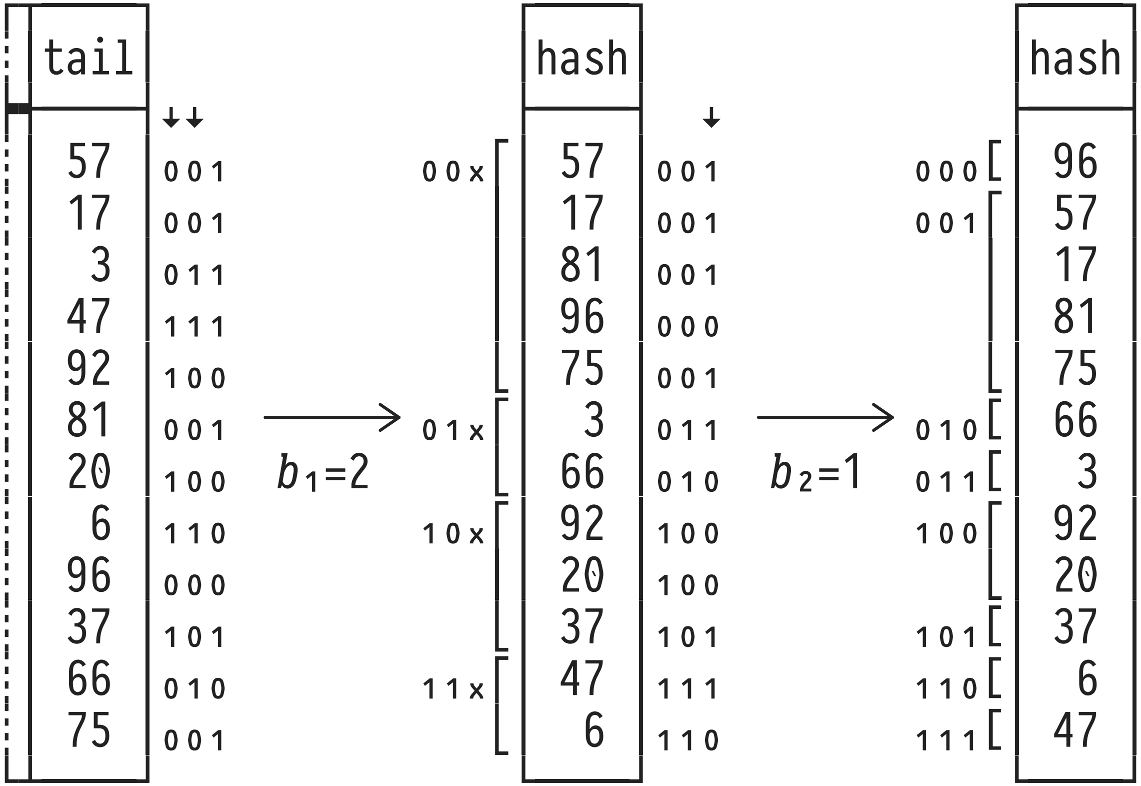
Partitioning BATs Into (Too) Many Buckets

- To prepare Hash Join, use $h(\cdot)$ to distribute rows into hash buckets.
- Requires random writes into n different memory locations.
- If n is (too) large:
  - Cache thrashing (# of cache lines exceeded). 👎
  - TLB[6] misses. 👎
- 💡 Reduce number of buckets considered at any one time.



[6] The CPU's *Translation Lookaside Buffer* stores recent translations from virtual into physical memory locations.

Radix-Clustering



	tail	↓↓
	57	001
	17	001
	3	011
	47	111
	92	100
	81	001
	20	100
	6	110
	96	000
	37	101
	66	010
	75	001

$\xrightarrow{}$ b_1=2

	hash	↓
00x	57	001
	17	001
	81	001
	96	000
	75	001
01x	3	011
	66	010
10x	92	100
	20	100
	37	101
11x	47	111
	6	110

$\xrightarrow{}$ b_2=1

	hash
000	96
001	57
	17
	81
	75
010	66
011	3
100	92
	20
101	37
110	6
111	47

- To distribute by B bits in p passes:

  ❶ Define b_i such that

  $$B = \sum_{i=1}^{p} b_i$$

  ❷ In pass i, distribute by b_i bits of the hash.

