Indexes

André Restivo

Index

Physical Schema

Storage

Sequential Files

Indexes

Ordered Indexes

Primary Indexes

Secondary Indexes

B+ Tree Indexes

Hash Indexes

PostgreSQL

Full Text Search

Database Tuning

Examples

Choosing Indexes

Denormalization

Physical Schema

Physical Schema

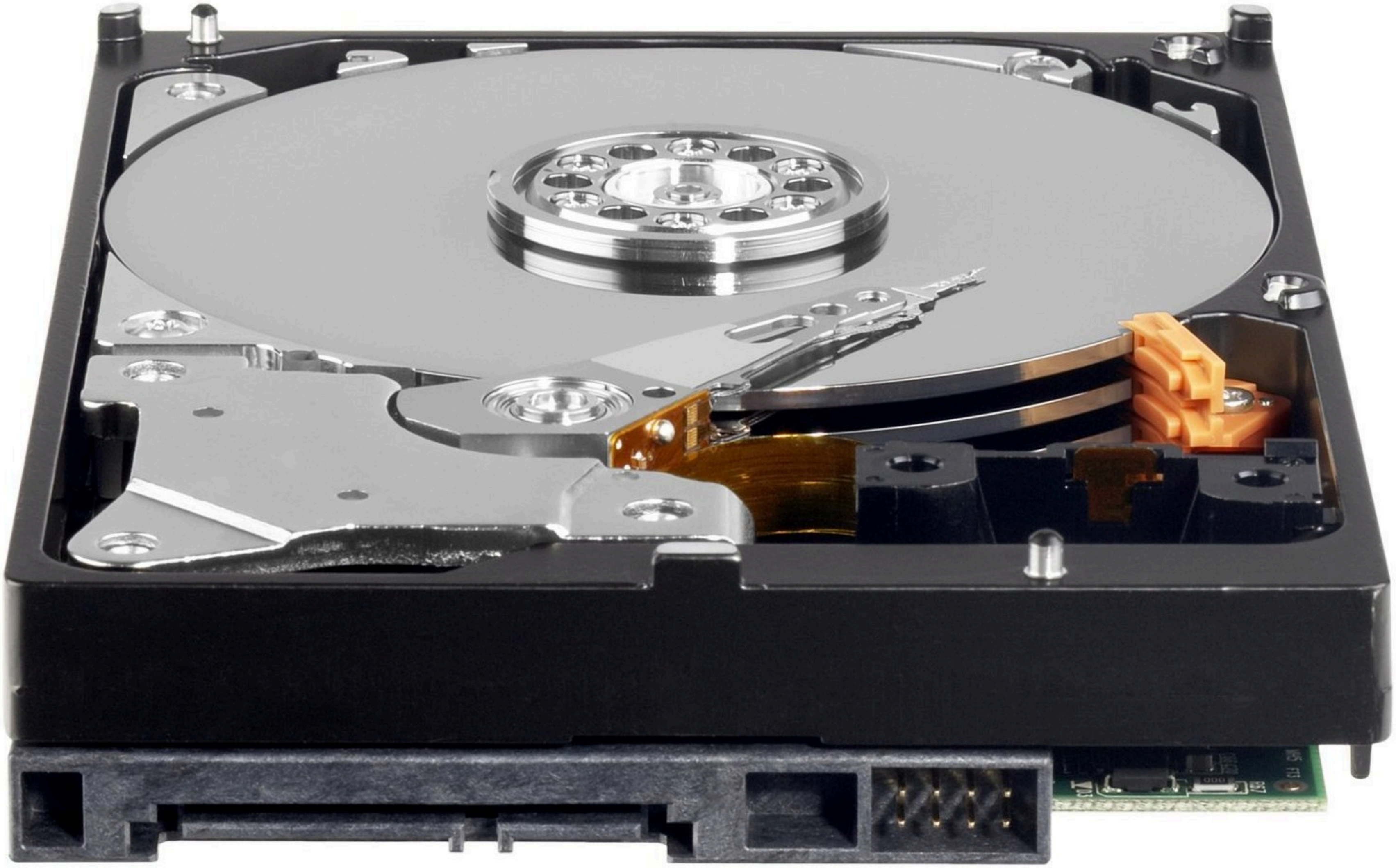
Logical Schema: A **design-centric** database structure built to meet your business requirements.

Physical Schema: How data is to be represented and stored.

- How are tables **stored**? Using files? With what structure?
- What **datatypes** are we going to use and how should they be stored?
- What **triggers** should be implemented?
- How can we make sure queries have a good performance? **denormalization**, **derived** attributes + **triggers**, **indexes**, ...

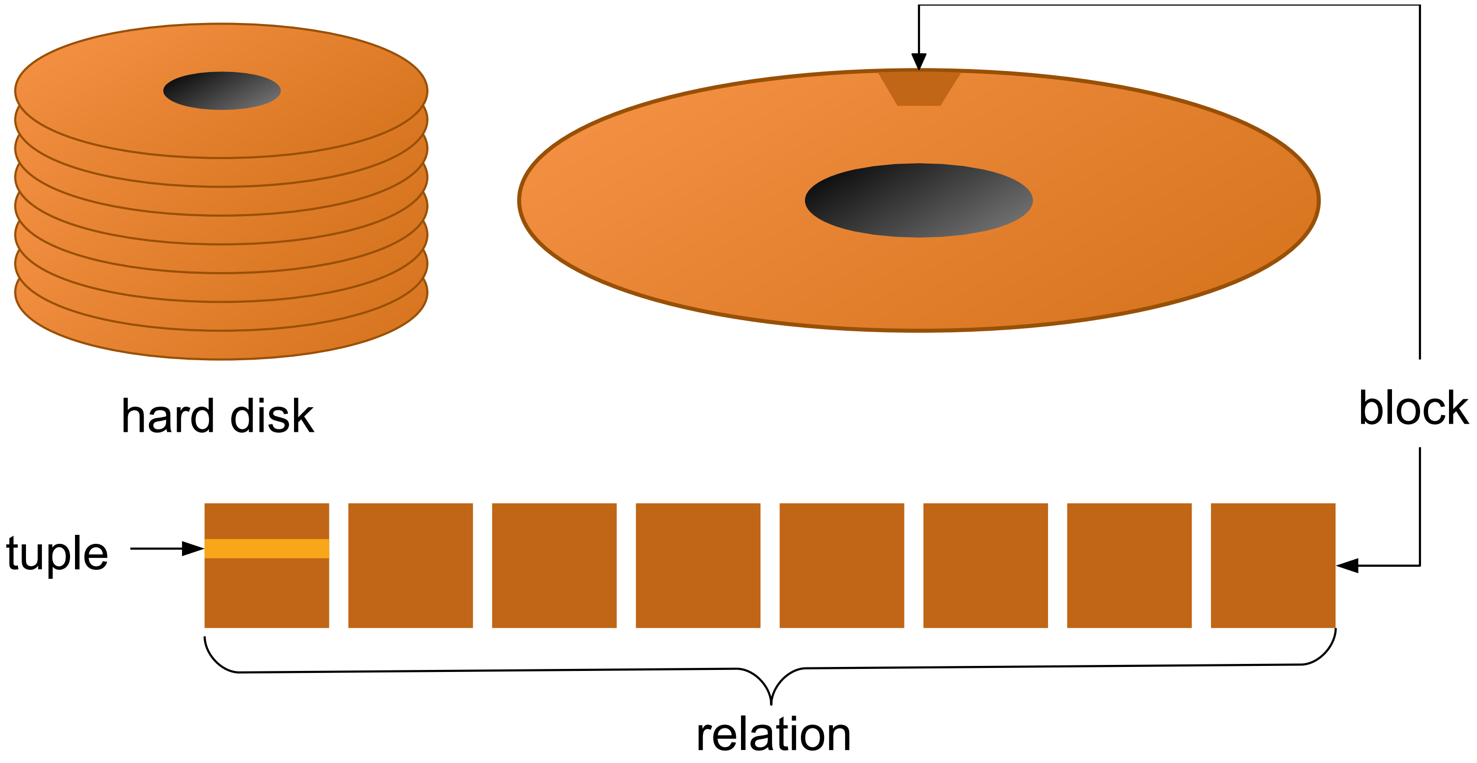
Storage

Hard Disk



Blocks

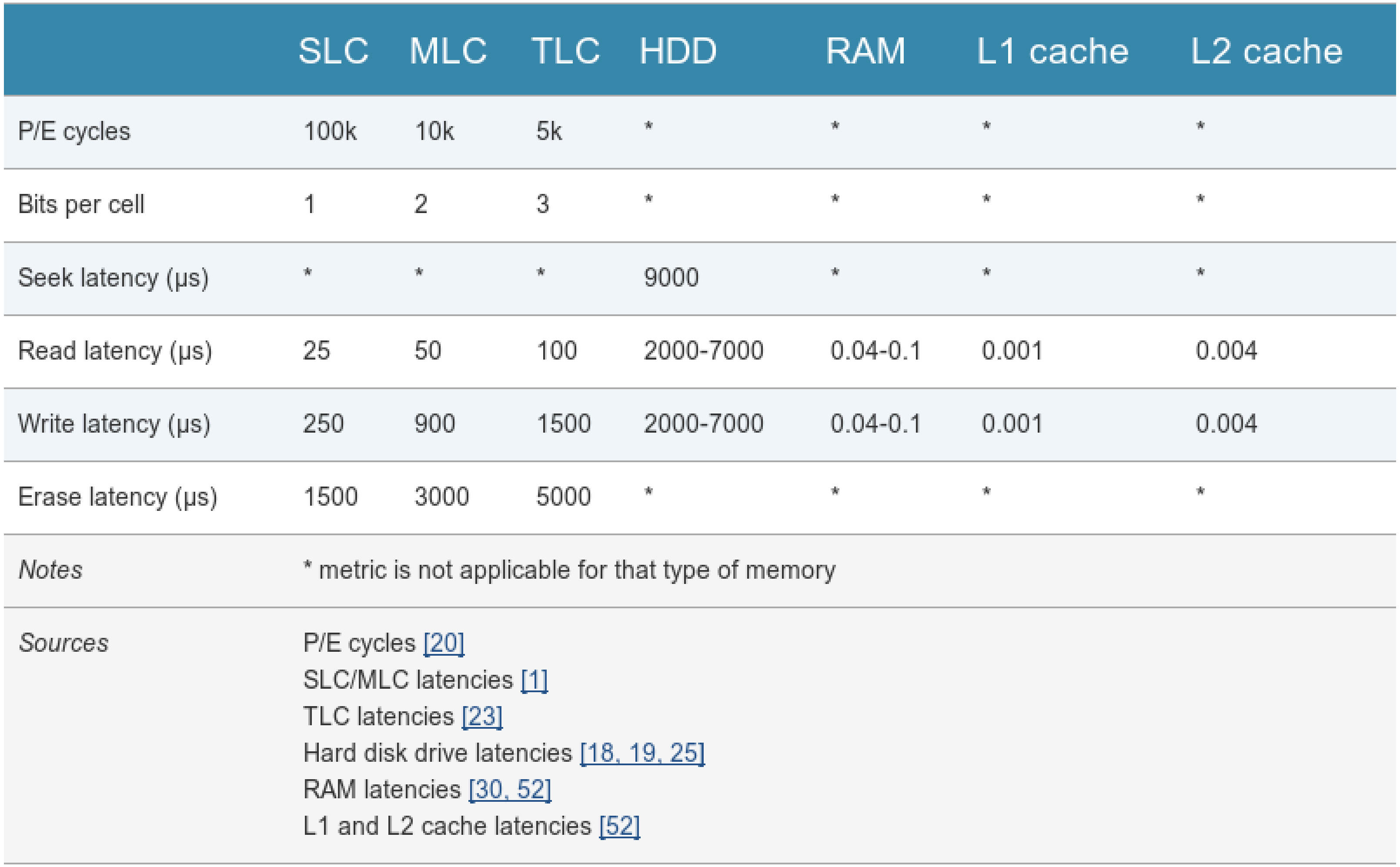
- Data is read or written from the hard disk a **whole block** at a time.
- Each block can contain **several tuples**.
- Table blocks are **not** necessarily **sequential**.



Performance

- Biggest database performance bottleneck is having too many **I/O operations**.
- Hard disk is accessed **block by block**.
- Block fetch requires about 5 to 10 **milliseconds** (10^{-3}), versus about 100 **nanoseconds** (10^{-9}) for memory access.
- It is important to **minimize** the number of blocks fetched.
- On many different operations:
    - search, insert, delete, update, sort, ranges, ...

