

DB 2

02 – Unary Table Storage

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1 : Q_1 — The Simplest SQL Probe Query

Let us send the very first **SQL probe** Q_1 . It doesn't get much simpler than this:¹

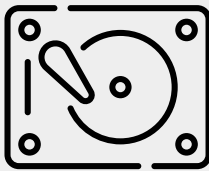
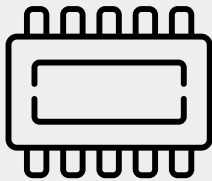
```
SELECT u.*           -- * ≡ access all columns of row u
FROM unary AS u
```


Retrieve all rows (in some arbitrary order) and all columns of table `unary`. For now, we assume that `unary` has a single column of type `int`.

¹ In PostgreSQL, there is an equivalent even more compact form for Q_1 : `TABLE unary`.

PostgreSQL vs. MonetDB

In the sequel, we use the badges below whenever we dive deep and discuss **material that is specific to a particular DBMS**:

PostgreSQL	MonetDB
	
disk-based	RAM-based

-  SQL syntax and semantics may (subtly) differ between both systems. This is a cruel fact of the current state of SQL and its implementations. Cope with it.



Aside: Populating Tables via `generate_series()`

Create and populate table `unary` as follows:

```
CREATE TABLE unary (a int);

INSERT INTO unary(a)
  SELECT i
  FROM   generate_series(1, 100, 1) AS i;
--
--                               ↑   ↑   ↑
--                               start/end/step of sequence
```

- Table function `generate_series(s,e, Δ)` enumerates values² from `s` to `e` (inclusive) with step `Δ` (default `$\Delta = 1$`).

² `s` and `e` both of type `int`, `numeric`, or `timestamp` (for the latter, `Δ` needs to have type `interval`).



Using **EXPLAIN** on Q_1

Let us try to understand the evaluation of Q_1 :

```
db2=# EXPLAIN VERBOSE
      SELECT u.*           -- }  $Q_1$  as before
      FROM   unary AS u;   -- }
```

QUERY PLAN

```
Seq Scan on public.unary (cost=0.00..2.00 rows=100 width=4)
  Output: a
```

(2 rows)

```
db2=# █
```



Using EXPLAIN

Show the **query evaluation plan** for SQL query `<Q>`:

- 1 `EXPLAIN <opt> <Q>`
- 2 `EXPLAIN (<opt>, <opt>, ...) <Q>`

`<opt>` controls level of detail and mode of explanation:

<code><opt></code>	Effect
<code>VERBOSE</code>	higher level of detail
<code>ANALYZE</code>	evaluate the query, then produce explanation
<code>FORMAT {TEXT JSON XML}</code>	output format (default: <code>TEXT</code>)
<code>⋮</code>	<code>⋮</code>

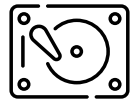
⚠ Without `ANALYZE`, `<Q>` is *not* evaluated \Rightarrow output is based on the DBMS's **best guess** of how the plan will perform.



2 : Sequential Scan (Seq Scan)

QUERY PLAN	
Seq Scan on public.unary (cost=0.00..2.00 rows=100 width=4)	
Output: a	type int

- **Seq Scan:** Sequentially scan the entire **heap file** of table **unary**, read rows in **some order**, emit all rows.
- Seq Scan returns rows in arbitrary order (*not*: insertion order) that may change from execution to execution. Meets bag semantics of the tabular data model (→ DB1).



Heap Files

The rows of a table are stored in its **heap file**, a plain row container that can grow/shrink dynamically.

- Row insertion/deletion simple to implement and efficient, no complex file structure to maintain. 👍
- Supports **sequential scan** across entire file.
- **No support for finding rows by column value** (no associative row access). If we need value-based row access, additional data maps (indexes) need to be created and maintained.



Heap Files and Sequential Scan

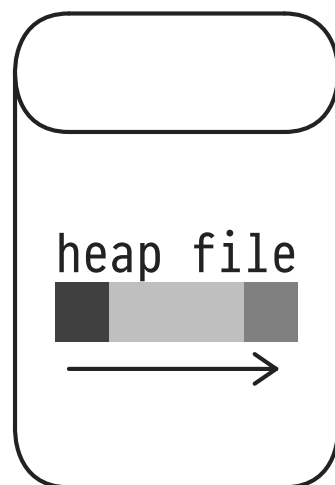
The DBMS may reorganize (e.g., compact or “vacuum”) a table's heap file at any time \Rightarrow no guaranteed row order:

Table unary

a
1
2
⋮
42
⋮
99
100

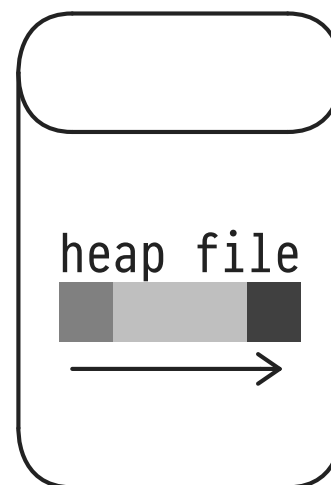


Disk



1 now

Disk



2 now + 1 s

Table unary

a
99
100
⋮
42
⋮
1
2





Heap File \equiv OS File

Most DBMSs store **heap files** in **regular files of the operating system's file system** (alternative: raw storage).

- Files held in a DBMS-controlled directory. In PostgreSQL:

```
db2=# show data_directory;
```

data_directory
/Users/grust/Library/App.../Postgres/var-15

- DBMS enjoys OS FS services (e.g., backup, authorization).



Row IDs and Heap File Locations

Heap files do not support value-based access. We can still **directly locate a row** via its **row identifier (RID)**:

- RIDs are **unique** within a table. Even if two rows r_1 , r_2 agree on all column values (in a key-less table), we still have $RID(r_1) \neq RID(r_2)$.
 - $RID(r)$ **encodes the location** of row r in its table's heap file. No sequential scan is required to access r .
 - If r is updated, $RID(r)$ remains stable.
- ⚠ RIDs do *not* replace the relational key concept.³

³ But see comments on free space management and `VACUUM` later on.

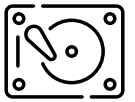


RIDs in PostgreSQL

RIDs are considered DBMS-internal and thus withheld from users. PostgreSQL externalizes RIDs via **pseudo-column `ctid`**:

```
SELECT u.ctid, u.*
FROM   unary AS u;
```

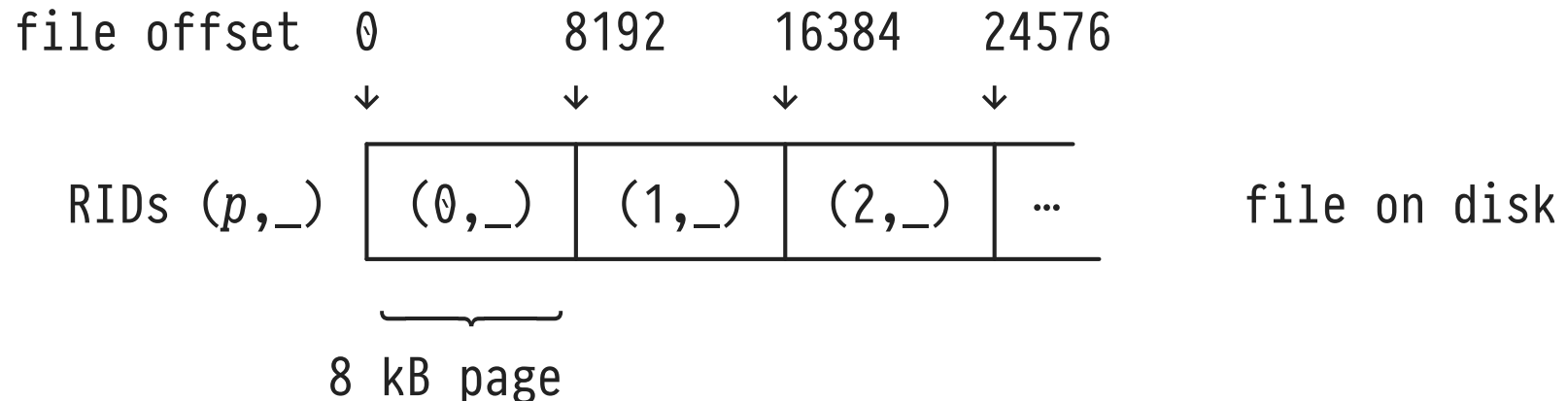
ctid	a
(0,1)	1
(0,2)	2
⋮	⋮
(1,1)	227
(1,2)	228
⋮	⋮
(4,95)	999
(4,96)	1000



File Storage on Disk-Based Secondary Memory

A PostgreSQL RID is a pair (**<page number>**, **<row slot>**):

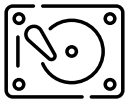
- **Page number** p identifies a **contiguous block of bytes** in the file.
- **Page size** B is system-dependent and configurable. Typical values are in range 4-64 kB. PostgreSQL default: **8 kB**.





