# Dissecting the Duck's Innards

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**The ART of Indexing**

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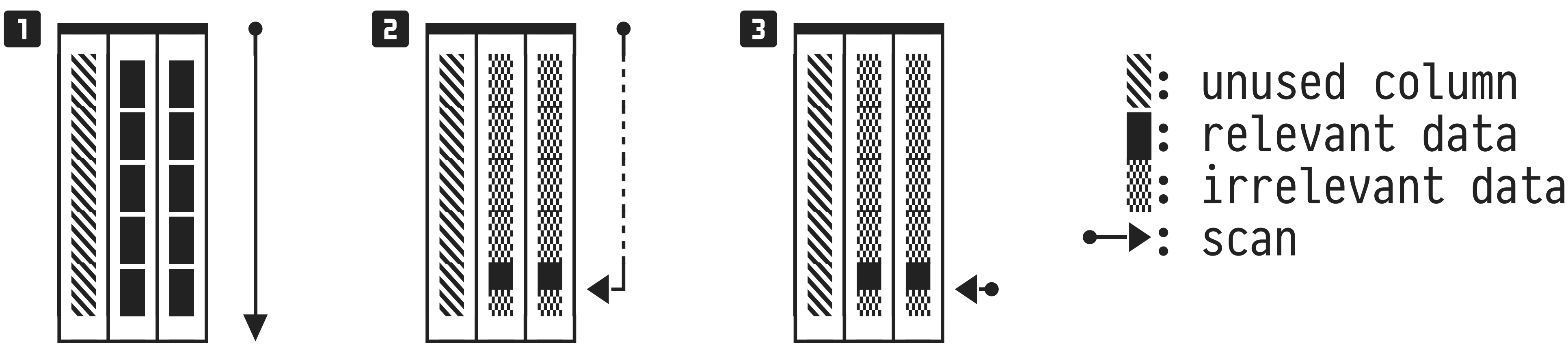
## 1 ┆ Scanning All Rows vs. Narrowing In On Few Rows

The internals of DuckDB have been designed to efficiently support analytical SQL queries: "***o**nline **a**nalytical **p**rocessing*" (**OLAP**).

- Typically, these queries read (and aggregate) *all rows* of the input tables **1**.
- Yet, scanning all rows wastes I/O and memory bandwidth **2** if a query focuses on *small row subsets (or even a single row)*:




scan & aggregate

scan & "forget"

hit target row(s)

**Indexes** help to implement **3**.

## Indexes in DuckDB

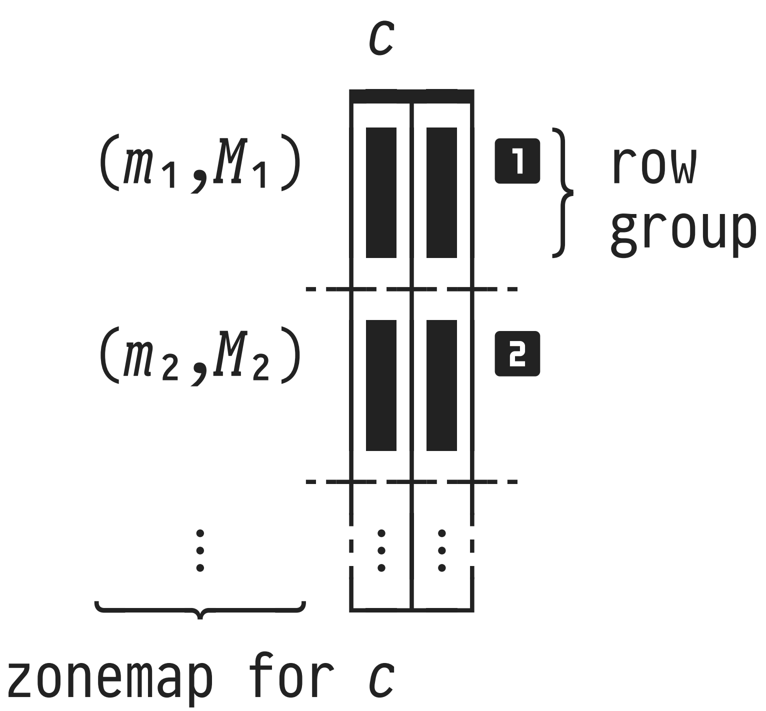
DuckDB implements two kinds of **indexes:**

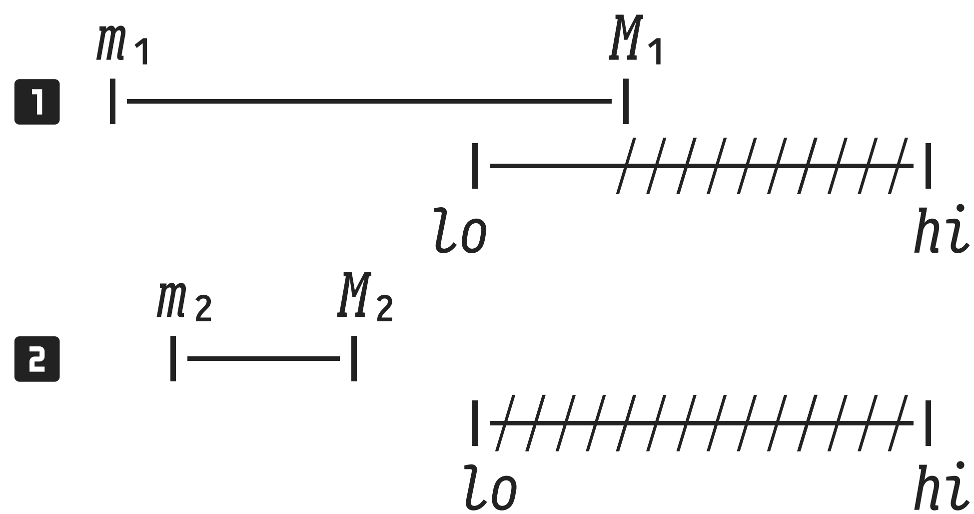
1. **Zonemaps** (also: *min-max indexes*) are integral part of the columnar table storage ▥.
   - Automatically created, always present for all columns.
   - Used when predicates are pushed down into Sequential Scan.