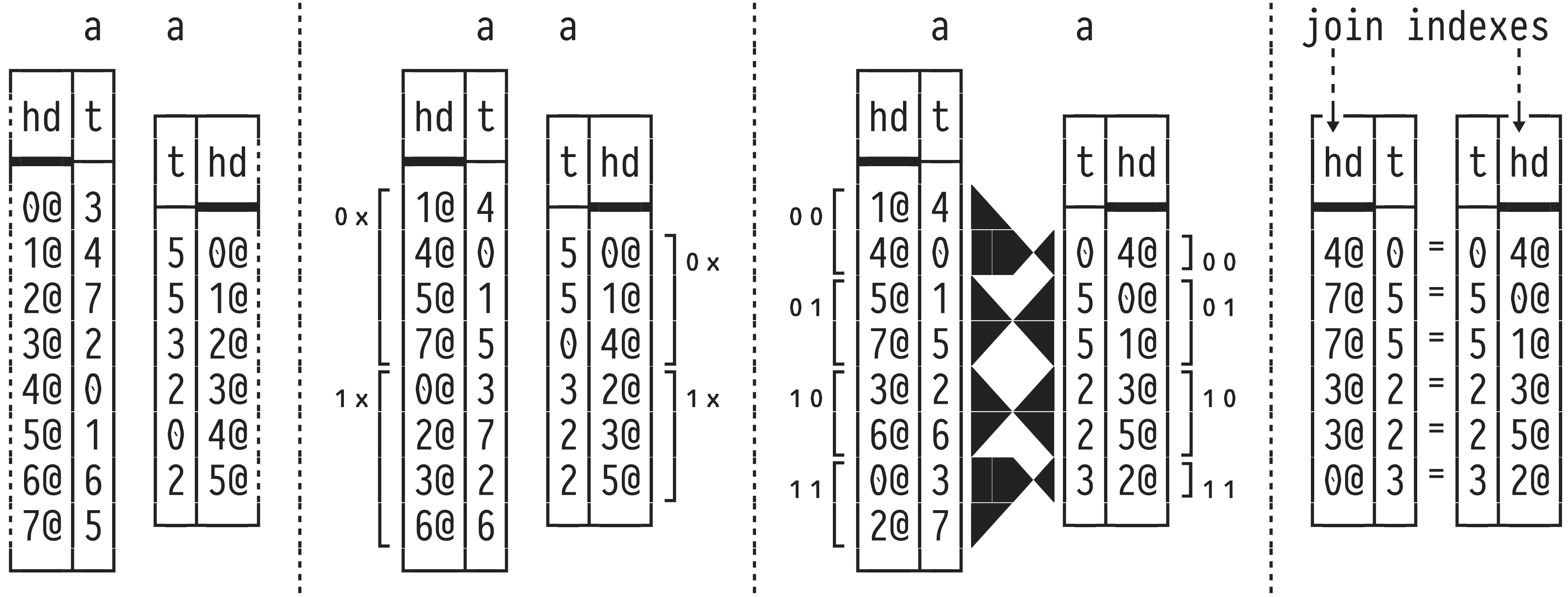
- # of buckets created:

  $$\prod_{i=1}^{p} 2\hat{}b_i$$

- Only write to $2\hat{}b_i$ buckets in each pass to avoid cache thrashing and TLB misses.

Radix-Cluster Equi-Join in Q_{11} (o.a = m.a)

- Two-pass (p = 2) radix-clustering with $b_1 = b_2 = 1$:



hd	t
0@	3
1@	4
2@	7
3@	2
4@	0
5@	1
6@	6
7@	5

t	hd
5	0@
5	1@
3	2@
2	3@
0	4@
2	5@

hd	t
1@	4
4@	0
5@	1
7@	5
0@	3
2@	7
3@	2
6@	6

t	hd
5	0@
5	1@
0	4@
3	2@
2	3@
2	5@

hd	t
1@	4
4@	0
5@	1
7@	5
3@	2
6@	6
0@	3
2@	7

t	hd
0	4@
5	0@
5	1@
2	3@
2	5@
3	2@

hd	t
4@	0
7@	5
7@	5
3@	2
3@	2
0@	3

t	hd
0	4@
5	0@
5	1@
2	3@
2	5@
3	2@

- Rows for cluster-local joins ⋈ fit into the CPU cache.