Block I/O on Disk-Based Secondary Memory

- Heap files are **read and written in units of 8 kB pages**.
 - Likewise, heap files grow/shrink by entire pages.
- This page-based access to heap files reflects the OS's mode of performing **disk input/output page-by-page**.
 - Terminology: DB \square **page** \equiv **block** \square OS
- **⚠** Any disk I/O operation will read/write at least one block (of 8 kB). Disk I/O *never* moves individual bytes.

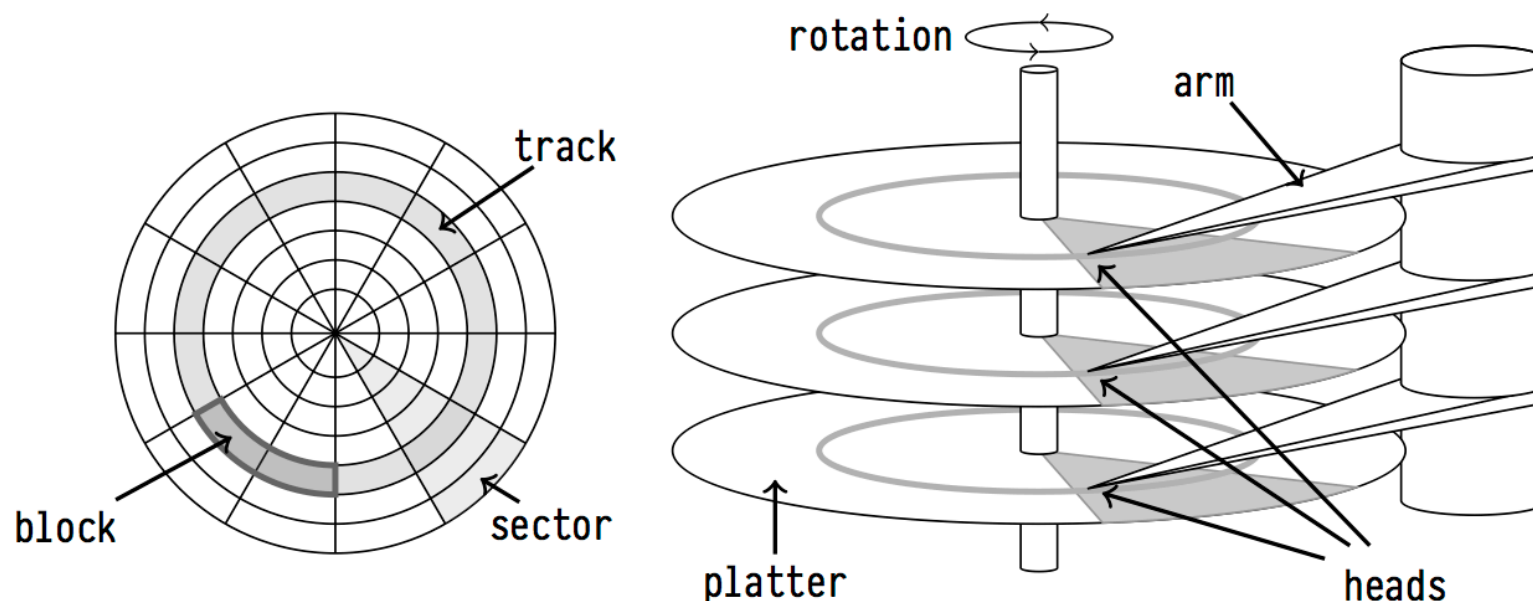


3 | Rotating Magnetic Hard Disk Drives (HDDs)



Steadily rotating platters and read/write heads of a HDD

HDDs: Tracks, Sectors, Blocks



- ❶ **Seek** Stepper motor positions array of R/W heads over wanted **track**.
- ❷ **Rotate** Wait for wanted **sector** of blocks to rotate under R/W heads.
- ❸ **Transfer** Activate one head to read/write **block** data.



HDDs: Access Time

A HDD design that involves motors, mechanical parts, and thus inertia has severe implications on the **access time** t needed to read/write one block:

$$t = \underbrace{t_s}_{\text{seek time}} + \underbrace{t_r}_{\text{rotational delay}} + \underbrace{t_{tr}}_{\text{transfer time}}$$

- Amortize seek time and rotational delay by transferring one block at a time (**random block access**).
- Transfer a sequence of adjacent blocks: longer t_{tr} but, ideally, $t_s = t_r = 0$ ms (**sequential block access**).