2. **Adaptive radix trees** (**ART**) are tree-shaped data structures maintained outside/in addition to table storage ▥+⁂.
   - Consume working memory space.
   - Require maintenance on table updates.
   - Created either
     - manually via SQL's DDL statement CREATE INDEX or
     - automatically when constraints UNIQUE, PRIMARY KEY, and FOREIGN KEY are declared for a table.

**Zonemaps** are baked into DuckDB's columnar table storage format:

- Each column $c$ is divided into *row groups* of 120K (122880) rows.
- Each row group holds a ($min$,$Max$) entry that—quite roughly—characterizes the contained values.
- Operator Sequential Scan can safely **skip row groups** for which a predicate $lo \leqslant c \leqslant hi$ will always fail (~~///~~):

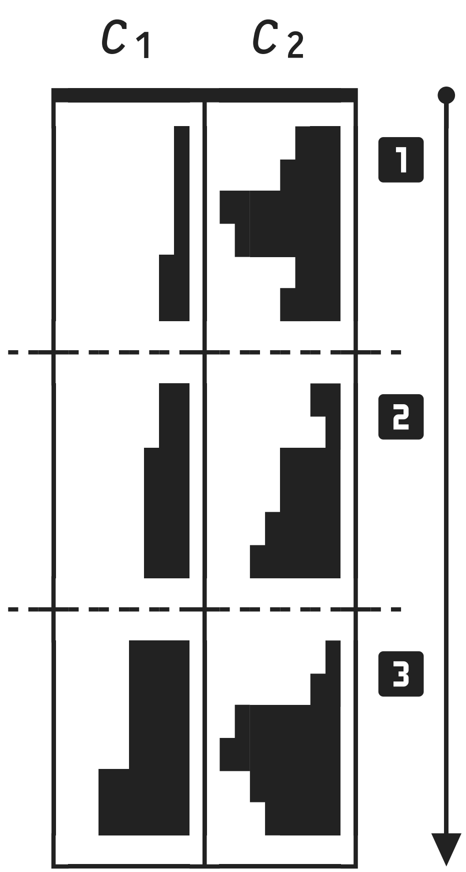



- Need to scan row group 1
- May skip row group 2

## Zonemaps and Column Ordering

Column ordering affects the effectiveness of zonemaps. #015




**$c_1$:** In each row group, the zonemap entries (*min*,*Max*) for $c_1$ have a small *span* |—|.

⇒ A large number of row groups will never satisfy $lo \leqslant c_1 \leqslant hi$. Can skip.

**$c_2$:** All spans in unordered column $c_2$ are wide |————————| and cover the active domain of $c_2$.

⇒ Most (all) row groups will potentially contain hits for $lo \leqslant c_2 \leqslant hi$. No skipping.

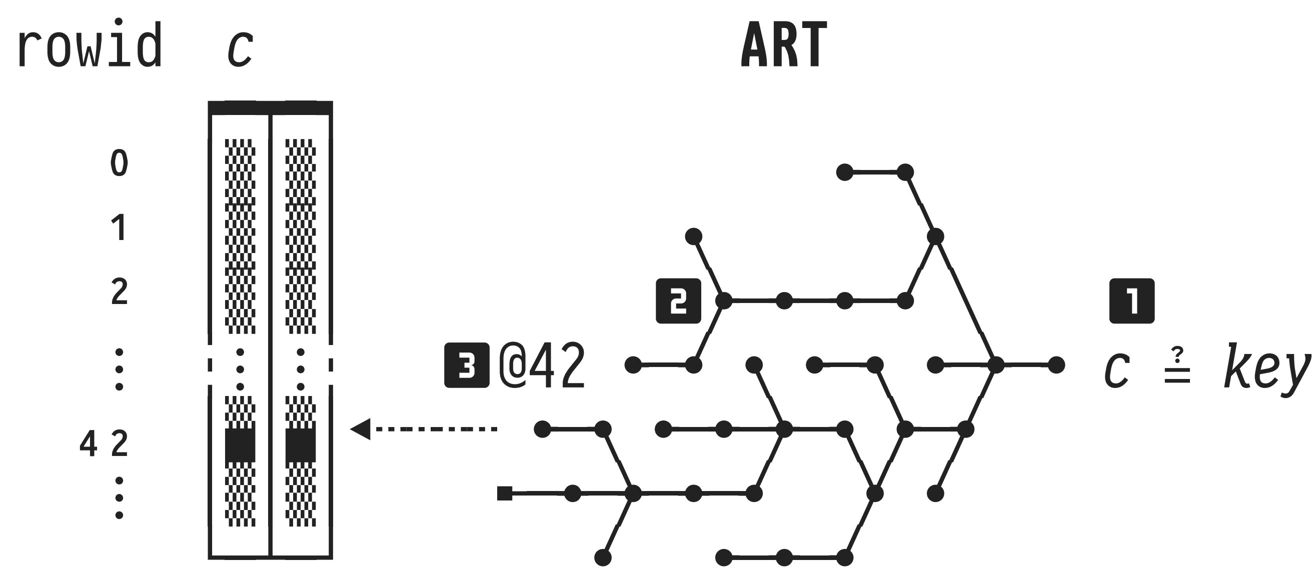
Keeping base tables ordered may help predicate evaluation.