SSD



	SLC	MLC	TLC	HDD	RAM	L1 cache	L2 cache
P/E cycles	100k	10k	5k	*	*	*	*
Bits per cell	1	2	3	*	*	*	*
Seek latency (μs)	*	*	*	9000	*	*	*
Read latency (μs)	25	50	100	2000-7000	0.04-0.1	0.001	0.004
Write latency (μs)	250	900	1500	2000-7000	0.04-0.1	0.001	0.004
Erase latency (μs)	1500	3000	5000	*	*	*	*
Notes	* metric is not applicable for that type of memory						
Sources	P/E cycles [20] SLC/MLC latencies [1] TLC latencies [23] Hard disk drive latencies [18, 19, 25] RAM latencies [30, 52] L1 and L2 cache latencies [52]						

Image from CodeCapsule

Indicators

Some important values that we will use throughout this presentation:

- Number of tuples: **t**
- Block size: **B** bytes
- Tuple size: **T** bytes

Typically B >= T

Some important indicators:

- Blocking Factor: **bfr** = B / T (how many tuples in each block)
- Block Number: **b** = t / bfr (how many blocks to store all tuples)

Running Example

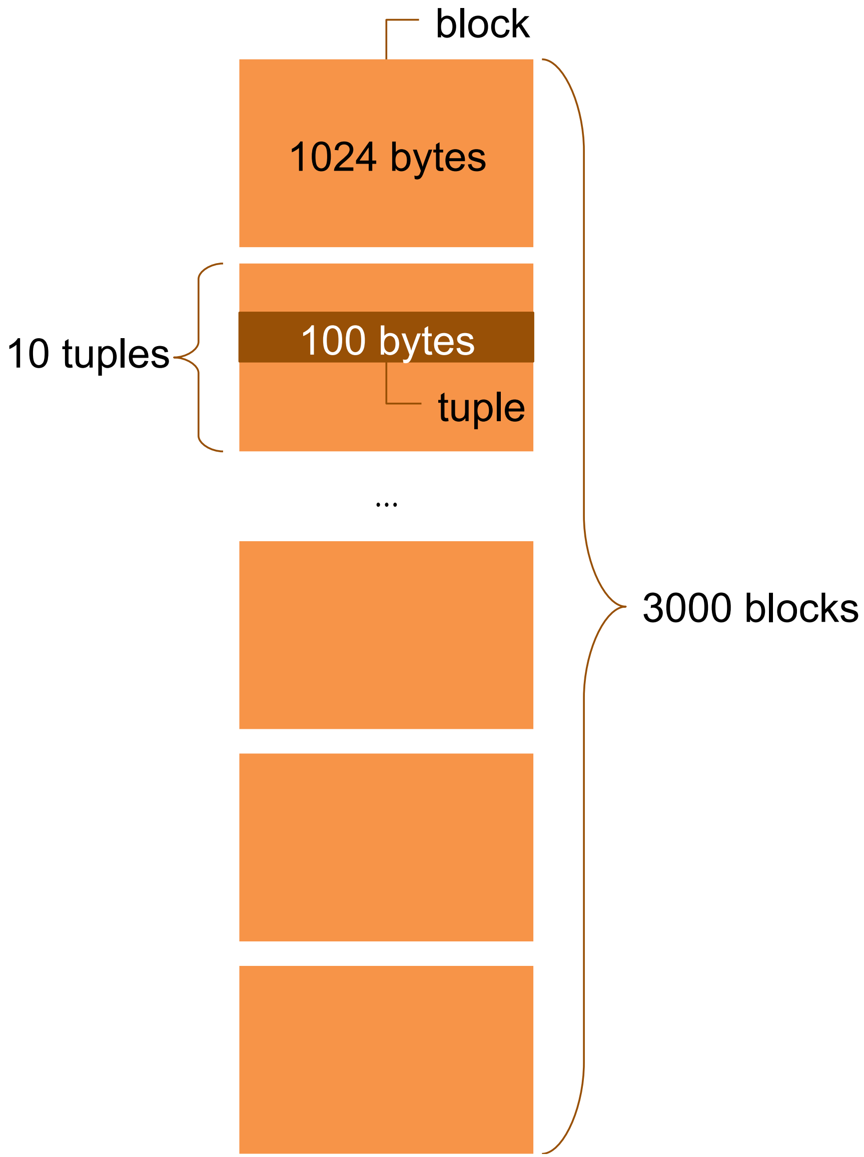
t = 30000 tuples

B = 1024 bytes

T = 100 bytes

bfr = 1024 / 100 = 10 tuples/block

b = 30000 / 10 = 3000 blocks



Sequential Files

Unordered Sequential File

- File has **no special order** between tuples.
- Inserting and updating is very **fast**.
- Searching and ordering very **slow**.

Key	
110	john
14	carl
76	lois
5	mary

54	jack
82	sarah
38	chris
33	ben

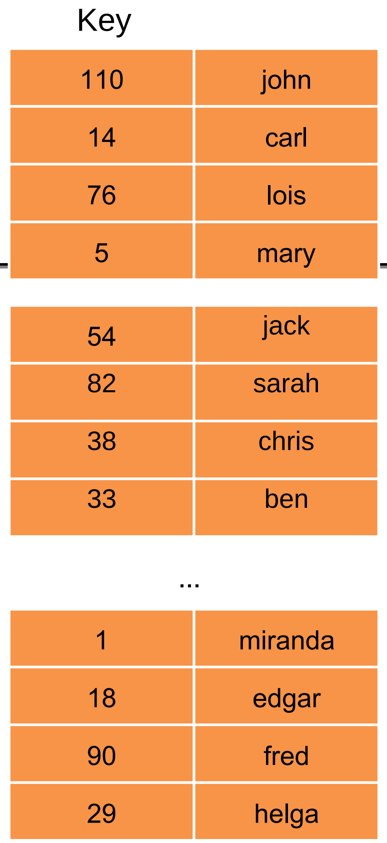
...

1	miranda
18	edgar
90	fred
29	helga

Unordered Sequential File

- File has **no special order** between tuples.
- Inserting and updating is very **fast**.
- Searching and ordering very **slow**.

- Searching:
  - Keys: b / 2 = 1500 blocks
  - Non-keys: b = 3000 blocks



Key	
110	john
14	carl
76	lois
5	mary
54	jack
82	sarah
38	chris
33	ben
...	
1	miranda
18	edgar
90	fred
29	helga

Ordered Sequential File

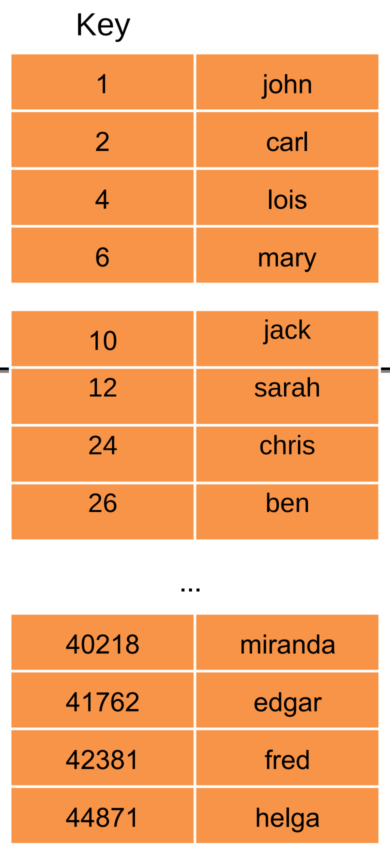
- File **ordered** by **primary key**.
- Inserting and updating can be **slow**. Unless sequentially or some space is wasted.
- Searching and ordering very **slow** except on primary key.

Key	
1	john
2	carl
4	lois
6	mary
10	jack
12	sarah
24	chris
26	ben
...	
40218	miranda
41762	edgar
42381	fred
44871	helga

Ordered Sequential File

- File **ordered** by **primary key**.
- Inserting and updating can be **slow**. Unless sequentially or some space is wasted.
- Searching and ordering very **slow** except on primary key.

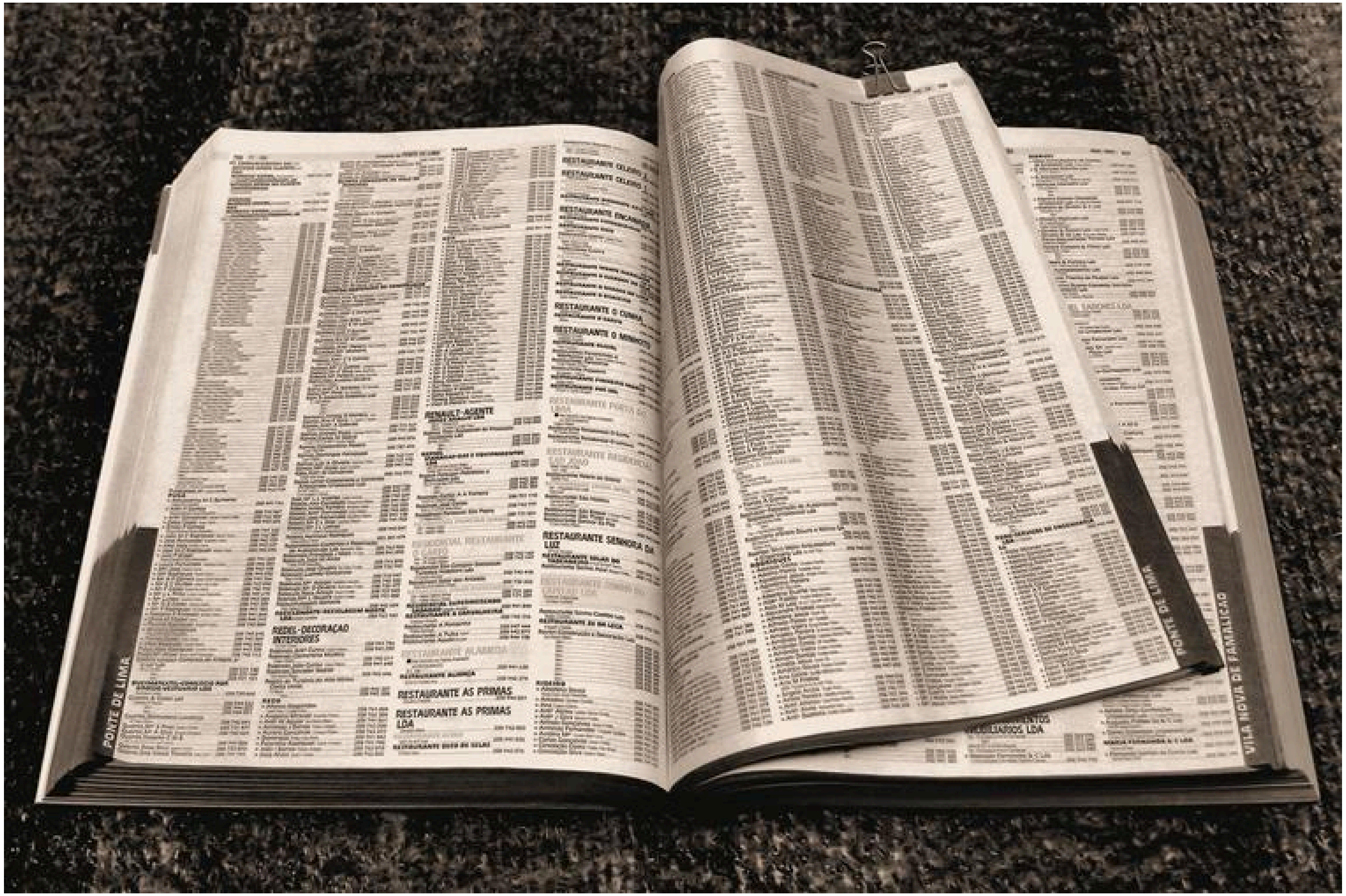
- Searching:
  - Primary Keys: $\log_2 b$ = **12** blocks
  - Other Keys: b / 2 = **1500** blocks
  - Non-keys: b = **3000** blocks



Key	
1	john
2	carl
4	lois
6	mary
10	jack
12	sarah
24	chris
26	ben
...	
40218	miranda
41762	edgar
42381	fred
44871	helga

Indexes

A Useful Metaphor



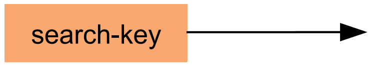
Indexes

- Mechanisms used to **speed up** data access.
- Index files are typically much **smaller** than the **original** file.
- Two basic kinds: **ordered** and **hashed**.
- Index evaluation: **genericity**, **performance** and **overhead**.

Ordered Indexes

Ordered Indexes

An ordered index typically consist of entries having a **search-key** and a **pointer**.



Entries (in the index) are sorted by their **search-key**.

- **Primary indexes:**

  An index having a *search-key* in the **same order** as the file.
  Only one per file.
  Also called **clustering index.**

- **Secondary indexes:**

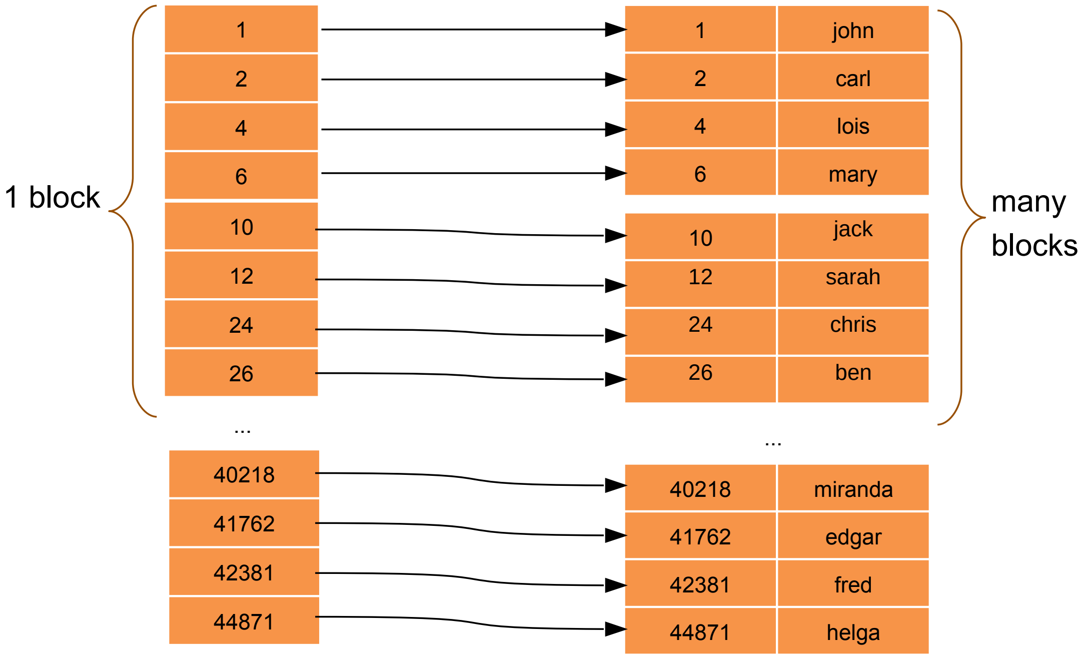
  An index having a **search-key** in a different order as the file.
  Many per file are possible.