HDDs: Random Block Access Time

Feature	
HDD layout	4 platters, 8 r/w heads
average data per track	512 kB
capacity	600 GB
rotational speed	15000 min ⁻¹
average seek time (t_s)	3.4 ms
track-to-track seek time	0.2 ms
transfer rate	≈ 163 MB/s

Data Sheet Seagate Cheetah 15K.7 HDD

- **Random access time t for a single 8 kB block:**
 - Average rotational delay t_r : $\frac{1}{2} \times (1/15000 \text{ min}^{-1}) = 2 \text{ ms}$
 - Transfer time t_{tr} : $8 \text{ kB} / (163 \text{ MB/s}) = 0.0491 \text{ ms}$
 - $\Rightarrow t_s + t_r + t_{tr} = 3.4 \text{ ms} + 2 \text{ ms} + 0.05 \text{ ms} = \underline{5.45 \text{ ms}}$



HDDs: Sequential Block Access Time

Feature	
⋮	⋮
average data per track	512 kB
track-to-track seek time	0.2 ms
⋮	⋮

Data Sheet Seagate Cheetah 15K.7 HDD

- **Random access time** for 1000 blocks of 8 kB:
 - $1000 \times t = 5.45 \text{ s}$ 🗑️
- **Sequential access time** for 1000 adjacent blocks of 8 kB:
 - 512 kB per track: 1000 blocks will span 16 tracks
 - $\Rightarrow t_s + t_r + 1000 \times t_{tr} + 15 \times 0.2 \text{ ms} = \underline{58.4 \text{ ms}}$
- Once we need to read more than $58.4 \text{ ms} / 5450 \text{ ms} = 1.07\%$ of a file, we better **read the entire file sequentially**.

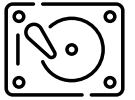


Solid State Disk Drives (SSDs)

SSDs rely on non-volatile flash memory and contain no moving/electro-mechanical parts:

- Non-volatility (battery-powered DRAM or NAND memory cells) ensures data persistence even on power outage.
- **No seek time, no rotational delay** ($t_s = t_r = 0$ ms), no motor spin-up time, no R/W head array jitter.
- Admits **low-latency random read access** to large data blocks (typical: 128 kB), however slow random writes.⁴

⁴ Groups of data blocks need to be erased, then can be written again. Memory cells wear out after 10^4 to 10^5 write cycles \Rightarrow SSDs use wear-leveling to spread data evenly across the device memory.



SSDs: Access Time

Feature	
device memory	NAND flash
capacity	2 TB
block size	128 kB
transfer rate	≈ 7.0 GB/s

Data Sheet Apple SSD AP2048Z

- **Random access time** for 1000 blocks of 8 kB:
 - Transfer time t_{tr} : $128 \text{ kB} / (7.0 \text{ GB/s}) = 0.02 \text{ ms}$
 - $1000 \times t_{tr} = \underline{20 \text{ ms}}$
 - **Sequential access time** for 1000 adjacent blocks of 8 kB:
 - $\lceil (1000 \times 8 \text{ kB}) / 128 \text{ kB} \rceil \times t_{tr} = \underline{1.25 \text{ ms}}$
- ⚠ Sequential still beats random I/O (by a smaller margin).

SSDs: Still a Disk? Already like RAM? (1)

Both SSDs and DRAM provide $t_s = t_r = 0$ ms. How do they compare regarding t_{tr} (i.e., transfer speed)?

- **SSD transfer speed test** (write 4 GB of zeroes):

```
$ cd /tmp
$ time dd if=/dev/zero of=bitbucket bs=1024k count=4096
4096+0 records in
4096+0 records out
4294967296 bytes transferred in 0.645687 secs
```

≈ 6.6 GB/s

SSDs: Still a Disk? Already like RAM? (2)

- **DRAM transfer speed test** (sequentially read 64 GB):

1. Allocate memory area of 32 MB ($> \sum$ cache sizes)
2. Repeatedly scan the area, writing 64-bit by 64-bit:

```
$ cc -Wall -O3 transfer.c -o transfer
$ ./transfer
time: 894147μs (result: 0)
```

time: 894147μs

≈ 71.5 GB/s

- Still faster: use SIMD instructions (r/w up to 256 bits) and multiple CPU cores (but: bus bandwidth is limited).

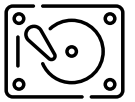
Heads-Up: System Latencies

During the entire course, be aware and recall the typical **latencies** (“wait times”) of a contemporary system:

Operation	Actual Latency \times	Human Scale 🤖
CPU cycle	0.4 ns	1 s
L1 cache access	0.9 ns	2 s
L2 cache access	2.8 ns	7 s
L3 cache access	28 ns	1 min
RAM access	\approx 100 ns	4 min
SSD I/O	50–150 μ s	1.5–4 days
HDD I/O	1–10 ms	1–9 months
Internet roundtrip (DE \leftrightarrow US)	90 ms	7 years

System Latencies (at Human Scale)

Many DB design decisions become a lot clearer in this light.