# 3 ┆ Adaptive Radix Tree (ART) Indexes

ART indexes are **ordered search tree structures** built to evaluate simple **equality and range predicates** (assume an ART on column *c*):

$c = key$ ┆ $c$ IN $(key_1, key_2, \ldots)$ ┆ $c < key$ ┆ $c > key$

- ARTs and tables are separate. These extra data structures
  - use **row IDs** to refer to rows in their associated table,
  - must be created, then maintained under table updates, and
  - occupy space in working memory.




**Index lookup:**

1 Enter at root

2 Navigate ART to leaf node

3 Use rowid @42 to access row

## Creating ART Indexes in DuckDB

1. **Manual:**

```
CREATE [UNIQUE] INDEX index ON table (column [, column, …]);
DROP INDEX [IF EXISTS] index;
```

   - **NB.** More indexes aid query evaluation but incur maintenance and space[1] overhead. A tradeoff in physical database design.

2. **Implicit** (supports constraint enforcement). DDL statement ❶ creates on a unique ART index on *t*(*c*) behind the scenes:

```
❶ CREATE TABLE t (…, c … PRIMARY KEY, …);  -- also: UNIQUE
❷ CREATE TABLE s (…, f … REFERENCES t(c), …);
```

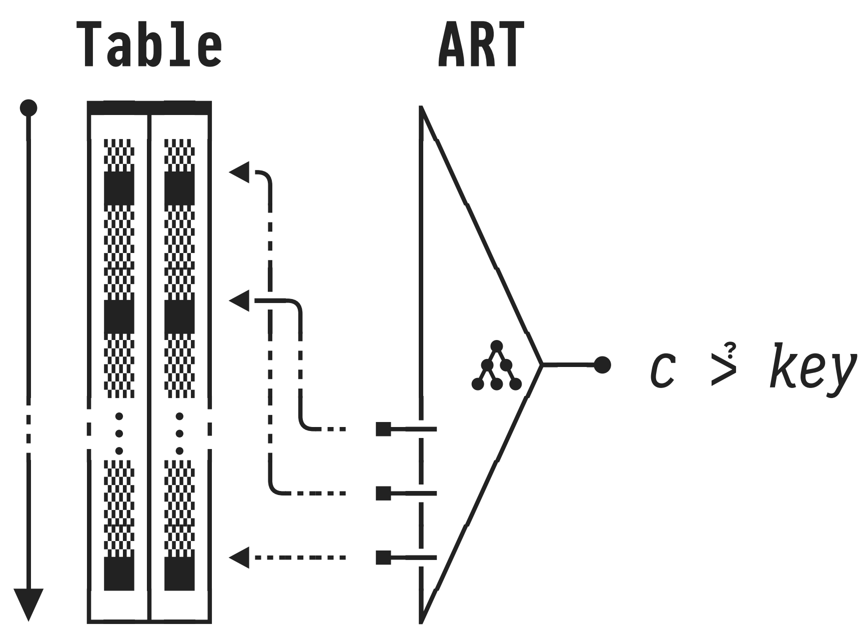
   - DDL statements like INSERT INTO *s* VALUES (…, *key*, …) or UPDATE *t* SET *c* = *key* lead to lookups $c \overset{?}{=} key$ in that index.

[1] As of DuckDB 1.4, memory occupied by ART indexes is under control of the buffer manager but cannot be evicted. Work to rectify this is underway as I type this.

# Use the Index? Ignore the Index?

An index lookup predicate $p$ may yield *multiple rows* in table $t$:

- $p \equiv c \overset{?}{=} key$: If $c$ is not unqiue in $t$: a single leaf node ─▪ holds multiple rowids ···▸ ···▸ ···▸.
- $p \equiv c \overset{?}{>} key$: ❶ perform lookup $c \overset{?}{=} key$, ❷ access rows using the rowids in all leaves ▪ ▪ ▪ following the found leaf:




- Lookup finds one leaf (or adjacent leaves ▪ ▪ ▪).