Primary Indexes

Dense Primary Indexes

Dense indexes have **one index entry** for each **search-key value** in the indexed file.

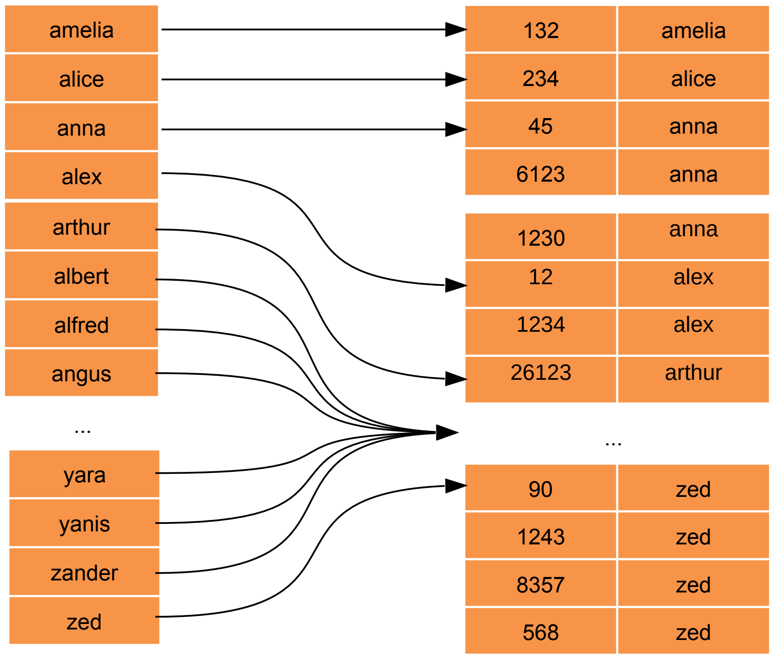
Dense index: file ordered by key



Index
1
2
4
6
10
12
24
26
...
40218
41762
42381
44871

1	john
2	carl
4	lois
6	mary
10	jack
12	sarah
24	chris
26	ben
...	
40218	miranda
41762	edgar
42381	fred
44871	helga

Dense index: file ordered by non-key



Index
amelia
alice
anna
alex
arthur
albert
alfred
angus
...
yara
yanis
zander
zed

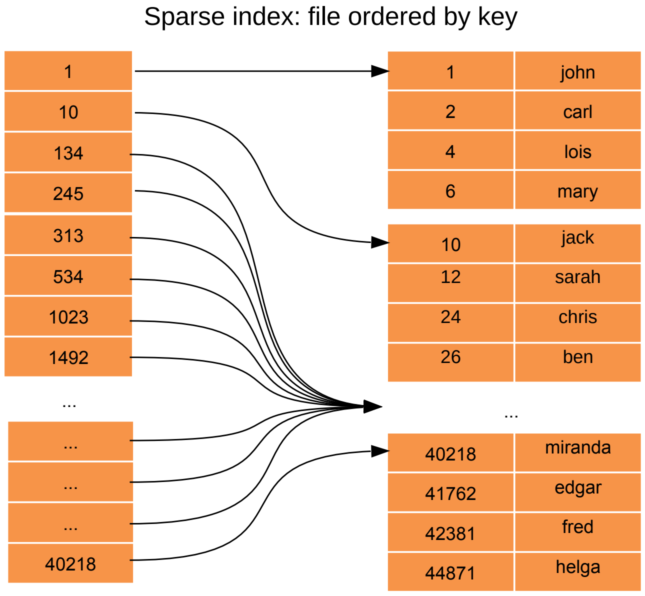
132	amelia
234	alice
45	anna
6123	anna
1230	anna
12	alex
1234	alex
26123	arthur
...	
90	zed
1243	zed
8357	zed
568	zed

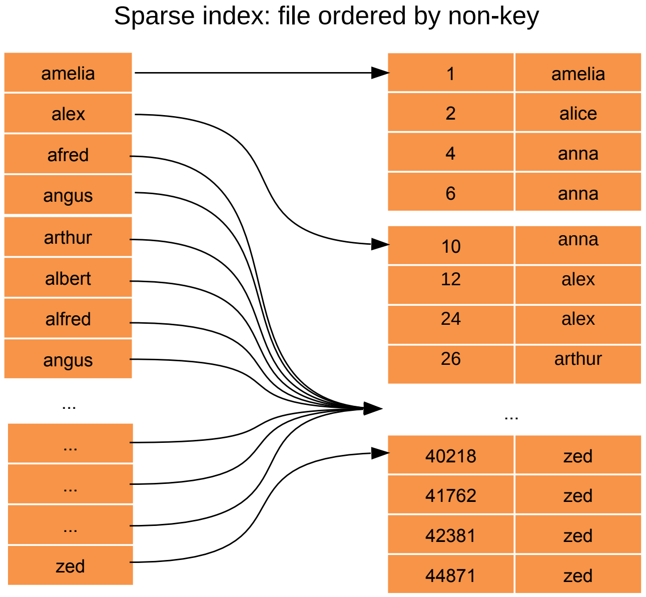
Sparse Primary Indexes

Sparse indexes contain entries for **only some** search-key values.

Normally **one entry per block.**

- Advantages: Less **space** and less **maintenance.**
- Disadvantages: Only applicable when entries are **ordered on search-key.**





Dense or Sparse

- **Search-key**: 9 bytes
- **Pointer**: 6 bytes (2.8 * 10^{14} tuples)

Dense Index

- **t_i**: 30000 (same as t)
- **T_i**: 15 bytes (9 + 6)
- **bfr_i**: 68 tuples/block (1024 / 15)
- **b_i**: 442 blocks (30000 / 68)

Sparse Index (one entry per block)

- **t_i**: 3000 (same as b)
- **T_i**: 15 bytes (9 + 6)
- **bfr_i**: 68 tuples/block (1024 / 15)
- **b_i**: 45 blocks (3000 / 68)

Dense or Sparse

- **Search-key**: 9 bytes
- **Pointer**: 6 bytes (2.8 * 10^{14} tuples)

Dense Index

- t_i: 30000 (same as t)
- T_i: 15 bytes (9 + 6)
- bfr_i: 68 tuples/block (1024 / 15)
- b_i: 442 blocks (30000 / 68)

Sparse Index (one entry per block)

- t_i: 3000 (same as b)
- T_i: 15 bytes (9 + 6)
- bfr_i: 68 tuples/block (1024 / 15)
- b_i: 45 blocks (3000 / 68)

Search on **dense**: $\log_2 442 + 1 = \mathbf{10}$ blocks

Search on **sparse**: $\log_2 45 + 1 = \mathbf{7}$ blocks

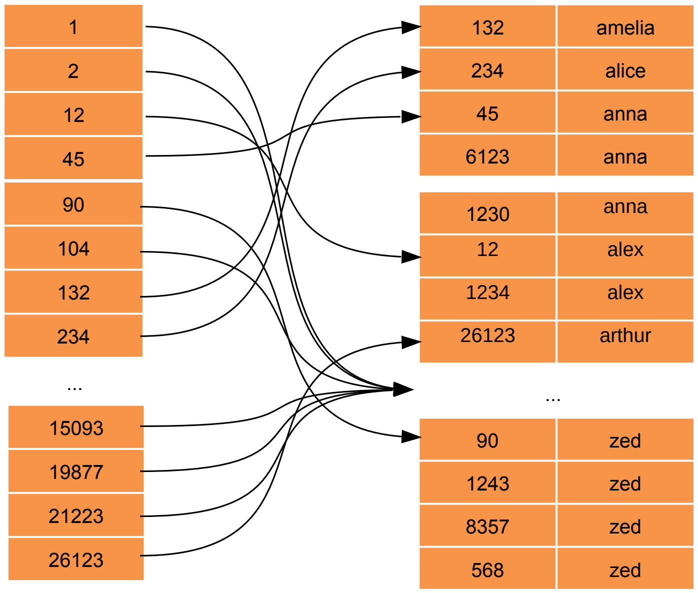
But search isn't everything...

Secondary Indexes

Secondary Indexes

- **Always** have to be **dense.**
- In non-key indexes, entries point to a **bucket of pointers** to the actual tuples.

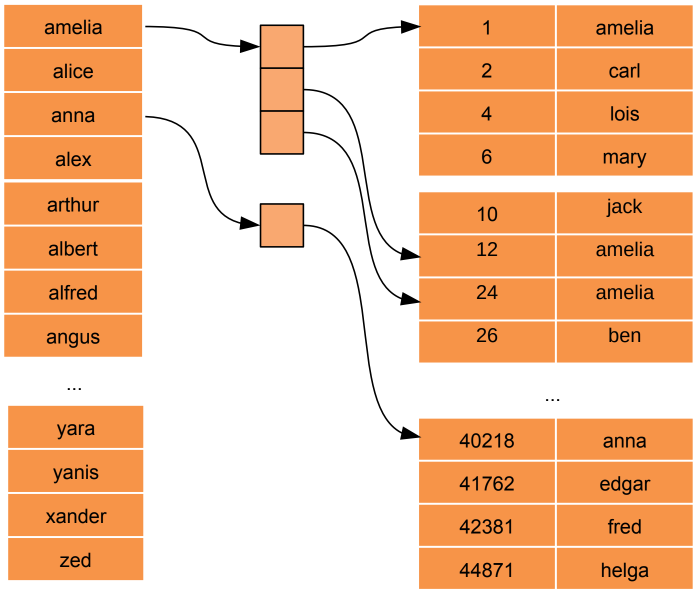
Secondary dense index to key field



1
2
12
45
90
104
132
234
...
15093
19877
21223
26123

132	amelia
234	alice
45	anna
6123	anna
1230	anna
12	alex
1234	alex
26123	arthur
...	
90	zed
1243	zed
8357	zed
568	zed

Secondary dense index to non-key field



amelia
alice
anna
alex
arthur
albert
alfred
angus
...
yara
yanis
xander
zed

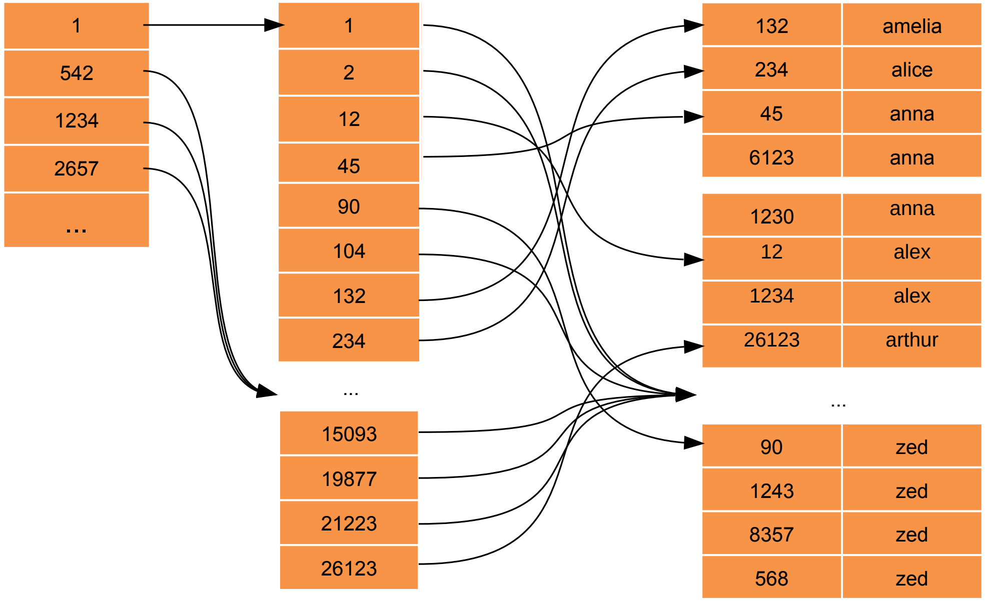
1	amelia
2	carl
4	lois
6	mary
10	jack
12	amelia
24	amelia
26	ben
...	
40218	anna
41762	edgar
42381	fred
44871	helga

Multi-Level Indexes

If an index does **not fit in memory**, access can become **expensive**.

Solution is to keep a first index (**inner** index) on disk and construct a sparse index on it (**outer** index).

If even outer index is too large to fit in main memory, yet **another level** of index can be created, and so on.



Multi-Level Indexes

- b_{i2}: 30000/68 = 442 blocks
- b_{i1}: 442/68 = 7 blocks
- b_{i0}: 7/68 = 1 blocks

Multi-Level Indexes

- b_{i2}: 30000/68 = 442 blocks
- b_{i1}: 442/68 = 7 blocks
- b_{i0}: 7/68 = 1 blocks

Search: 4 blocks (3 if outer index kept in memory)

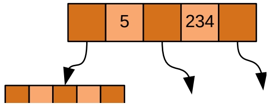
One for each index + 1 for the block containing the tuple.