4 : Heap Files: Free Space Management

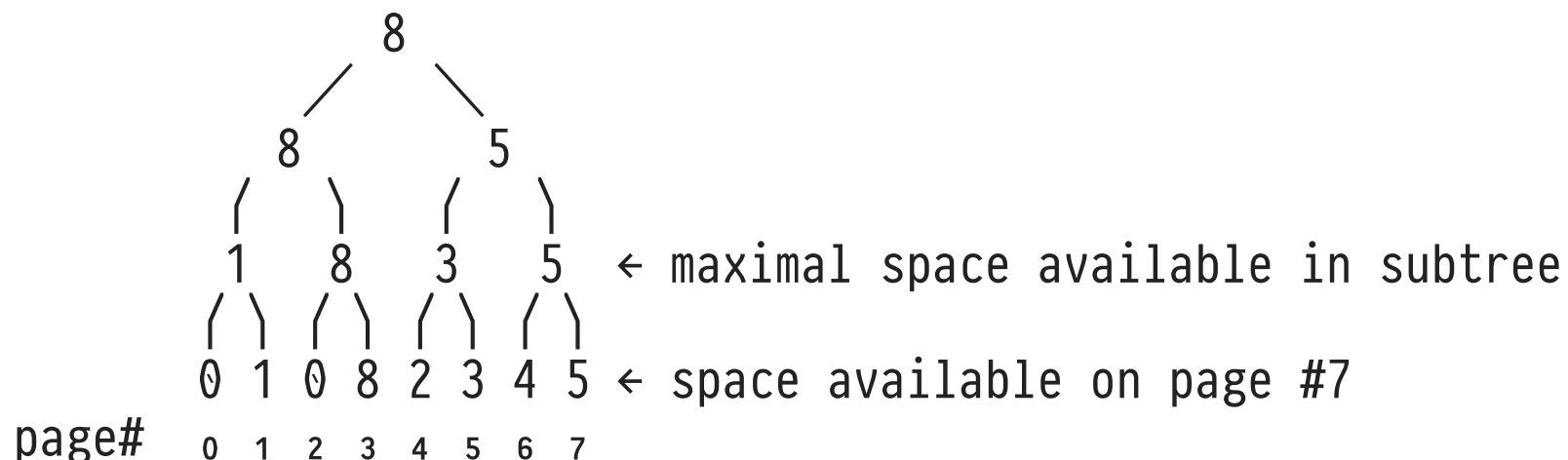
Row updates and deletions may lead to heap file pages that are not 100% filled. New records could fill such “holes.”

- DBMS maintains a **free space map** (FSM) for each heap file, recording the (approximate) number of bytes available on each 8 kB page.
- Required FSM operations:
 1. Given a row of n bytes, which page p (in the vicinity) has sufficient free space to hold the row?
 2. Free space on page p has been reduced/enlarged by n bytes. Update the FSM.



Heap Files: Free Space Management

PostgreSQL maintains a **tree-shaped FSM** for each heap file:

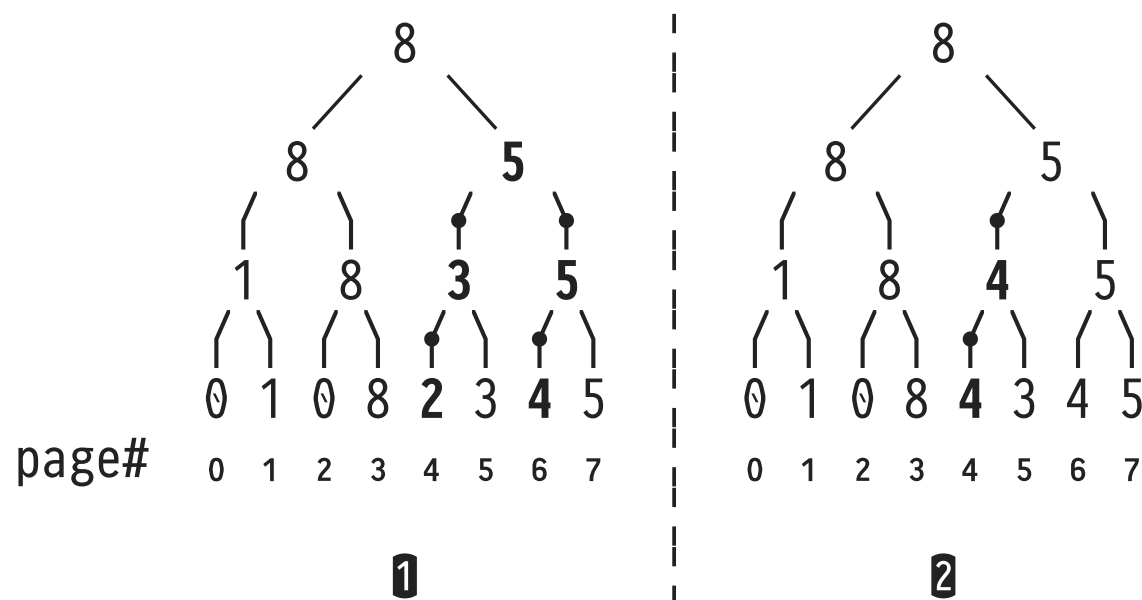


- Leaf nodes: space available in heap file page.⁵
- Inner nodes: maximal space found in this file (segment).

⁵ PostgreSQL: space measured in 32 byte units (= 1/256 of a 8 kB page).



Heap Files: Free Space Management



- ❶ Find a page with at least 4 available slots in the vicinity of page #4 (traverses $2 \uparrow 3 \uparrow 5 \downarrow 5 \downarrow 4$ along \nearrow).
- ❷ Update page #4 to provide 4 available slots (traverses \nearrow , updates 3 to $\max(3, 4) = 4$, stops when $\max(4, 5) = 5$).

5 : Q_1 — The Simplest SQL Probe Query

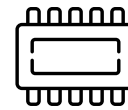
Recall our very first **SQL probe** Q_1 :

```
SELECT u.*           -- *  $\equiv$  access all columns of row s  
FROM unary AS u
```

Retrieve all rows (in some arbitrary order) and all columns of table **unary**. For now, the table has a **single column** of type **int**.



- How does **MonetDB** cope with Q_1 ?



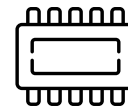
Aside: Populating Tables via `generate_series()`

One way to create and populate table `unary` in MonetDB:

```
CREATE TABLE unary (a int);

INSERT INTO unary(a)
  SELECT value -- ← fixed column name
  FROM   generate_series(1, 101, 1);
--
--               ↑   ↑   ↑
--               start/end+1/step of sequence
```

- Table function `generate_series(s,e, Δ)` enumerates values from `s` to `e` (exclusive) with step `Δ` (default `$\Delta = 1$`).

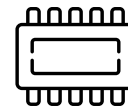


Using **EXPLAIN** on Q_1

Evaluate Q_1 in MonetDB's SQL REPL, **mclient**:

```
sql> EXPLAIN
      SELECT u.*           -- }  $Q_1$  as before
      FROM   unary AS u;  -- }

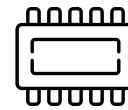
+-----+
| mal                                         |
+=====+
| function user.s10_0():void;                 |
|   X_1:void := querylog.define("explain select u.  |
|   :                                              |
| #total                                     actions=27 time=247 usec |
+-----+
sql> █
```



MonetDB Query Plan \equiv MAL Program

```
⋮  
X_4      := sql.mvc();  
C_5:bat[:oid] := sql.tid(X_4, "sys", "unary");  
X_8:bat[:int] := sql.bind(X_4, "sys", "unary", "a", 0:int);  
X_17     := algebra.projection(C_5, X_8);  
⋮
```

- Queries are compiled into (mostly) linear **MonetDB Assembly Language (MAL)** programs.
 - Program \equiv sequence of assignment statements:
`<var> := <expression>`. Any `<var>` assigned only once.
- The **MonetDB kernel** implements a **MAL virtual machine (VM)**.



MAL: Scalar Data Types (Atoms)

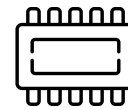
Once assigned, a MAL variable has a fixed defined **type**:

- **Scalar data types (atoms):**

Scalar Type τ	Literal ⁶	Domain
<code>bit</code>	<code>1:bit</code>	bit
<code>bte</code> , <code>sht</code> , <u><code>int</code></u> , <code>lng</code> , <code>hge</code>	<code>42:τ</code>	signed {8,16,32,64,128}-bit value
<code>oid</code>	<code>42@0</code>	32-bit row ID (\equiv table offset)
<u><code>flt</code></u> , <code>dbl</code>	<code>4.2</code>	{32,64}-bit floating point
<code>str</code>	<code>"42"</code>	variable-length UTF-8 string

- Each type τ comes with a constant `nil: τ` (“*undefined*”, cf. SQL's `NULL`).

⁶ Polymorphic literals without explicit type cast `: τ` are implicitly assigned the underlined type.