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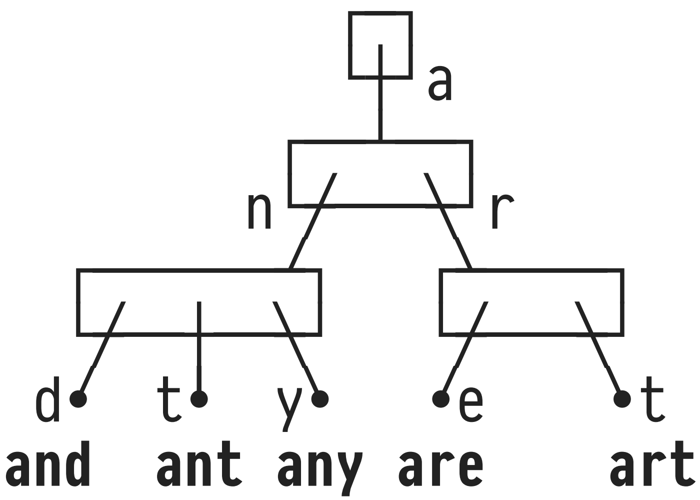
- Yet the rowids ···▸ may point all over table $t$. May need to "jump around" to collect rows. Violates memory locality. 👎

💡 Use index only if **selectivity** $sel(p)$ of predicate $p$ is low:

$$0 \leqslant sel(p) \overset{\text{def}}{=} (\textbf{SELECT}\ \text{count}(*)\ \textbf{FILTER}\ (p)\ /\ \text{count}(*)\ \textbf{FROM}\ t) \leqslant 1$$

An ART on $t(c)$ uses the **bit-wise representation of values** in column $c$ to organize itself. Values are *not* hashed or compared.

- Divide values into groups of $s$ bits each ($s$ is the *span*).
- During tree traversal, the next $s$ bits of $key$ determine the child node to descend into.




- Example: $c$ :: text, span $s$ = 8 bits.
- Values have $k$ = 24 bits.

$$\begin{array}{rl} \textbf{ant} =_2 & \overbrace{01000001}^{s \text{ bits}}\ 01001110\ \overbrace{01001110}^{\textbf{ant} < \textbf{any}} \\ \textbf{any} =_2 & \underbrace{01000001\ 01001110}_{\text{common prefix} \equiv \text{shared path in ART}}\ 01011001 \end{array}$$

## ART Internals: Mapping Values to Bit Sequences

Map values to bit sequences whose **lexicographic order** properly reflects value sort order:

- **Unsigned ints:** use standard binary representation (little-endian machines: reverse byte order so that MSB comes first).
- **Signed ints** (in two's complement): flip the sign bit, then treat like unsigned ints.
- **IEEE 754 floats:** ❶ always flip the sign bit, ❷ if the sign bit was orignally set, now flip all bits. #017
- **Text strings:** map UTF-8 byte sequence to binary[2], end strings with ␀ (values must not be prefixes of other values).
- **Composite values** $(v_1,\ldots,v_n)$: map the individual fields $v_i$, then *concatenate* the resulting bit sequences.
- **NULL**: increase bit length $k$ (*e.g.*, by one bit/one byte) to accomodate the additional value.

[2] DuckDB uses function ucol_getSortKey() of the C/C++ library ICU to perform this mapping.

## ART Internals: What is a Good Span?

- The height of ARTs depend on the value bit length $k$ (*not* the number $n$ of entries).
  - An ART for $k$-bit values has $\lceil k/s \rceil$ levels of inner nodes.
  - ART lookup and insert operations have complexity $O(k)$.

- ARTs *vs.* binary search trees (BSTs):
  - Height: if $n > 2^{k/s}$, ARTs have smaller height than BSTs ($\log_2(n)$).
  - Lookup: for values of $k$ bits ($k$ large), comparison ($<$) is $O(k)$. Complexity of BST lookup thus is $O(k \cdot \log_2(n))$.

Optimize ART **performance:** Work with a large span $s$!

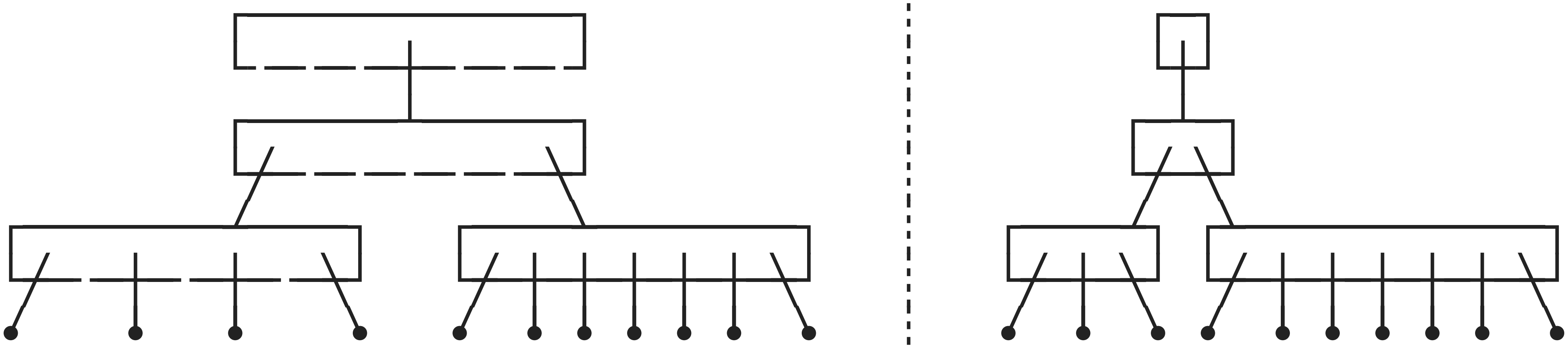
But how about the **space usage** of such ARTs?

## ART Internals: Designing Inner Nodes

- A simple representation of inner ART nodes:
  - Array of $2^s$ child pointers. (Nodes would have **fixed size.**)
  - Use *s*-bit chunk of *key* to index array + access child node.