B+ Tree Indexes

B+ Tree Indexes

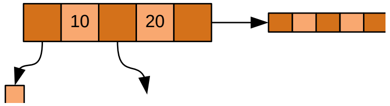
Uses a tree-like data structure where each tree node has:

- **q** pointers to another node
- **q − 1** values



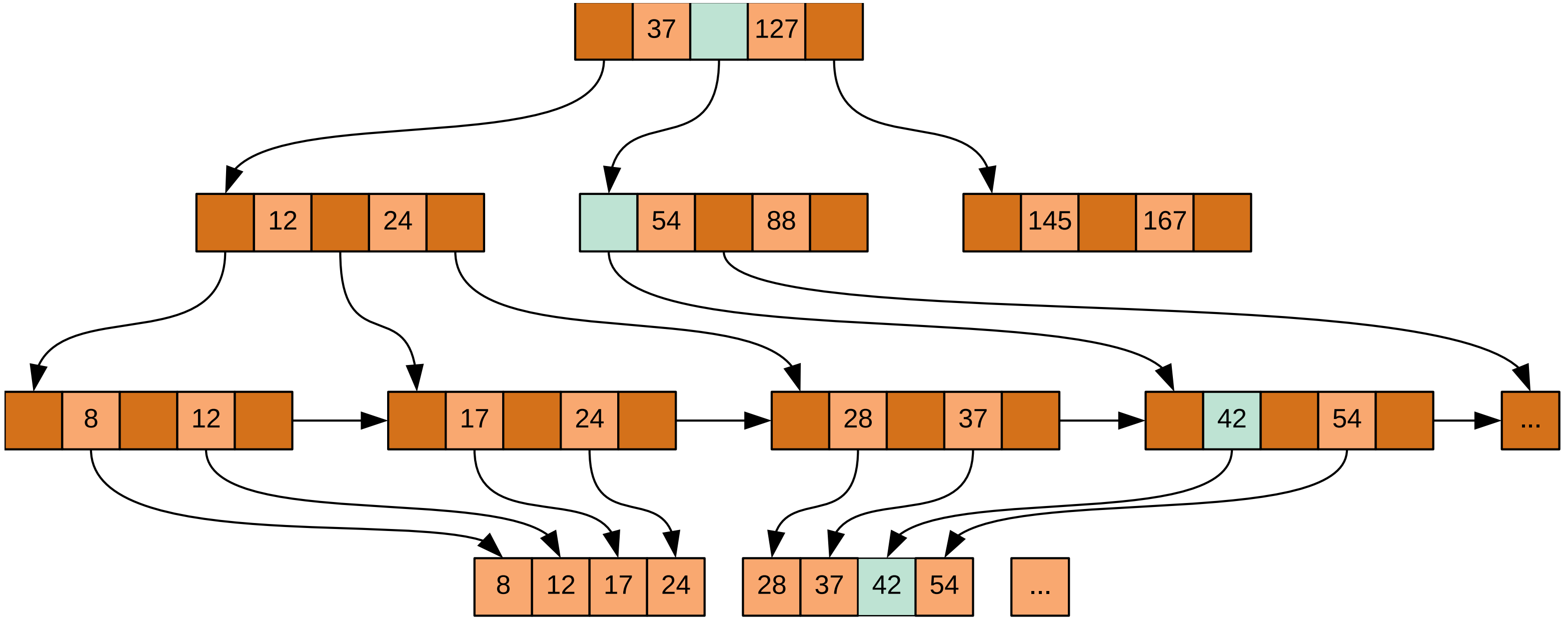
The last level nodes (leafs) have:

- **q − 1** pointers to tuples/blocks
- **q − 1** values
- **1** pointer to the next leaf node



Allows searching, sorting, range search.

B+ Tree Indexes



B+ Tree Indexes

- Use **partially full blocks** to speed insertions and deletions.
- When a level is too full, create a new level.
- In a B+ Tree that is 70% full in each level:
    - 34 value-pointer pairs per node.
    - 34 * 0.7 = 22 values and 23 pointers.
    - Root: 1 node = 22 values and 23 pointers.
    - Level 1: 23 nodes = 506 values and 529 pointers.
    - Level 2: 529 nodes = 11638 values and 12167 pointers.
    - Leafs: 12167 nodes = 255507 pointers to blocks.
    - Each block has 10 tuples: 2.5 million tuples indexed

B+ Tree Indexes

- Use **partially full blocks** to speed insertions and deletions.
- When a level is too full, create a new level.
- In a B+ Tree that is 70% full in each level:
    - 34 value-pointer pairs per node.
    - 34 * 0.7 = 22 values and 23 pointers.
    - Root: 1 node = 22 values and 23 pointers.
    - Level 1: 23 nodes = 506 values and 529 pointers.
    - Level 2: 529 nodes = 11638 values and 12167 pointers.
    - Leafs: 12167 nodes = 255507 pointers to blocks.
    - Each block has 10 tuples: 2.5 million tuples indexed

B+ Tree vs Ordered Indexes

Ordered Indexes:

- **performance degrades** as file changes.
- periodic **reorganization** of entire file is required.

B+ Trees:

- automatically reorganizes itself with **small local changes**.
- **reorganization** of entire file is **not required**.
- extra insertion and **deletion overhead**, **space overhead**.

Summary:

- Advantages of B+ Trees **outweigh** disadvantages.
- B+ Trees are used extensively.

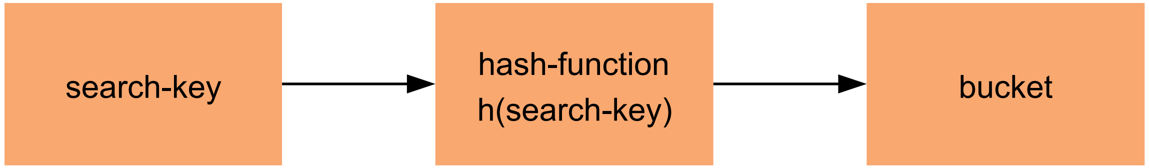
Hash Indexes

Hash Indexes

- A **bucket** is a unit of storage containing one or more tuples (typically a block).
- We obtain the bucket of a tuple directly from its search-key value using a **hash** function.
- Hash function is a function from the set of all **search-key** values to the set of all **bucket** addresses.
- Tuples with different search-key values may be mapped to the same bucket; thus entire bucket has to be searched **sequentially** to locate a tuple.
- Buckets can **overflow**: link buckets together.

Hash Function

- A hash-function receives a search key and returns the bucket for that search-key.
- An ideal hash function is **uniform**: each bucket is assigned the same number of search-key values (from all possible values).
- An ideal hash function is **random**: each bucket will have the same number of tuples (whatever tuples exist).



Example: Simple Hash Function

Consider we have 10 buckets.

An hash function that receives a string, calculates the binary representation of each character (a = 1, b = 2, ...) and returns the sum of those representations *modulo* 10.

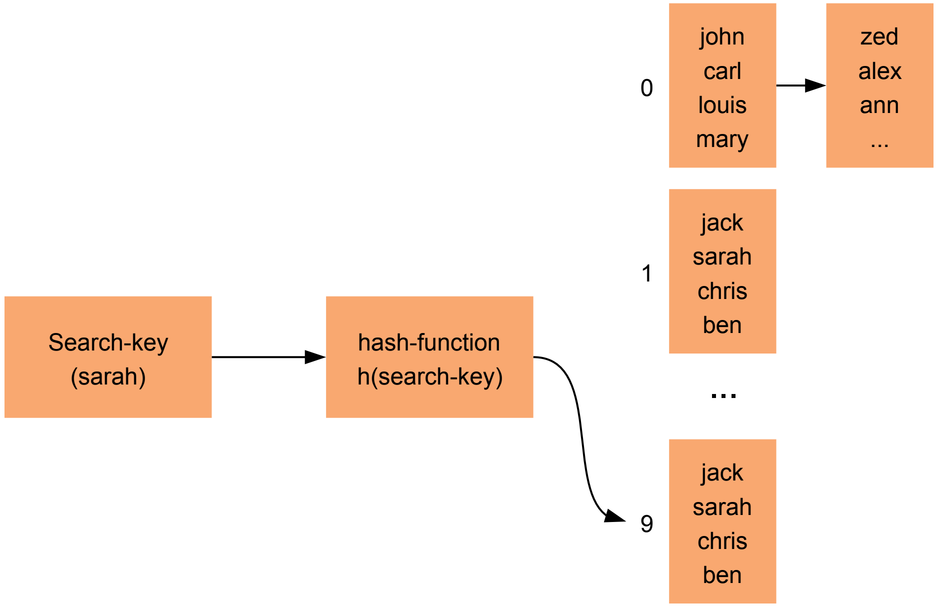
```
int h(string word) {
  int sum = 0;
  for (int i = 0; i < word.length(); i++)
    sum += word[i] - 'a';
  return sum % 10;
}
```

h(john) = 3; h(carl) = 0; h(gustafsson) = 1; ...

Real hash functions are, obviously, **more complex** than this.

Hash Indexes

- The overflow buckets of a given bucket are chained together in a **linked list**.
- Hash indexes are always **secondary** indexes.
- Hash Indexes **do not allow sorting or range** searches.



Indexes in PostgreSQL

Creating Indexes

PostgreSQL supports both B+ Tree and Hash indexes:

```sql
CREATE INDEX name ON table (column); -- btree by default
CREATE INDEX name ON table USING btree (column);
CREATE INDEX name ON table USING hash (column);
```

PostgreSQL does not support primary indexes. All indexes are secondary and thus, dense.

Multicolumn Indexes

An index can be defined on more than one column of a table.

```
CREATE INDEX name ON table (column_a, column_b);
```

Works well on queries searching for values in columns *a* and *b* simultaneously or just on column *a*; but not just on column *b*.

For example, a phone book is indexed on (*last name*, *other names*) making it easy to look for *John Doe* but not for *John*.

Unique Indexes

Indexes can also be used to enforce uniqueness of a column's value, or the uniqueness of the combined values of more than one column.

```
CREATE UNIQUE INDEX name ON table (column);
```

Unique indexes are **automatically** created on unique and primary key constraints.

In fact, primary and unique keys are **enforced** by these automatic unique indexes.

Indexes on Expressions

An index column need not be just a column of the underlying table, but can be a **function** computed from one or more columns of the table.

```
CREATE INDEX idx_name ON employees (lower(name));
```

This index would be automatically used in this query:

```
SELECT * FROM employees WHERE lower(name) = 'john';
```

This can also be used to enforce constraints that are not definable as simple unique constraints:

```
CREATE UNIQUE INDEX idx_mail ON employees (lower(email));
```

Partial Indexes

A partial index is an index built over a **subset** of a table.

One reason for using a partial index is to avoid indexing common values.

```
CREATE INDEX idx_type ON employees (type) WHERE type <> 'normal';
```

Would be automatically used in this query:

```
SELECT * FROM employees WHERE type <> 'normal';
```

Another possible use for partial indexes is to enforce constraints in a subset of the table:

```
CREATE UNIQUE INDEX idx_mail ON employees (mail) WHERE type <> 'admin';
```

Clustering

PostgreSQL does not support primary indexes but the *CLUSTER* command can be used to reorder a table based on one — **and only one** — index.

```
CLUSTER table_name USING index_name;
```

Clustering is a **one-time** operation: when the table is subsequently updated, the changes are not clustered.

If needed, clustering can be set to run periodically using cron. PostgreSQL remembers which indexes were clustered, so a single CLUSTER command with **no parameters** is enough.

Generalized Indexes in PostgreSQL

Besides Hash and B-tree, PostgreSQL also provides several other index types:

- GiST - Generalized Inverted Seach Tree:
    - **Lossy**. May produce false positives.
    - Works by hashing components of the data into a single bit.
    - Best for **dynamic** data. Faster to update.
- GIN - Generalized Inverted Index:
    - Faster than GiST and handles large ammounts of different data better.
    - Best for **static** data. Slower to update.

Both these indexes are able to implement **arbitrary** indexing schemes.

They can be used for Full Text Search (FTS), geometric and spatial data, ...

Full Text Search

Why not just ILIKE?

When we execute a query like this one:

```
SELECT * FROM employee WHERE name ILIKE 'john%';
```

A B+ Tree index can be used to speed up the query. But for this one:

```
SELECT * FROM employee WHERE name ILIKE '%john%';
```

- There is no way in which a normal index can help us.
- Think of it as trying to find all people having *john* in their name in a phone book.
- We need to index each word individually.

Lexemes and the *tsvector* type

- FTS is based on lexemes.
- A *tsvector* value is a sorted list of distinct lexemes.

```
SELECT to_tsvector('english', 'The quick brown fox jumps over the lazy dog')
```

```
'brown':3 'dog':9 'fox':4 'jump':5 'lazi':8 'quick':2
```

- The *to_tsvector* function **normalizes** words into lexemes, removes **duplicates**, removes **stop words** and records the **position** of each lexeme.

Searching using *tsqueries*

- A *tsquery* value stores the *lexemes* that we want to search.
- Lexemes can be combined using the boolean operators & (AND), | (OR), and ! (NOT):

```
SELECT to_tsquery('english', 'jumping & dog');
```

```
'jump' & 'dog'
```

- The function *plainto_tsquery* simplifies this operation:

```
SELECT plainto_tsquery('english', 'the jumping dog'); -- same result
```

Matching *tsqueries* to *tsvectors*

The @@ operator is used to assert if a *tsvector* matches a *tsquery*:

```
SELECT title
FROM posts
WHERE to_tsvector('english', title || ' ' || body) @@ plainto_tsquery('english', 'jumping dog');
```

Note: The || operator concatenates strings but it also concatenates *ts_vectors*.

```
SELECT title
FROM posts
WHERE (to_tsvector('english', title) || to_tsvector('english', body)) @@ plainto_tsquery('english', 'jumping dog');
```

FTS weights

Sometimes we want to give more **importance** to some specific fields.

We can use the *setweight* to attach a **weight** to a certain *ts_vector*.

Weights go from 'A' (more important) to 'D' (less important).

```
SELECT
   setweight(to_tsvector('english', 'The quick brown fox jumps over the lazy dog'), 'A') ||
   setweight(to_tsvector('english', 'An English language pangram. A sentence that contains
                                  all of the letters of the alphabet.'), 'B')
```

```
'alphabet':24B 'brown':3A 'contain':17B 'dog':9A 'english':11B
'fox':4A 'jump':5A 'languag':12B  'lazi':8A 'letter':21B 'pangram':13B
'quick':2A 'sentenc':15B
```

As you can see, we can concatente *tsvectors* directly.

Ranking FTS results

The *ts_rank* and *ts_rank_cd* functions, return a **score** for each returned row for a certain match between a *tsquery* and *tsvector*.

```
SELECT
  ts_rank(
    setweight(to_tsvector('english', 'The quick brown fox jumps over the lazy dog'), 'A') ||
    setweight(to_tsvector('english', 'An English language pangram. A sentence that contains
                                     all of the letters of the alphabet.'), 'B'),
    plainto_tsquery('english', 'jumping dog')
  )could
```

```
0.9524299
```

You can also change the weights of the *ts_vector* classes (A to D) and set how normalization, due to different document lengths, should be performed.

```
ts_rank([ weights float4[], ] vector tsvector, query tsquery [, normalization integer ])
```

Pre-calculate FTS

For **performance** reasons, we should consider adding a column to tables where FTS is to be performed containg the *ts_vector* values of **each row**.

This column should be updated whenever a row changes or is inserted. This can be done easily using a **trigger**:

```
CREATE FUNCTION post_search_update() RETURNS TRIGGER AS $$
BEGIN
  IF TG_OP = 'INSERT' THEN
    NEW.search = to_tsvector('english', NEW.title);
  END IF;
  IF TG_OP = 'UPDATE' THEN
      IF NEW.title <> OLD.title THEN
        NEW.search = to_tsvector('english', NEW.title);
      END IF;
  END IF;
  RETURN NEW;
END
$$ LANGUAGE 'plpgsql';
```

Putting it all together

To select all posts containing *jumping* and *dog* we can use the following query:

```
SELECT title
FROM posts
WHERE search @@ plainto_tsquery('english', 'jumping dog')
ORDER BY ts_rank(search, plainto_tsquery('english', 'jumping dog')) DESC
```

Considering that *search* is a pre-calculated column containing the *ts_vector* of the columns we want to search.

Indexing FTS

To improve the performance of our full text searches, we can use GIN or GiST indexes:

```
CREATE INDEX search_idx ON posts USING GIN (search);
```

```
CREATE INDEX search_idx ON posts USING GIST (search);
```

Note: We could also used a index on a *ts_vector* expression directly.

Which type to use?

- GIN index lookups are about three times **faster** than GiST.
- GIN indexes take about three times **longer** to build than GiST.

So use GIN if updates to searchable terms are rare and you want to make searches fast.

Database Tuning

Query Log Analysis

Sometimes we realize that our database isn't performing as well as we expected.

Are our indexes the correct ones? To help us answer this question, a query log analyzer tool is invaluable.

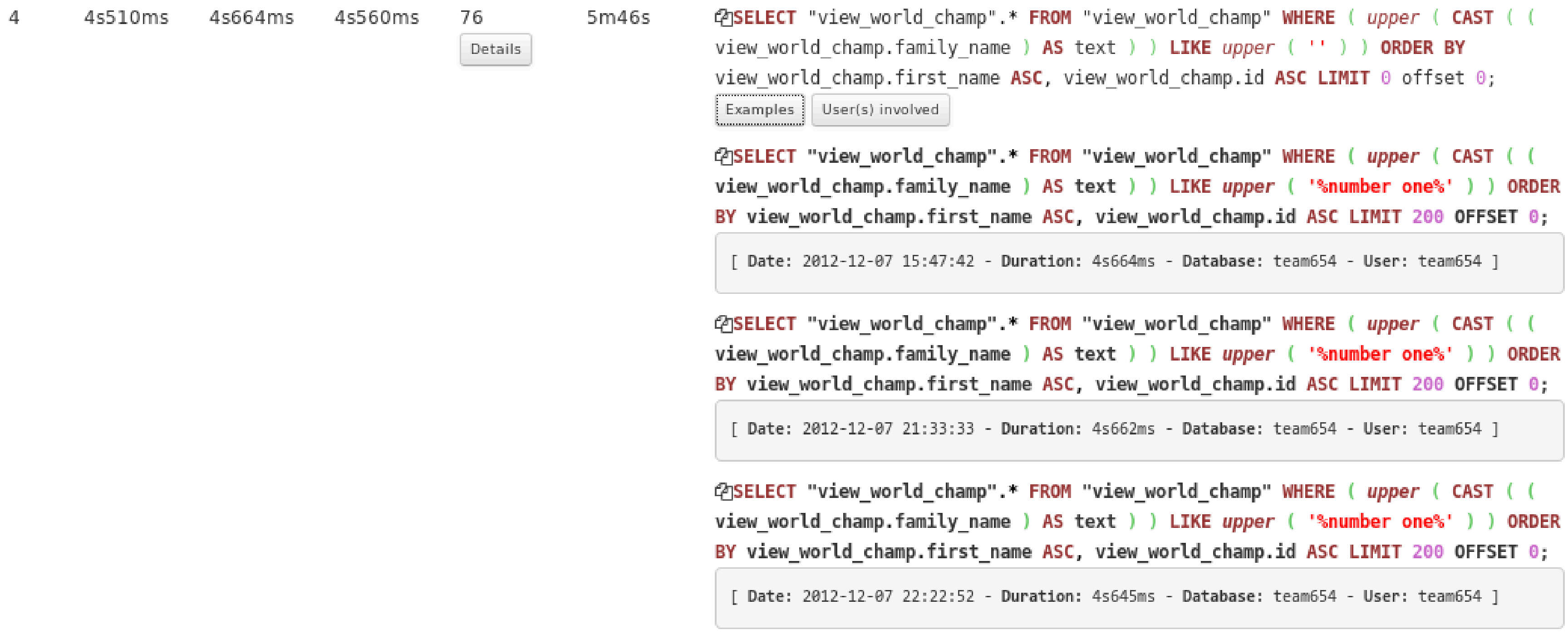
One such tool is pgBadger (a sucessor to the older, and discontinued, pgFouine).

Fouine vs Badger

pgBadger

To use *pgBadger*, we must first turn on **query logging** (this will make PostgreSQL slower, so be careful) and run *pgBadger* against the generated log.

The ammount of statistical data generated by *pgBadger* is staggering, but in this case we will focus on *pgBadger*'s abbility to identify **time consuming queries**. Here's a sample report:



```
4    4s510ms    4s664ms    4s560ms    76    5m46s

SELECT "view_world_champ".* FROM "view_world_champ" WHERE ( upper ( CAST ( ( view_world_champ.family_name ) AS text ) ) LIKE upper ( '' ) ) ORDER BY view_world_champ.first_name ASC, view_world_champ.id ASC LIMIT 0 offset 0;

SELECT "view_world_champ".* FROM "view_world_champ" WHERE ( upper ( CAST ( ( view_world_champ.family_name ) AS text ) ) LIKE upper ( '%number one%' ) ) ORDER BY view_world_champ.first_name ASC, view_world_champ.id ASC LIMIT 200 OFFSET 0;
[ Date: 2012-12-07 15:47:42 - Duration: 4s664ms - Database: team654 - User: team654 ]

SELECT "view_world_champ".* FROM "view_world_champ" WHERE ( upper ( CAST ( ( view_world_champ.family_name ) AS text ) ) LIKE upper ( '%number one%' ) ) ORDER BY view_world_champ.first_name ASC, view_world_champ.id ASC LIMIT 200 OFFSET 0;
[ Date: 2012-12-07 21:33:33 - Duration: 4s662ms - Database: team654 - User: team654 ]

SELECT "view_world_champ".* FROM "view_world_champ" WHERE ( upper ( CAST ( ( view_world_champ.family_name ) AS text ) ) LIKE upper ( '%number one%' ) ) ORDER BY view_world_champ.first_name ASC, view_world_champ.id ASC LIMIT 200 OFFSET 0;
[ Date: 2012-12-07 22:22:52 - Duration: 4s645ms - Database: team654 - User: team654 ]
```

PostgreSQL Planner

When executing a query, PostgreSQL:

- Starts by analyzing all possible ways to scan **each table** using all available indexes (or no index at all).
- If the query requires **joining** two or more relations, plans for joining relations are considered:
  - The right relation is scanned once for every row found in the left relation (*nested loop* — might use existing indexes).
  - Each relation is sorted on the join attributes before the join starts (*merge join* — might use existing indexes).
  - The right relation is first scanned and loaded into a hash table (*hash join*).
- When the query involves more than two relations, the planner examines different possible join sequences.

Analyzing Plans

After identifying a **problematic query**, we might want to understand how *PostgreSQL* is executing it.

For that we can use the EXPLAIN command that displays the **execution plan** that the PostgreSQL planner generates for the supplied statement:

```
EXPLAIN <query>
```

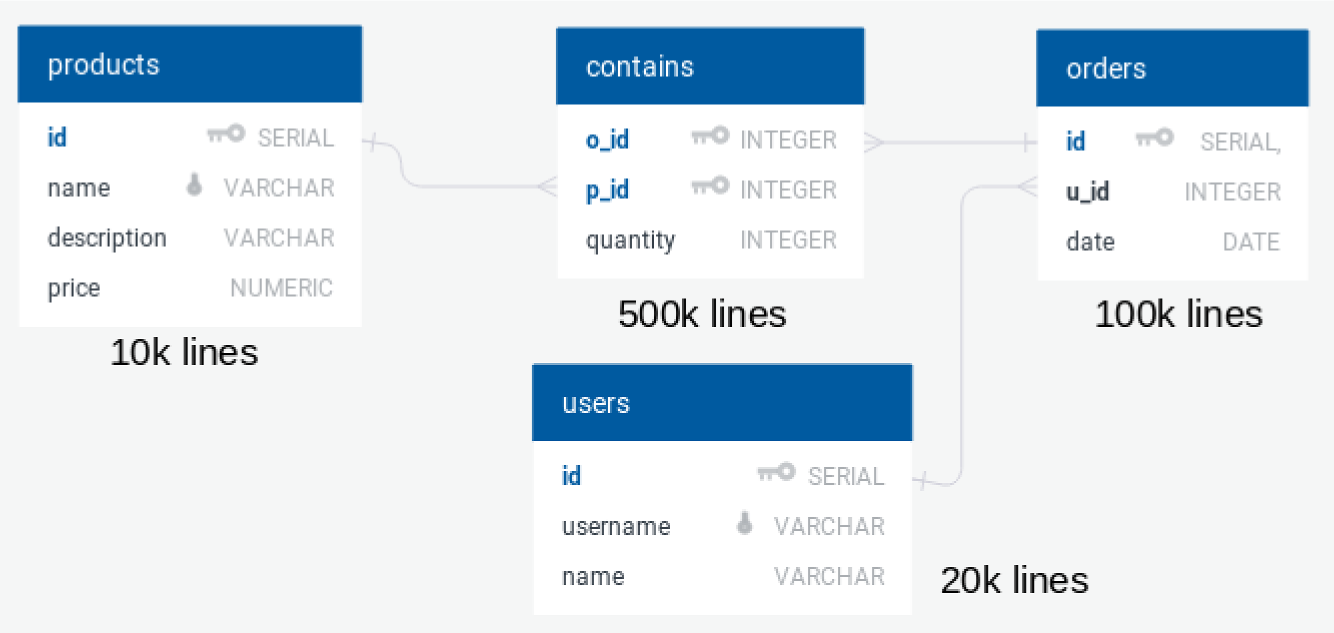
Or EXPLAIN ANALYZE that causes the statement to be actually executed, not only planned.

```
EXPLAIN ANALYZE <query>
```

Examples

Example 1

Consider the following database:



products	
id	SERIAL
name	VARCHAR
description	VARCHAR
price	NUMERIC

10k lines

contains	
o_id	INTEGER
p_id	INTEGER
quantity	INTEGER

500k lines

orders	
id	SERIAL,
u_id	INTEGER
date	DATE

100k lines

users	
id	SERIAL
username	VARCHAR
name	VARCHAR

20k lines

Example 1

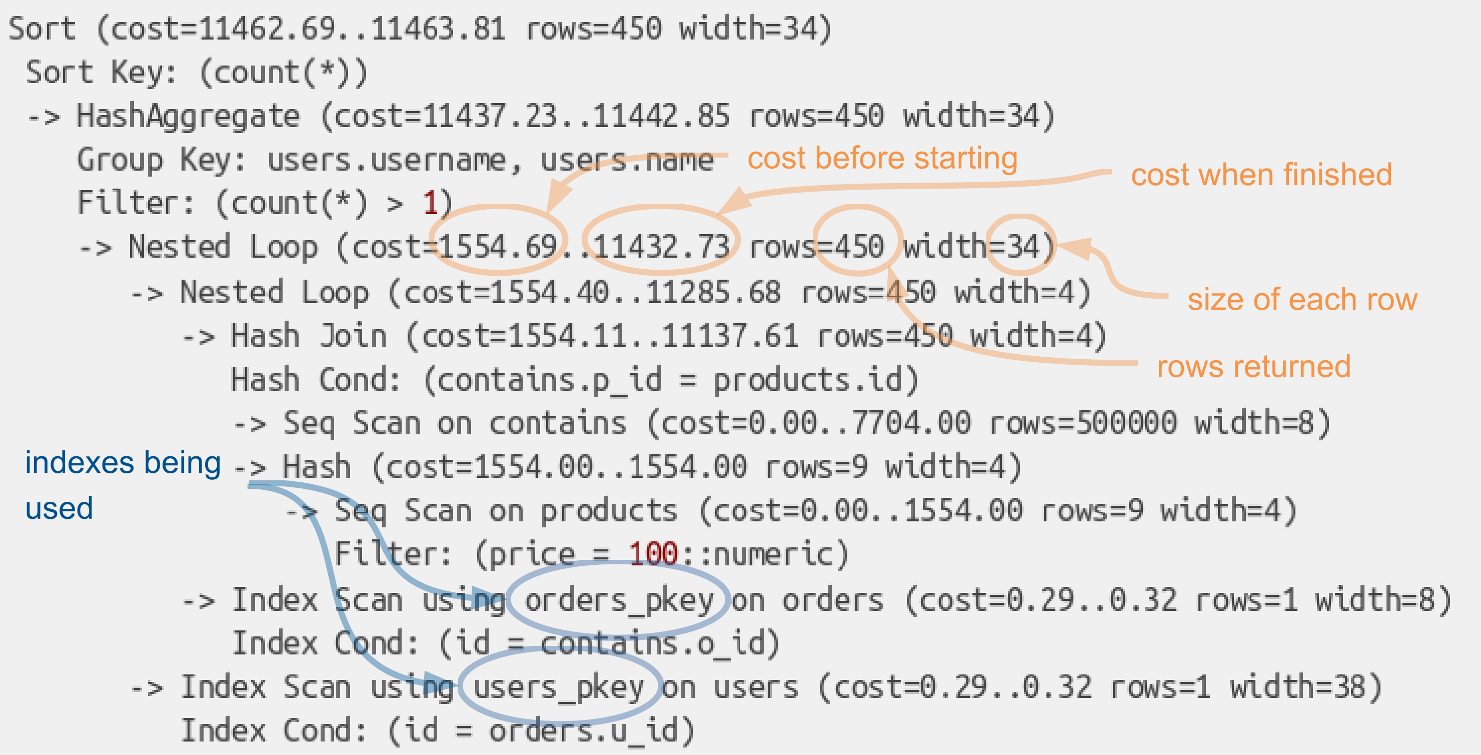
And the following query that selects *all users that ordered more than one product costing 100*:

```
EXPLAIN SELECT users.name, COUNT(*)
FROM orders JOIN
     contains ON orders.id = contains.o_id  JOIN
     products ON products.id = contains.p_id JOIN
     users ON orders.u_id = users.id
WHERE products.price = 100
GROUP BY username, users.name
HAVING COUNT(*) > 1
ORDER BY COUNT(*) DESC
```

Notice that we added the EXPLAIN clause in the beginning.

Example 1

The result is a tree structure showing the plan as idealized by PostgreSQL:



```
Sort (cost=11462.69..11463.81 rows=450 width=34)
 Sort Key: (count(*))
 -> HashAggregate (cost=11437.23..11442.85 rows=450 width=34)
    Group Key: users.username, users.name
    Filter: (count(*) > 1)
    -> Nested Loop (cost=1554.69..11432.73 rows=450 width=34)
       -> Nested Loop (cost=1554.40..11285.68 rows=450 width=4)
          -> Hash Join (cost=1554.11..11137.61 rows=450 width=4)
             Hash Cond: (contains.p_id = products.id)
             -> Seq Scan on contains (cost=0.00..7704.00 rows=500000 width=8)
             -> Hash (cost=1554.00..1554.00 rows=9 width=4)
                -> Seq Scan on products (cost=0.00..1554.00 rows=9 width=4)
                   Filter: (price = 100::numeric)
          -> Index Scan using orders_pkey on orders (cost=0.29..0.32 rows=1 width=8)
             Index Cond: (id = contains.o_id)
       -> Index Scan using users_pkey on users (cost=0.29..0.32 rows=1 width=38)
          Index Cond: (id = orders.u_id)
```

Cost is measured, generically, in blocks read from the disk.

Example 1

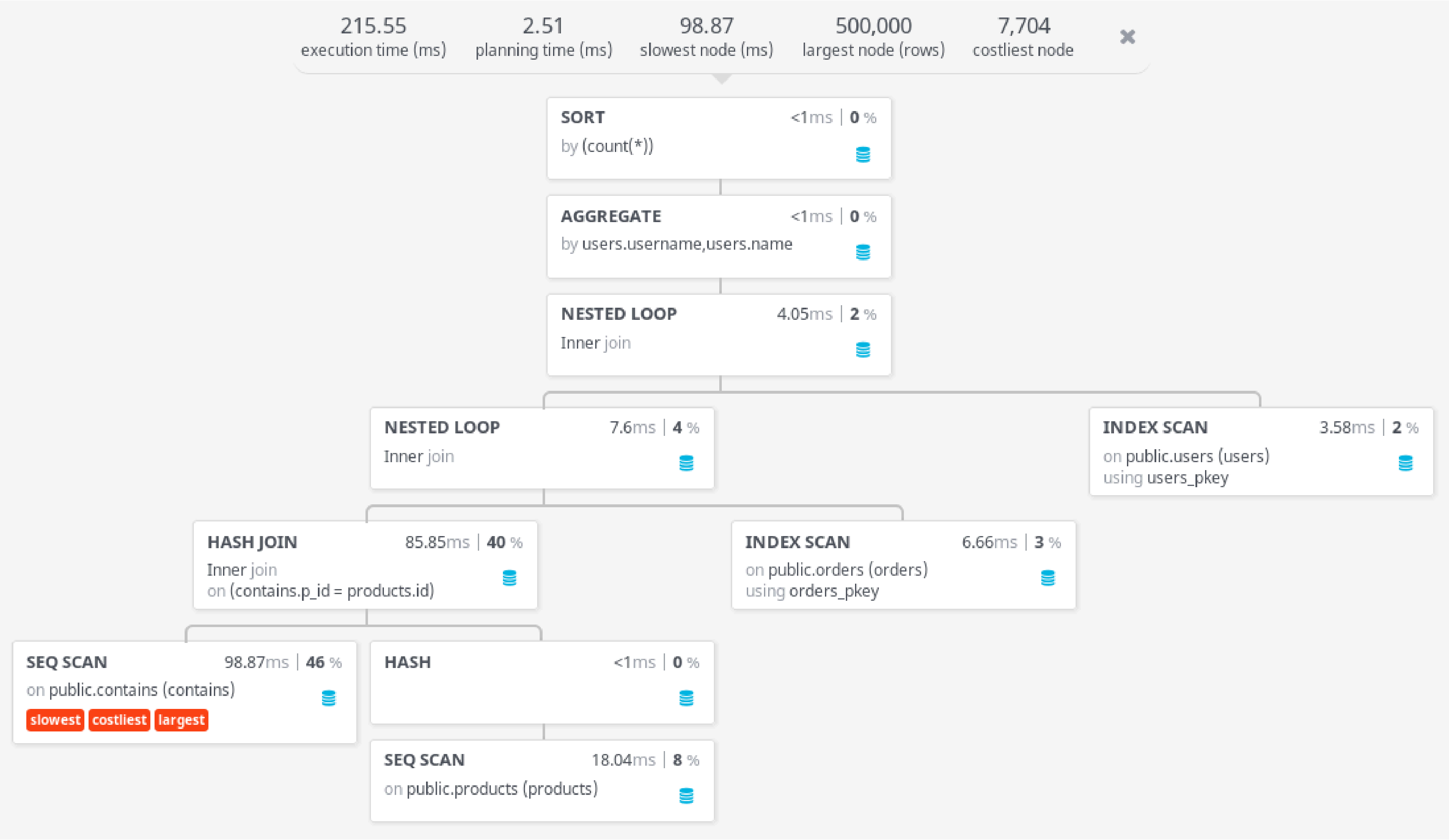
Luckily, there are some tools that can help us understand these plans easier:

- Like the Postgres EXPLAIN Visualizer by Alex Tatiyants.
- Or pgAdmin

So let's try it again with *PEV*.

Example 1

Much better. But it seems PostgreSQL is **losing** a lot of time **joining** the *contains* and *products* table.



215.55 execution time (ms)

2.51 planning time (ms)

98.87 slowest node (ms)

500,000 largest node (rows)

7,704 costliest node

SORT <1ms | **0** %
by (count(*))

AGGREGATE <1ms | **0** %
by users.username,users.name

NESTED LOOP 4.05ms | **2** %
Inner join

NESTED LOOP 7.6ms | **4** %
Inner join

INDEX SCAN 3.58ms | **2** %
on public.users (users)
using users_pkey

HASH JOIN 85.85ms | **40** %
Inner join
on (contains.p_id = products.id)

INDEX SCAN 6.66ms | **3** %
on public.orders (orders)
using orders_pkey

SEQ SCAN 98.87ms | **46** %
on public.contains (contains)
slowest costliest largest

HASH <1ms | **0** %

SEQ SCAN 18.04ms | **8** %
on public.products (products)

Example 1

Why is this happening?

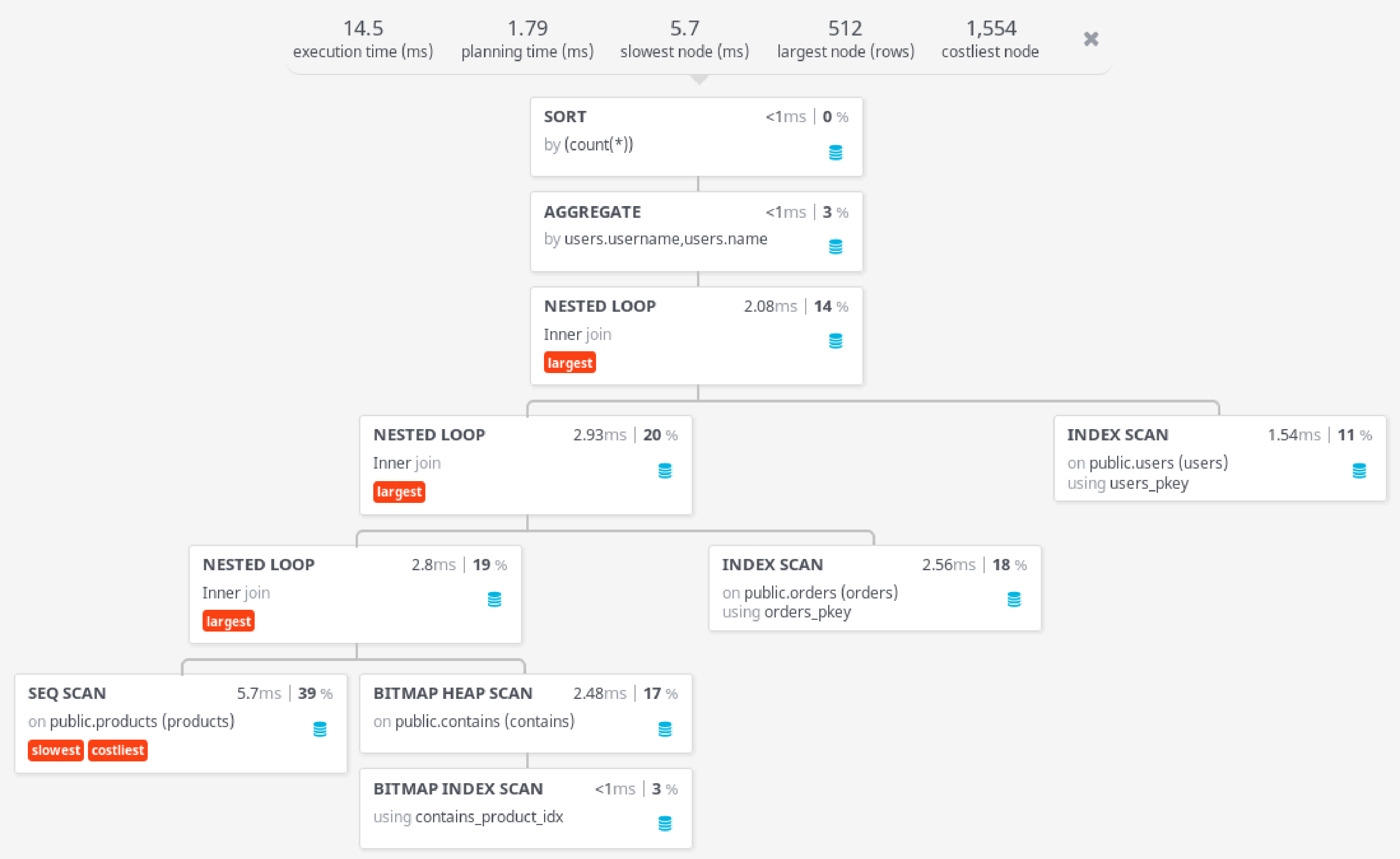
- After getting all products with the desired price, PostgreSQL has to find **all orders containing those products**.
- That table (*contains*) has **500k lines** and PostgreSQL is taking almost *100ms* doing it.

An **index** on the *contains.p_id* column could help us minimize this cost.

```
CREATE INDEX contains_product_idx ON contains USING btree (p_id);
```

Example 1

From 200ms to 14ms by just creating the right index.