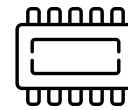


Columns (BATs)

MonetDB implements a *single* collection type `bat[: τ]`, the **Binary Association Tables (BATs)** of values of type τ :

	head	tail	
densely ascending	0@0	42	} scalars of type τ (\equiv int) (BAT “payload”)
sequence of row IDs	1@0	42	
of type oid	2@0	0	
(row at offset i	3@0	-1	
has oid $i@0$)	4@0	nil	

- **Head:** store sequence base 0@0 only (“virtual oids”, `void`)
- **Tail:** one **ordered column** (or vector) of data

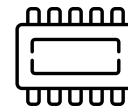


Using MAL to Process SQL

MAL program for Q_1 , shortened and formatted:

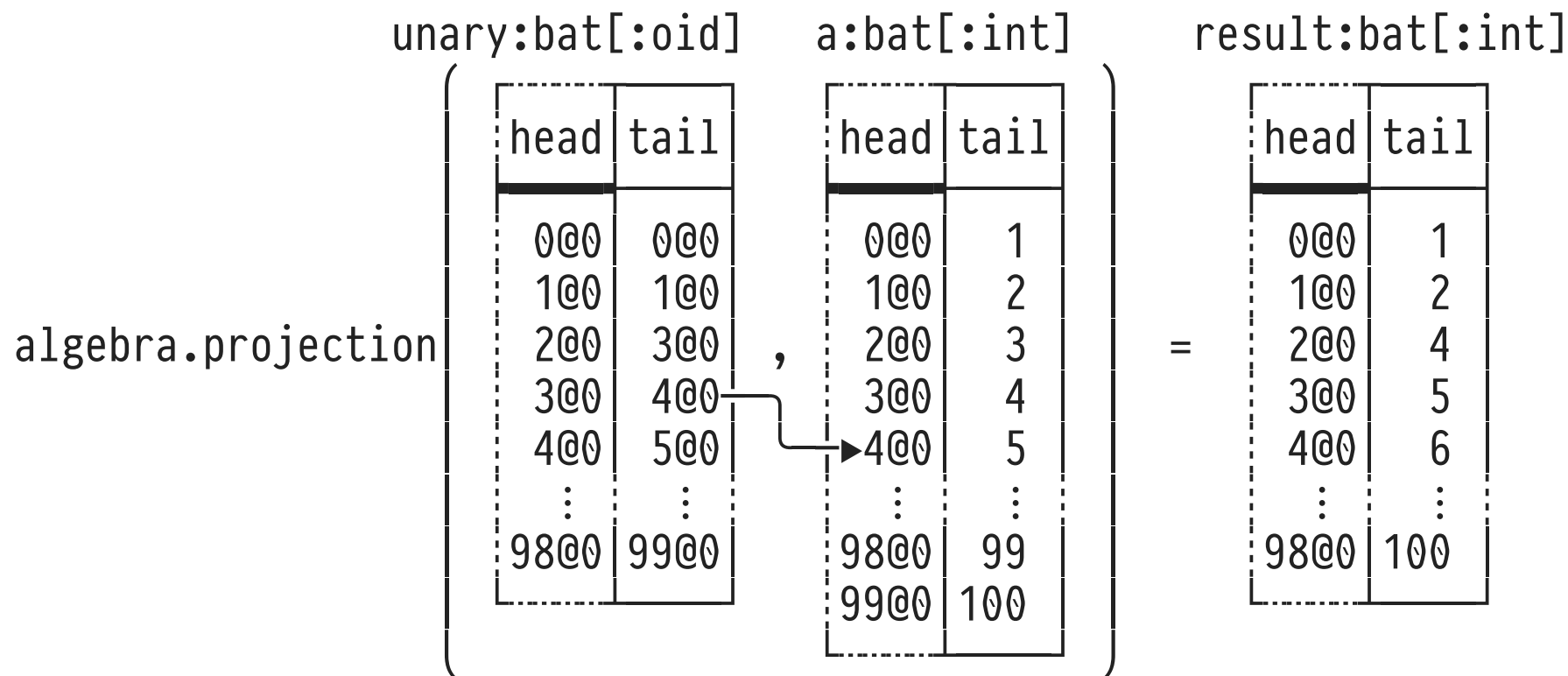
```
⋮  
❶ sql          := sql.mvc();  
❷ unary :bat[:oid] := sql.tid( sql, "sys", "unary");  
❸ a       :bat[:int] := sql.bind(sql, "sys", "unary", "a",...);  
❹ result:bat[:int] := algebra.projection(unary, a);  
⋮
```

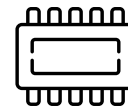
- ❶ Get database catalog handle (also: TX management).
- ❷ Get IDs of all **currently visible** rows in table `unary`.
- ❸ Get all values in column `a` of table `unary`.
- ❹ Compute result column of all visible `a` values.