  - But: Most child pointers will be NULL (└──), space usage will be excessive if *s* is large (grows exponentially):

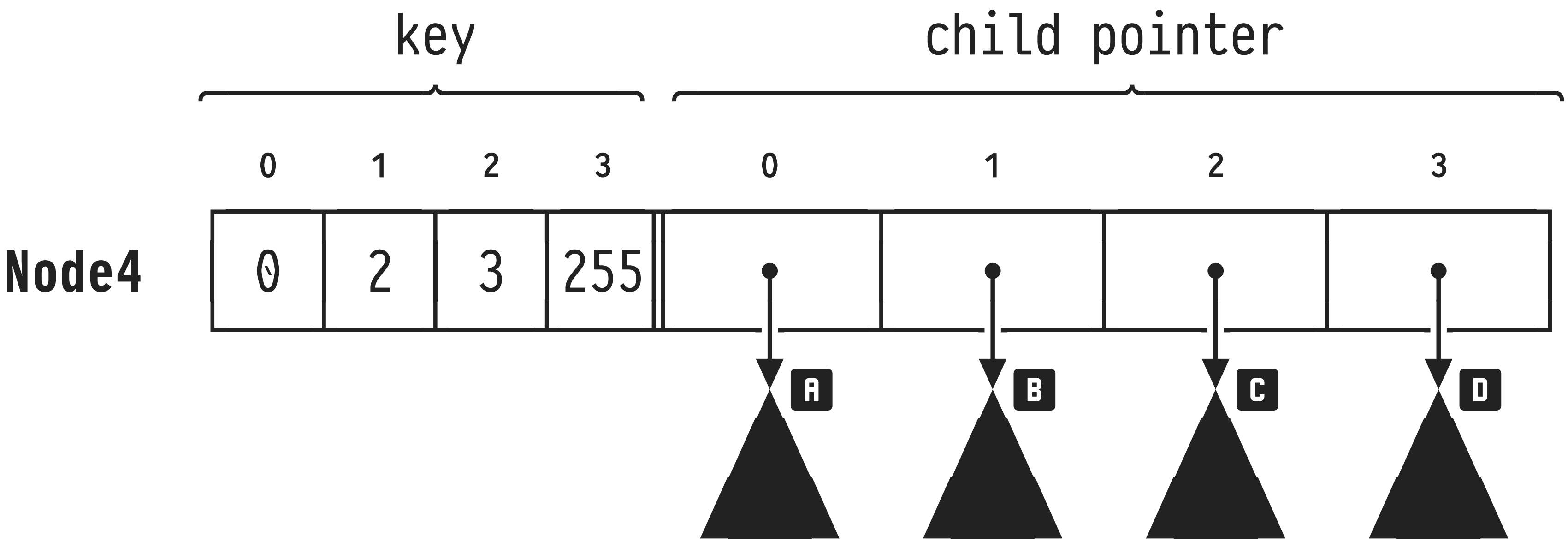
**Node size fixed** **Node size adaptive**



💡 Use a fixed large *s* but **adapt node size** (use variable fanout).

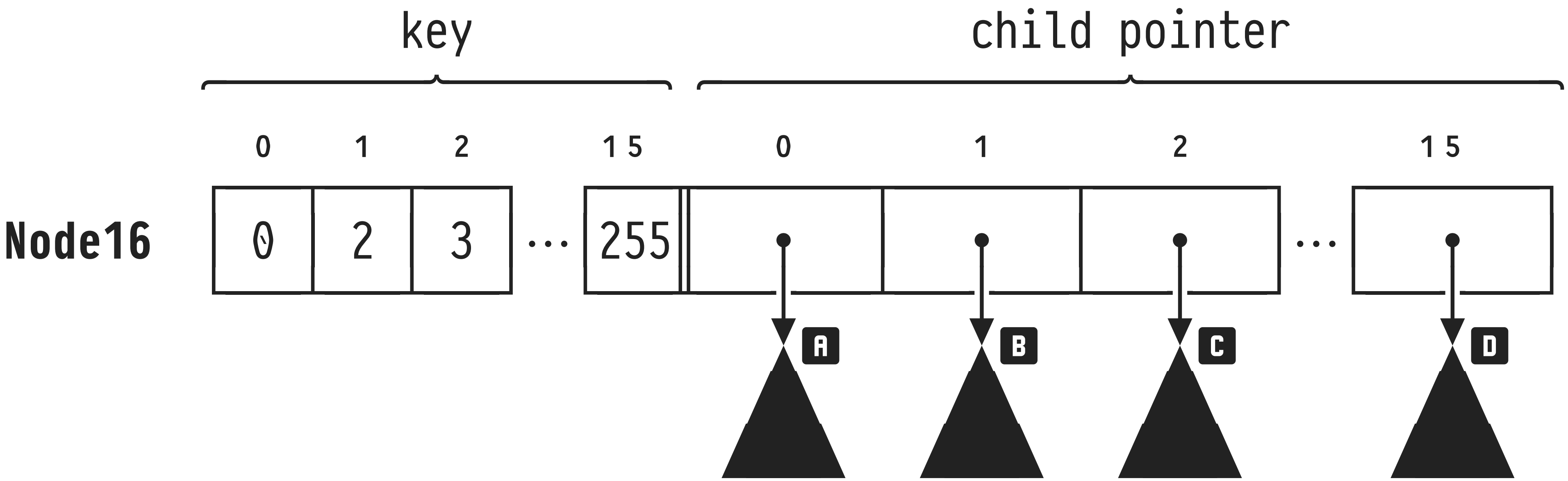
## ART Internals: Four Inner Node Types ❶

- DuckDB: $s$ = 8 (can cut values into bytes, admits large fanout).
- Choose inner node type based on the number of non-NULL child pointers: 4, 16, 48, or 256 (= $2^s$).
  - On value insertion/deletion, switch to larger/smaller node type when node overflows/underflows.




- **Node4:** Array of 4 keys is ordered (search left to right).
- Value/pointer pairs stored at corresponding indices 0…3.

## ART Internals: Four Inner Node Types ❷




- **Node16:** stores 5…16 child/pointer pairs.
- Locate current *key* byte by binary search or parallel SIMD comparisons.

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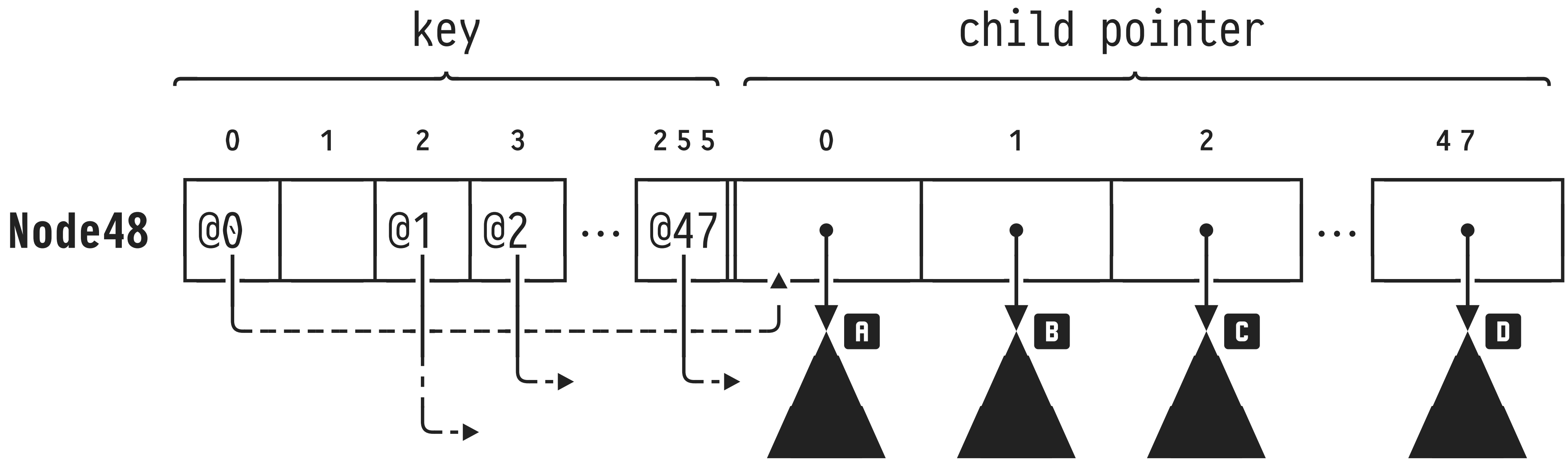
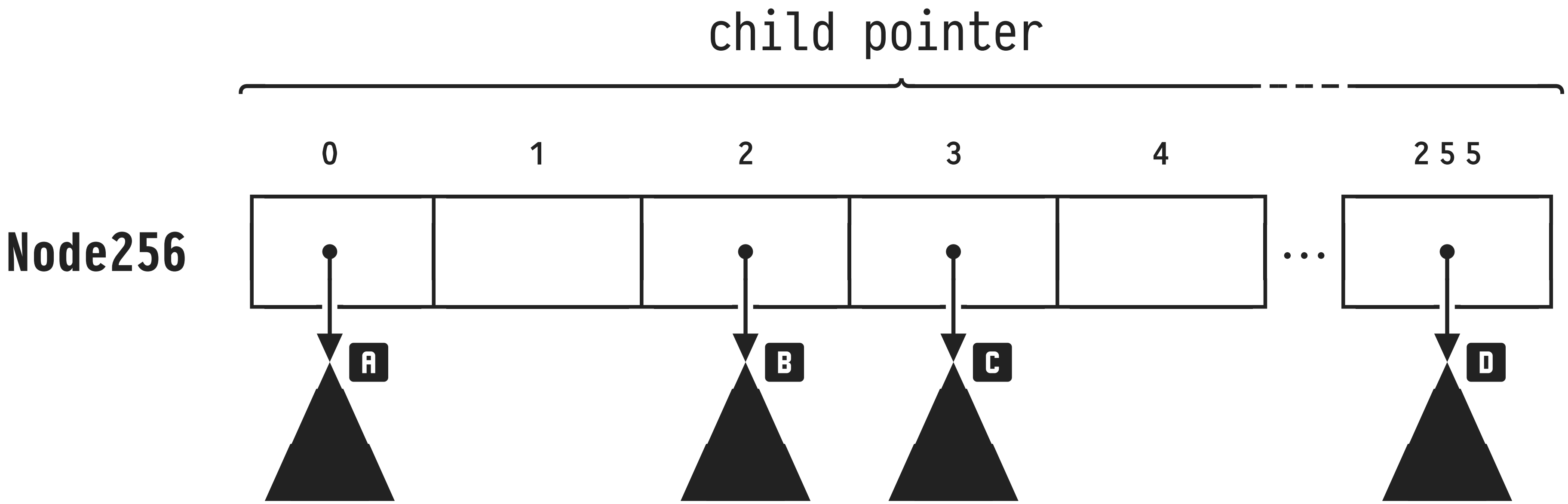
## ART Internals: Four Inner Node Types ❸




- **Node48:** With 17…48 values in a node, searching the value array becomes expensive. Thus: do *not* store values. Instead:
  - Use current byte of *key* as index into array of 256 indices.
  - key[‹*key* byte›] holds the index @*i* ∈ {0…47} of the corresponding child pointer. Access pointer[@*i*].
- Saves space compared to an array of 256 8-byte pointers: 640B = 256B + 48 × 8B < 256 × 8B = 2048B.

# ART Internals: Four Inner Node Types ❸

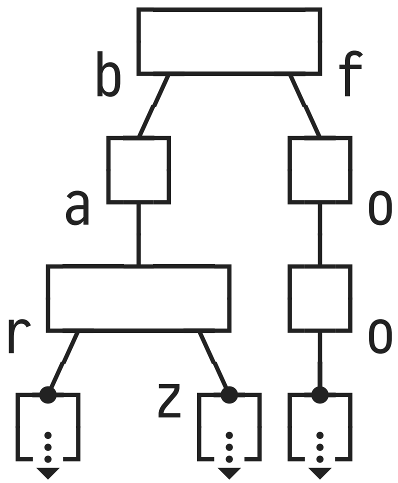



- **Node256:** If an inner node needs to hold 49…256 entries, invest 256 × 8B = 2kB to hold an array of 256 child pointers.
  - Simply return `pointer[<key byte>]`.

# ART Internals: Leaf Nodes

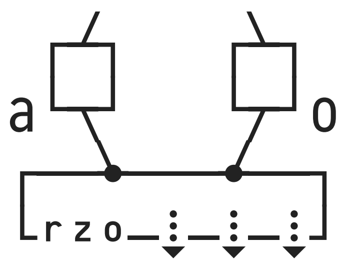
In an ART for *t(c)*, **leaf nodes** hold rowids that point to the rows in table *t* in which column *c* holds the search value *key*.

- Possible ART leaf designs:




(This is an ART for values **bar**, **baz**, **foo**.)

**Single-entry leaves**, each hold rowids (⋮) for one value *val*.



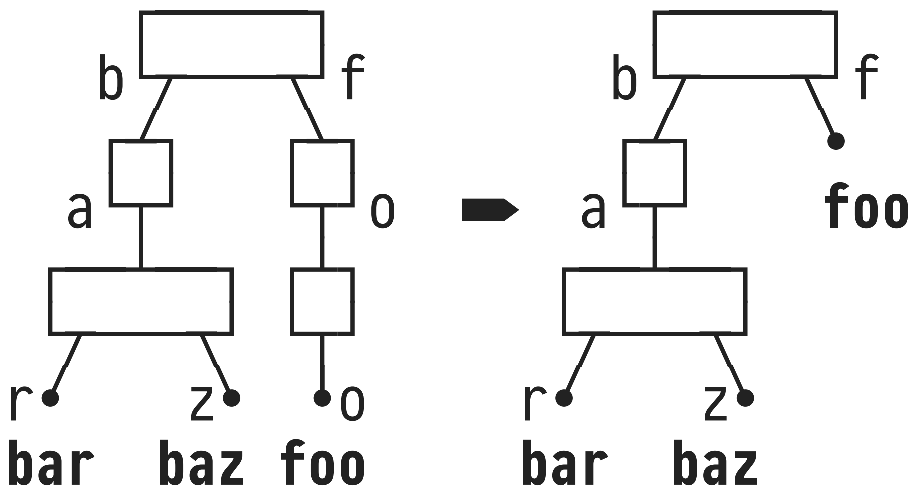

**Multi-entry leaf**, holds rowids for multiple values. DuckDB has Leaf7/Leaf15/Leaf256 much like Node4…256 (hold rowids, not pointers).

## ART Optimizations: Lazy Expansion + Path Compression

To efficiently use space and save tree traversal effort during lookups, try to remove inner ART nodes—and thus **reduce tree height**—if possible.

Most effective if values are long (bit length *k* is large).

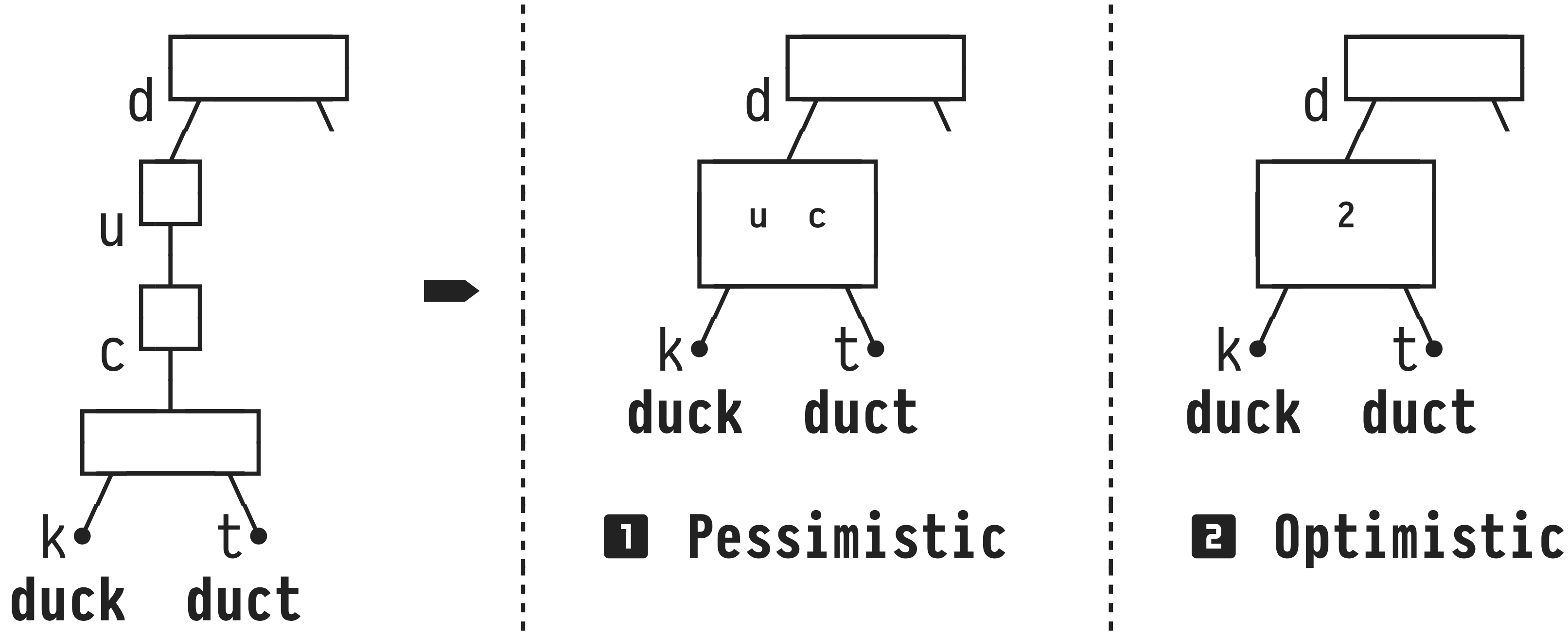
1. **Lazy expansion:** create inner nodes only if they are required to distinguish at least two leaf nodes.




- Saves two inner nodes on the path to leaf **foo**.
- Expand path if another leaf with prefix **f** is added.
- Path does not spell **foo**: store at leaf or in table.

## ART Optimizations: Lazy Expansion + Path Compression

2. **Path compression:** remove inner nodes that have a single child.




- 1 Inner node holds byte sequence (here: uc) of preceding single-child nodes. Compare this sequence against *key*.
- 2 Inner holds count (2) of removed single-child nodes. Skip that many bytes in *key*. At a leaf, compare its value to *key* to ensure that traversal indeed reached the proper leaf.

# ART: Index Lookup (Lazy Expansion + Pessimistic Path Compression)

```
search(node, key, depth):
if node = NULL                                search failed (findChild()
⌊ return NULL                                   returned NULL)
if isLeaf(node)                               reached leaf level?
│ if leafMatches(node, key)                   reached the proper leaf?
│ ⌊ return node                                 yes, success
⌊ return NULL                                   no, failure
s ← byteSequence(node)                        byte sequence in inner node
if s ≠ key[depth…depth+len(s)]                does partial key match
⌊ return NULL                                   byte sequence?
depth ← depth + len(s)                        skip to next key byte
child ← findChild(node, key[depth])           key byte selects child
return search(child, key, depth+1)            descend into subtree
```

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- Invoke with **search**(*node*: ‹*ART root*›, *key*: 'duck', *depth*: 0).
- Returns leaf node that holds rowid(s) or NULL.

DuckDB is an OLAP DBMS, optimized to scan entire tables. Basic index support is present—but there certainly is unused potential.

- The following predicates *could* be evaluated by Index Scan:[3]

| Predicate | Index Constellation | Index used by 🦆? |
| --- | --- | --- |
| $c_1$ ⧀ $val_1$ | $t(c_1)$ | 👍 (if selective) |
| | $t(c_1, c_2)$ (composite) | 👎 |
| $c_1$ ⧀ $val_1$ **AND** $c_2$ ⧀ $val_2$ | $t(c_1, c_2)$ (composite) | 👎 |
| | $t(c_1)$ and/or $t(c_2)$ | 👎 |
| $c_1$ ⧀ $val_1$ **OR** $c_2$ ⧀ $val_2$ | $t(c_1)$ and $t(c_2)$ | 👎 |
| $c_1$ **LIKE** '*p_tt?rn*' | $t(c_1)$ | 👎 |

Index support in DuckDB (as of version 1.4)

- (PostgreSQL🐘 is optimized to operate as an OLTP DBMS and can use indexes in all of these scenarios.)

[3] In this table, ⧀ represents a SQL comparison operator: <, <=, =, >=, >.

## Index Traversals

**Index traversals** (beyond equality-based index lookups for a key *val*) can support **range predicates:** #019

- $c_1$ >= $val_1$ or $c_1$ >= $val_1$ **AND** $c_1$ <= $val_2$: perform lookup for $val_1$, then scan leaves left to right (until > $val_2$). 1
- $c_1$ **LIKE** '*prefix%*': perform lookup for *prefix*, hit inner node. Scan leaves in subtree. 2