14.5 execution time (ms) | 1.79 planning time (ms) | 5.7 slowest node (ms) | 512 largest node (rows) | 1,554 costliest node

SORT <1ms | 0 %
by (count(*))

AGGREGATE <1ms | 3 %
by users.username,users.name

NESTED LOOP 2.08ms | 14 %
Inner join
largest

NESTED LOOP 2.93ms | 20 %
Inner join
largest

INDEX SCAN 1.54ms | 11 %
on public.users (users)
using users_pkey

NESTED LOOP 2.8ms | 19 %
Inner join
largest

INDEX SCAN 2.56ms | 18 %
on public.orders (orders)
using orders_pkey

SEQ SCAN 5.7ms | 39 %
on public.products (products)
slowest costliest

BITMAP HEAP SCAN 2.48ms | 17 %
on public.contains (contains)

BITMAP INDEX SCAN <1ms | 3 %
using contains_product_idx

Example 1

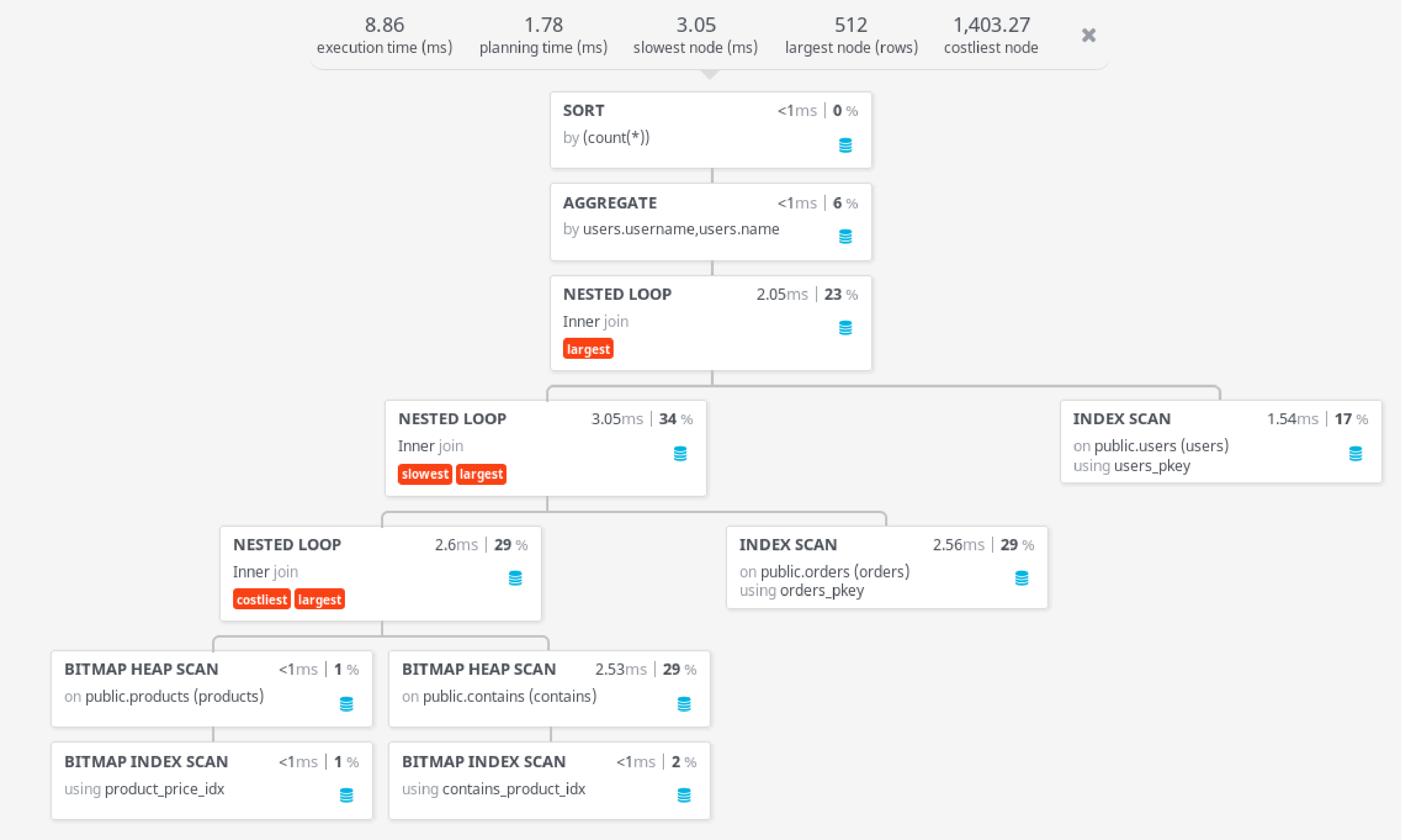
Now most of the time is spent **looking for the products** with the **desired price**.

Let's try creating another index:

```sql
CREATE INDEX product_price_idx ON products USING btree (price);
```

Example 1

Not as dramatic as before but still some improvement. Remember, indexes have theirs costs (slower updates, space, ...).



8.86 execution time (ms)
1.78 planning time (ms)
3.05 slowest node (ms)
512 largest node (rows)
1,403.27 costliest node

SORT <1ms | 0 %
by (count(*))

AGGREGATE <1ms | 6 %
by users.username,users.name

NESTED LOOP 2.05ms | 23 %
Inner join
largest

NESTED LOOP 3.05ms | 34 %
Inner join
slowest largest

INDEX SCAN 1.54ms | 17 %
on public.users (users)
using users_pkey

NESTED LOOP 2.6ms | 29 %
Inner join
costliest largest

INDEX SCAN 2.56ms | 29 %
on public.orders (orders)
using orders_pkey

BITMAP HEAP SCAN <1ms | 1 %
on public.products (products)

BITMAP HEAP SCAN 2.53ms | 29 %
on public.contains (contains)

BITMAP INDEX SCAN <1ms | 1 %
using product_price_idx

BITMAP INDEX SCAN <1ms | 2 %
using contains_product_idx

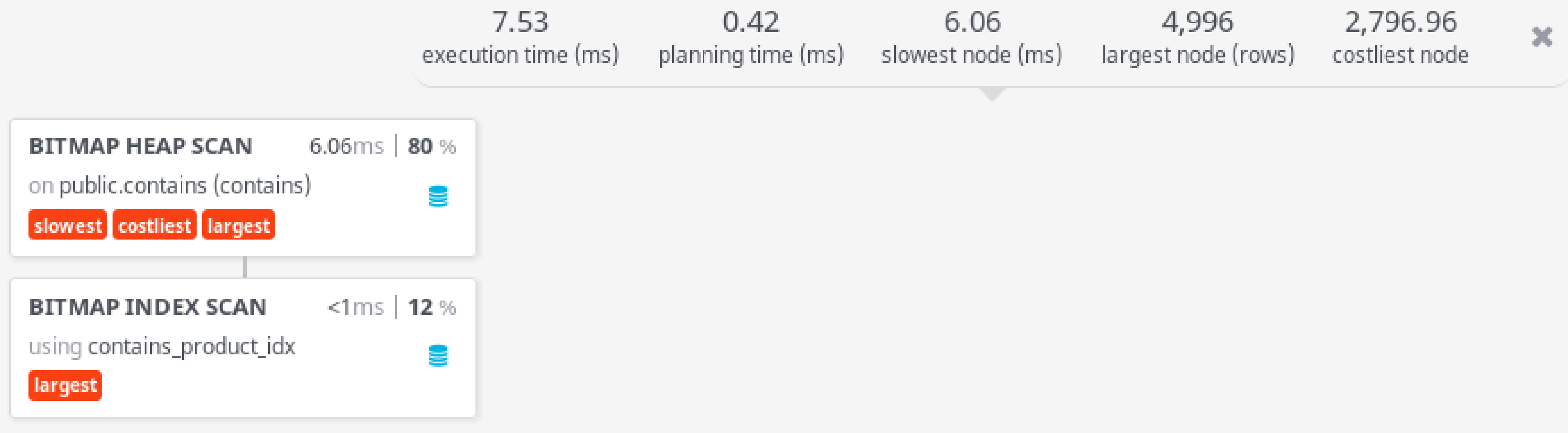
Example 2

Now, let's consider this other query that selects *all orders containing product with ids between 200 and 300*:

```sql
EXPLAIN SELECT o_id
FROM contains
WHERE p_id > 200 AND p_id < 300
```

Example 2

We already have an index on the *p_id* column so the query should be pretty fast:



7.53 execution time (ms)

0.42 planning time (ms)

6.06 slowest node (ms)

4,996 largest node (rows)

2,796.96 costliest node

BITMAP HEAP SCAN 6.06ms | 80 %
on public.contains (contains)
slowest costliest largest

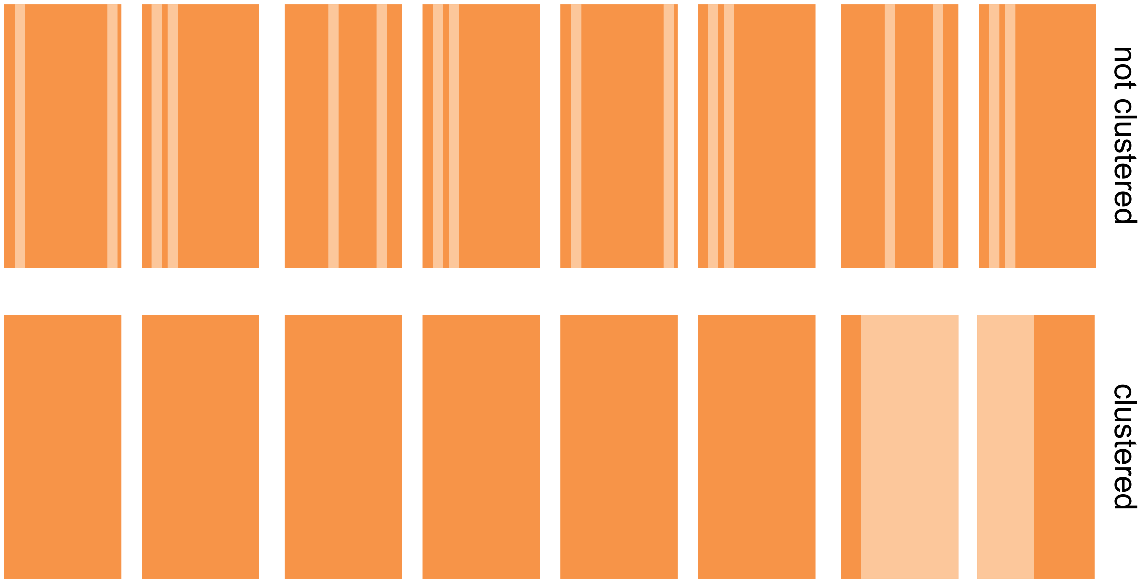
BITMAP INDEX SCAN <1ms | 12 %
using contains_product_idx
largest

Example 2

But we can do better. Because the index on *p_id* is not clustered, it means most blocks have only a **few** wanted rows.

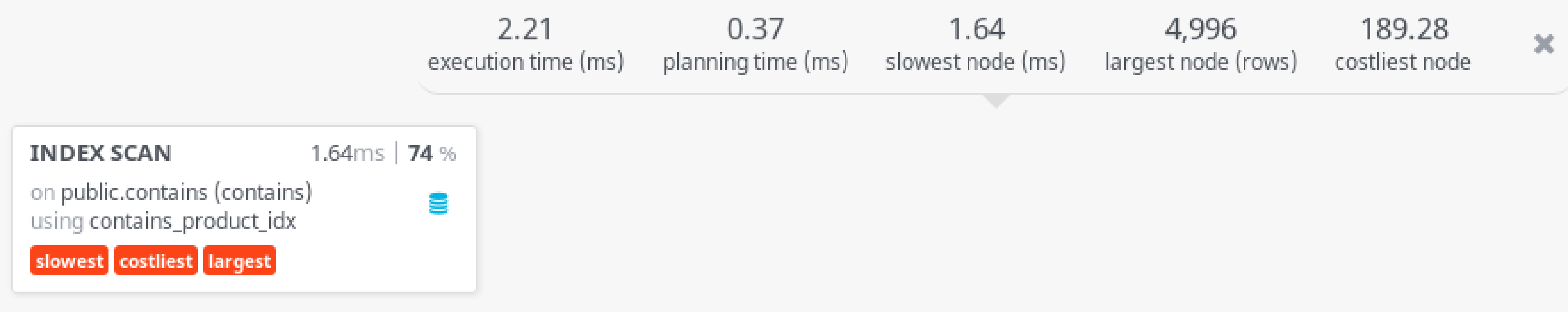
If we try clustering the index, a much **lower number of blocks** has to be read:

```
CLUSTER contains
USING contains_product_idx;
```



Example 2

We get the **same data** in **fewer blocks** and end up getting our results faster:



2.21 execution time (ms)

0.37 planning time (ms)

1.64 slowest node (ms)

4,996 largest node (rows)

189.28 costliest node

INDEX SCAN 1.64ms | 74 %

on public.contains (contains)

using contains_product_idx

Example 3

We now have a single table containing **all** Wikipedia titles:

```
wikipedia (id, title)
```

The table has approximately **44 Million** rows and we want to search the table for some words.

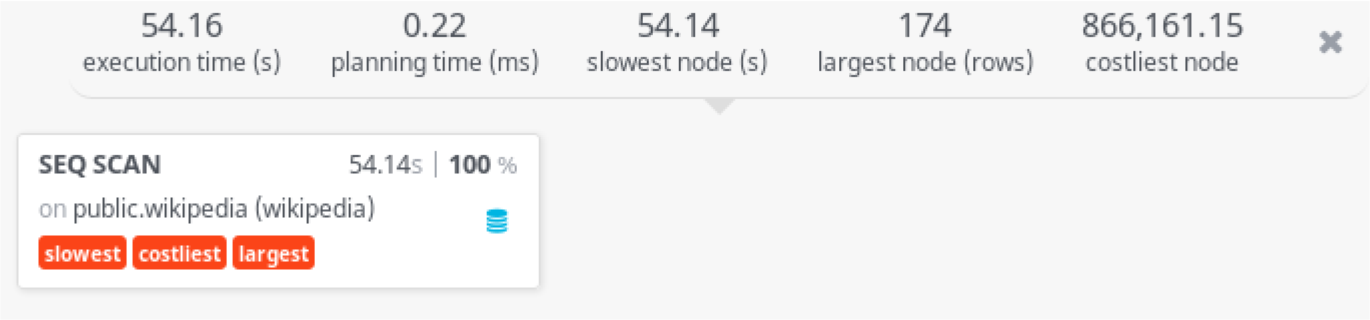
The total table size on the hard disk is **2436 MB**. The primary key index occupies an extra **950 MB**.

Example 3

If we try to search for *oil painting* using ILIKE:

```
SELECT * FROM wikipedia
WHERE title ILIKE '%oil%painting%'
```

We get 174 rows in 54 seconds:



54.16 execution time (s)
0.22 planning time (ms)
54.14 slowest node (s)
174 largest node (rows)
866,161.15 costliest node

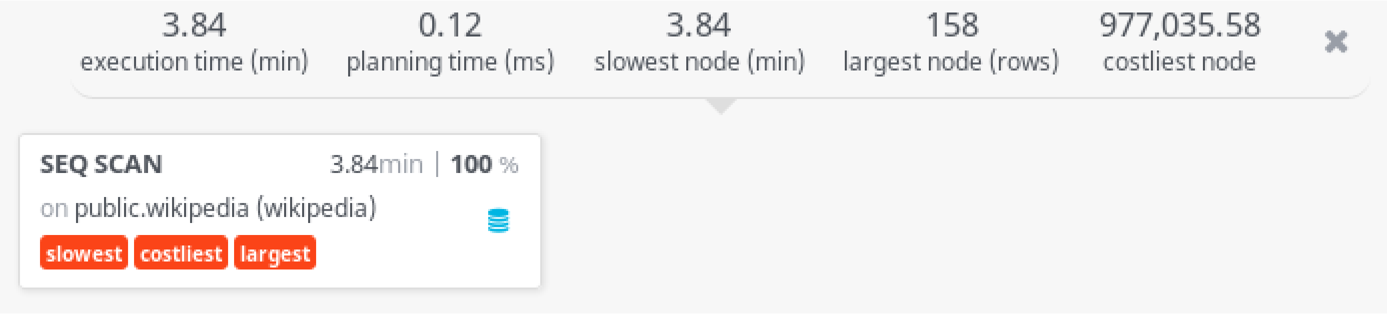
SEQ SCAN 54.14s | 100 %
on public.wikipedia (wikipedia)

Example 3

If we try using *ts_vectors* and a *ts_query* with no indexes:

```
SELECT * FROM wikipedia
WHERE to_tsvector('english', title) @@
      to_tsquery('english', 'oil & painting')
```

The query returns **158 rows in 4 minutes**. The added time is due to having to calculate *ts_vectors* for all rows:



3.84 execution time (min)
0.12 planning time (ms)
3.84 slowest node (min)
158 largest node (rows)
977,035.58 costliest node

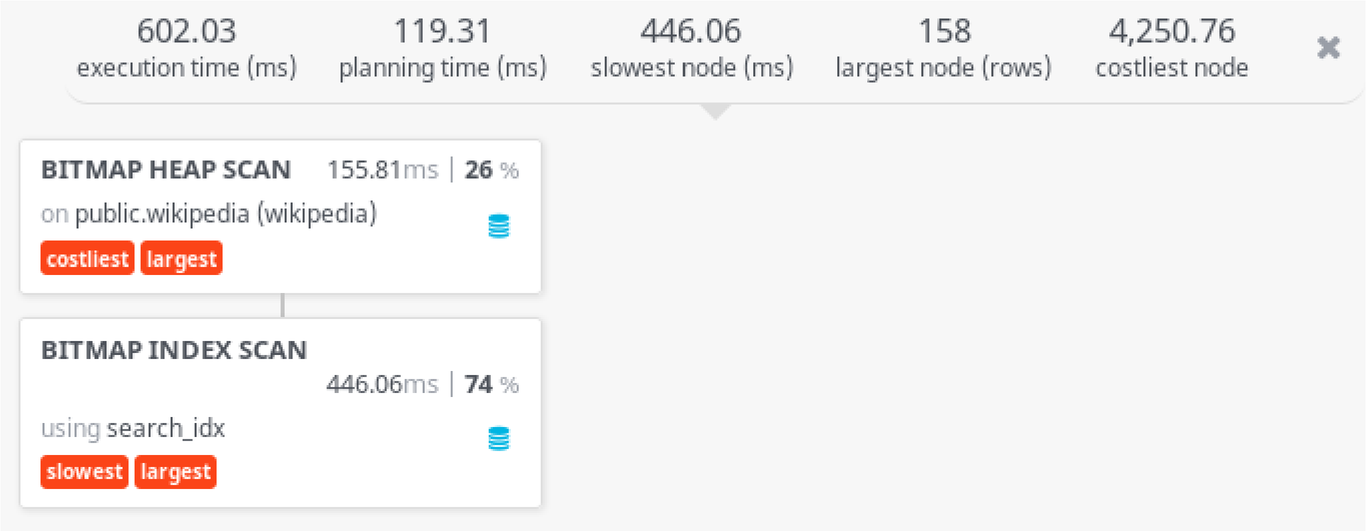
SEQ SCAN 3.84min | 100 %
on public.wikipedia (wikipedia)
slowest costliest largest

Example 3

If we execute the same query but we add a GiST index first:

```
CREATE INDEX search_idx ON wikipedia USING GIST (to_tsvector('english', title));
```

It now takes only **600 ms**. Creating the index took **52 minutes** and used **1708 MB** but you only have to do it once:



602.03
execution time (ms)

119.31
planning time (ms)

446.06
slowest node (ms)

158
largest node (rows)

4,250.76
costliest node

BITMAP HEAP SCAN 155.81ms | 26 %
on public.wikipedia (wikipedia)
costliest largest

BITMAP INDEX SCAN
446.06ms | 74 %
using search_idx
slowest largest

Statistics

When calculating the ideal plan for a certain query, PostgreSQL relies on some **key statistics** collected about the columns in the database:

- The fraction of the column's entries that are null.
- The number of distinct *non null* data values in the column.
- Numerical statistics including histograms of the column values.

To force PostgreSQL to update these statistics when can use the ANALYZE command:

```
ANALYZE [table] [(column1, column2, ...)]
```

ANALYZE analyzes all tables by default but we can choose to analyze only one table or only some columns.

It's important to keep these statistics updated (use a *cron* job).

Vacuum

- In PostgreSQL, tuples that are deleted or obsoleted by an update are not physically removed from their table.
- The VACUUM command **reclaims** this storage by making available for reuse.
- The VACUUM FULL command **reclaims** this storage by rewriting the entire contents of the table into a new disk file with no extra space.
- It's important to do VACUUM periodically, especially on frequently updated tables.

```
VACUUM [FULL] [ANALYZE] [table] [(column1, column2, ...)]
```

- VACUUM reorganizes all tables by default but we can choose to reorganize only one table or only some columns.
- We can VACUUM and ANALYZE tables at the same time.
- VACUUM FULL is slow and requires an exclusive lock making it not recommended for production.

Choosing Indexes

Workload

In order to choose our indexes, we must first estimate the workload of the system:

- The most important queries (SELECT) and how often they arise.
- The most important updates (UPDATE, DELETE) and how often they arise.
- The desired performance for these queries and updates.
- An estimate of the number of tuples for each relation.

Table Estimates

We start by estimating the number of tuples in each relation:

Relation reference	Relation Name	Order of magnitude	Estimated growth
R01	Users	tens of thousands	hundreds per day
R02	Products	tens of thousands	hundreds per week
R03	Orders	hundreds of thousands	hundreds per day
R04	Contains	millions	thousands per day

Important queries

We then start describing each one of the most important queries:

Query reference	SELECT01
Query description	Selects all orders made by a specific client.
Query frequency	hundreds per hour
SQL code	

```sql
SELECT *
FROM orders
WHERE c_id = ?
```

Cardinality

The **uniqueness** of data values contained in a particular column. The lower the cardinality, the more duplicate values in the column. Examples:

- **high** cardinality - primary key
- **medium** cardinality - last name in a customer table
- **low** cardinality - boolean column

Cardinality is used by the PostgreSQL *planner*, amongst other statistics, to estimate the number of rows returned by a WHERE clause. This is then used to decide if, and what, indexes should be used.

When to Cluster?

- To **reduce** the number of block reads:
  - When the number of tuples to be read is high enough and there are many tuples per block.
  - Normally on **medium** cardinality columns in tables with small tuples.
- To allow **sequential** reading of blocks:
  - Normally on range searches or **low** cardinality columns.
  - Specially in hard-disks (not important on SSD).

Clustering is useful whenever **many tuples** are to be retrieved, but **not too many**.

Choosing Indexes

Index reference	IDX01
Query references	SELECT01, ...
Index relation	R03
Index attribute	c_id
Index type	Hash
Cardinality	Medium
Clustering	Yes
Justification	Table is very large, query SELECT01 has to be fast as it is executed many times, doesn't need range query support, cardinality is medium so it is a good candidate for clustering.
SQL code	

```
SELECT *
FROM orders
WHERE c_id = ?
```

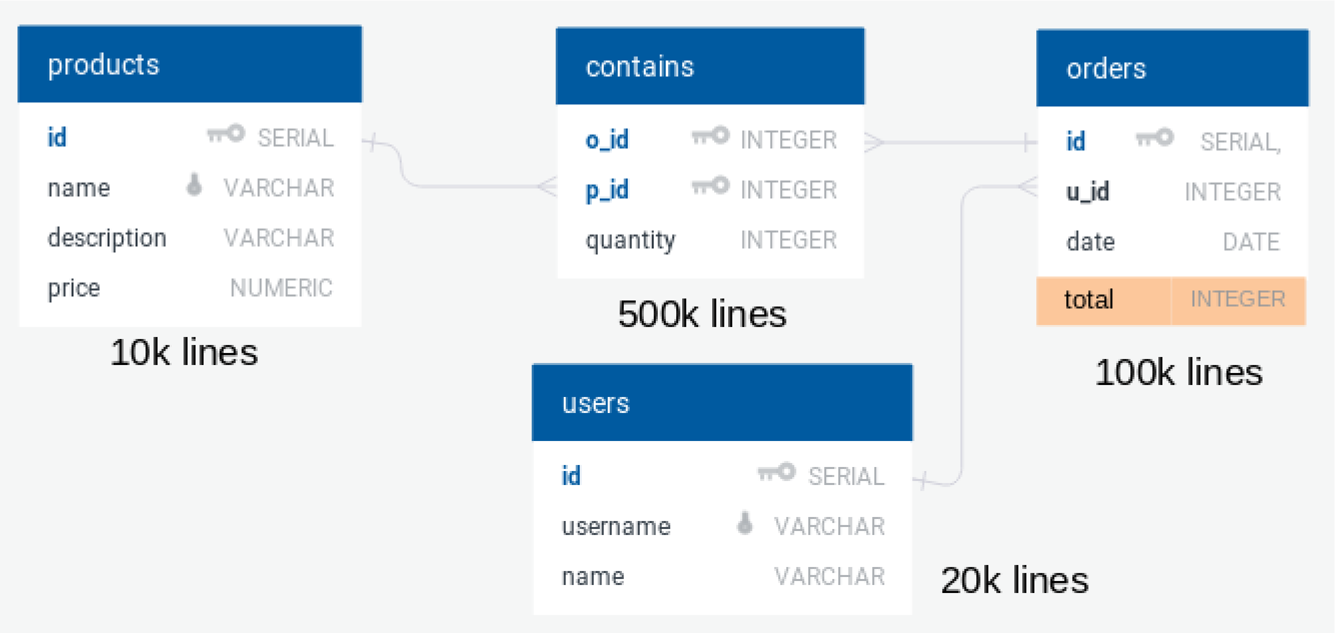
Denormalization

Denormalization

- A strategy used on a **previously normalized** database to increase performance.
- Denormalization is the process of trying to improve performance of a database by adding **redundant** copies of data or by chosing **alternative** 3NF (or even lower NFs) schemas.
- Redundant data should be kept consistent. For example, using triggers.

Example

Adding a redundant **total** column to the *orders* table to prevent having to calculate it everytime.



products	
id	SERIAL
name	VARCHAR
description	VARCHAR
price	NUMERIC

10k lines

contains	
o_id	INTEGER
p_id	INTEGER
quantity	INTEGER

500k lines

orders	
id	SERIAL,
u_id	INTEGER
date	DATE
total	INTEGER

100k lines

users	
id	SERIAL
username	VARCHAR
name	VARCHAR

20k lines

Keeping Data consistent

```
CREATE OR REPLACE FUNCTION calculate_total(order_id integer)
RETURNS trigger AS $$
BEGIN
  UPDATE orders
  SET total = (SELECT SUM(quantity * price)
               FROM products JOIN
                    contains ON p_id = id
               WHERE o_id = order_id)
  WHERE id = order_id;
  RETURN NEW;
END;
$$ LANGUAGE plpgsql;
```

```
CREATE TRIGGER contains_ins_upd
AFTER INSERT or UPDATE
ON contains
FOR EACH ROW
EXECUTE PROCEDURE calculate_total(NEW.order_id);
```

Another trigger is needed for UPDATE or DELETE using OLD.order_id as the parameter.

Materialized Views

An **alternative** to denormalization is the usage of materialized views.

A materialized view **stores** the result of a query in a table and can be **refreshed** as needed.

```
CREATE MATERIALIZED VIEW orders_total AS
SELECT orders.*, SUM(quantity * price)
FROM orders JOIN
     contains ON orders.id = o_id JOIN
     products ON products.id = p_id
GROUP BY orders.id
```

```
REFRESH MATERIALIZED VIEW orders_total
```

“ Premature optimization is the root of all evil. ”

— Donald Knuth