Using MAL to Process SQL

Assume that the row with $a = 3$ (oid 200) has been deleted (BAT `unary` reflects this update, thus no 200 in its tail):

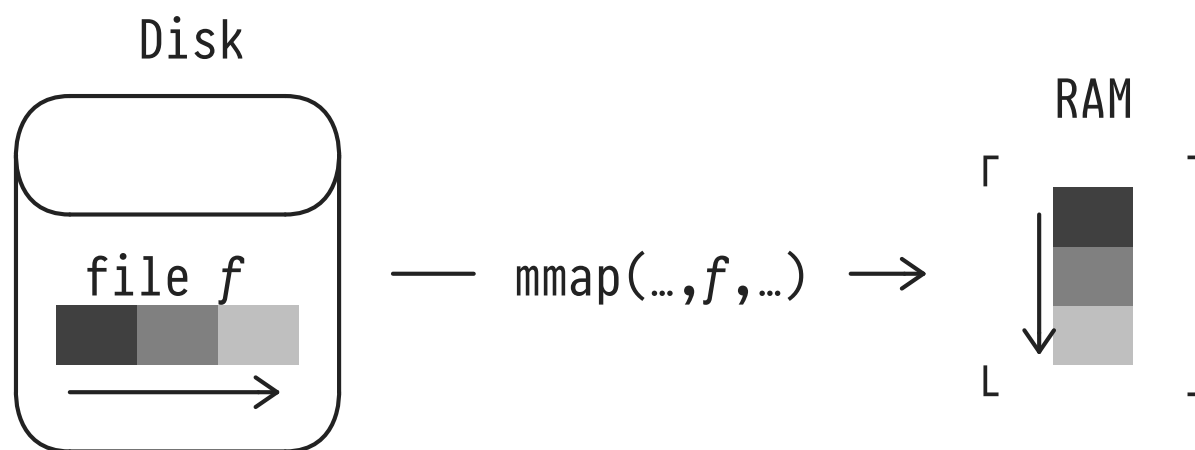


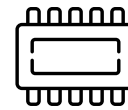


6 : MonetDB: A Main-Memory DBMS

All BATs are processed as in-memory arrays of fixed-width elements (atoms).

- **Transient** BATs exist in RAM only.
- **Persistent** BATs live on disk and are `mmap(2)`ed into RAM:





UNIX `mmap(2)`: Map Files into Memory

MMAP(2)

BSD System Calls Manual

MMAP(2)

NAME

`mmap` -- allocate memory, or map files or devices into memory

LIBRARY

Standard C Library (libc, -lc)

SYNOPSIS

```
#include <sys/mman.h>
```

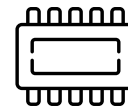
```
void *
```

```
mmap(void *addr, size_t len, int prot, int flags, int fd, off_t offset);
```

DESCRIPTION

The `mmap()` system call causes the pages starting at `addr` and continuing for at most `len` bytes to be mapped from the object described by `fd`, starting at byte offset `offset`. [...]

- The contents of file `fd` are **mapped 1:1 into contiguous memory**. No conversion or transformation takes place—compare this to PostgreSQL's row storage (later).
- OS implements virtual memory: can map even huge files.



Peeking into a MonetDB BAT

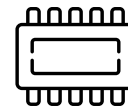
Use MAL builtin function `bat.info()` to collect details about the BAT for column `unary(a)` of 100 32-bit `ints`:

```
mysql> a := sql.bind(sql, "sys", "unary", "a", ...);
mysql> (i1,i2) := bat.info(a);
mysql> io.print(i1,i2);
# void  str  str  # type
#-----#
[...]
```

[7@0,	"tail",	"int"]	
[8@0,	"batPersistence",	"persistent"]	← persistent BAT
[32@0,	"tail.free",	"400"]	← size on disk
[36@0,	"tail.filename",	"05/546.tail"]	← OS file

```
[...]
```

> █



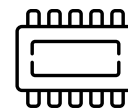
Fixed-Width Tail Columns and Row Offsets

- Each tail column entry in a MonetDB BAT of type `bat[: τ]` is of **fixed width** (e.g., for $\tau \equiv \text{int}$, width is 4 bytes).
- Runtime representation of **tail column as a C array**, say `a`. Access entry with oid `i@0` simply via

`a[i - hseqbase]`

effective address: $a + (i - \text{hseqbase}) \times \text{size of } \tau$

- \Rightarrow BAT processing routines (like `algebra.projection()`) implemented as (tight) loops over C arrays. 🚀



Variable-Width Tail Columns: Dictionary Files

Use fixed-width tail column and separate hashed dictionary:

