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]

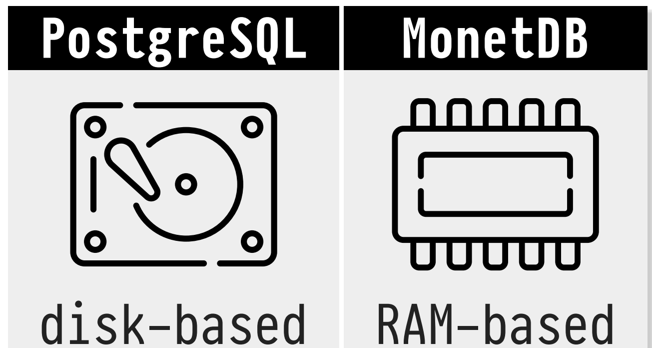
```
SELECT u.*              -- * ≡ access all columns of row u
FROM   unary AS u
```

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:**



- ⚠️ 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 values[2] 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.*                -- } Q₁ 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:

‹*opt*›	Effect
VERBOSE	higher level of detail
ANALYZE	**evaluate** the query, then produce explanation
FORMAT {TEXT|JSON|XML}	output format (default: TEXT)
⋮	⋮

⚠️ Without ANALYZE, ‹*Q*› is *not* evaluated ⇒ 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.

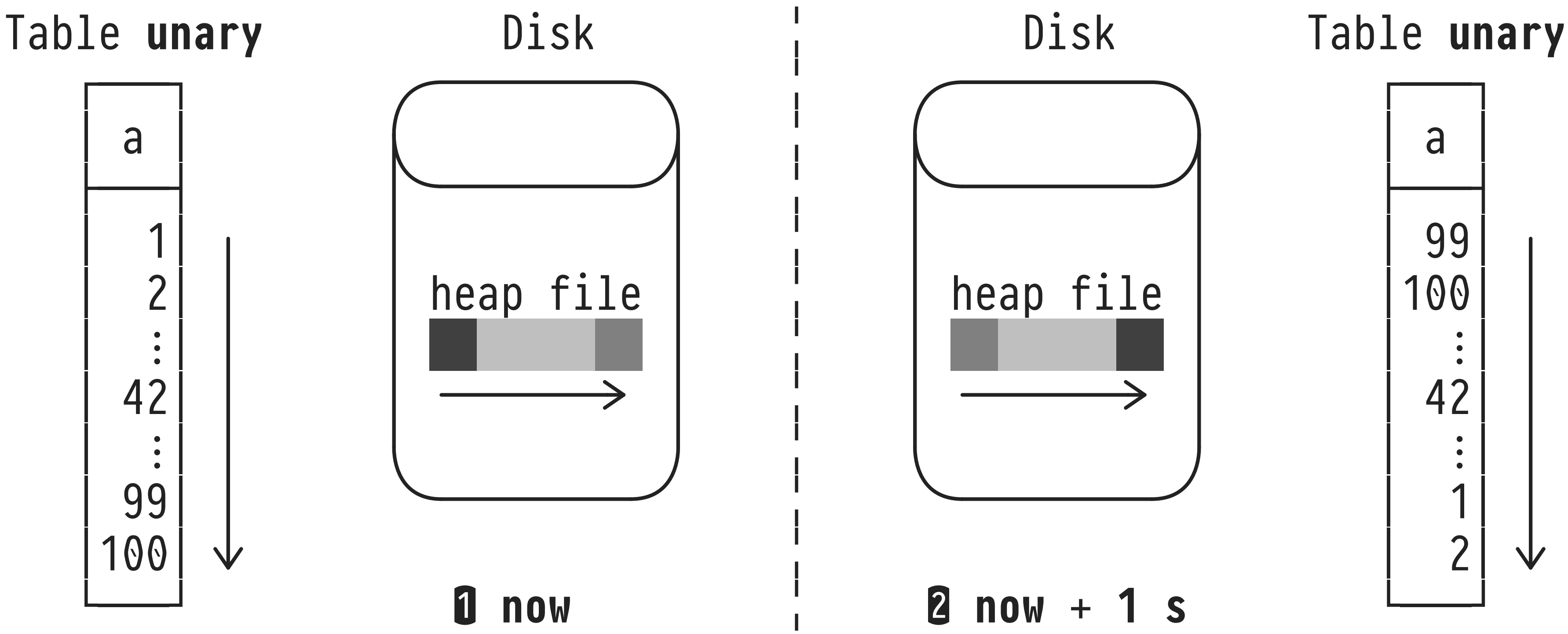
- Row insertion/deletion simple to implement and efficient, no complex file structure to maintain. 👍

- 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 ⇒ no guaranteed row order:



Heap File ≡ 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-14

- 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 $\mathrm{RID}(r_1) \neq \mathrm{RID}(r_2)$.
- $\mathrm{RID}(r)$ **encodes the location** of row r in its table's heap file. No sequential scan is required to access r.
- If r is updated, $\mathrm{RID}(r)$ 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**:

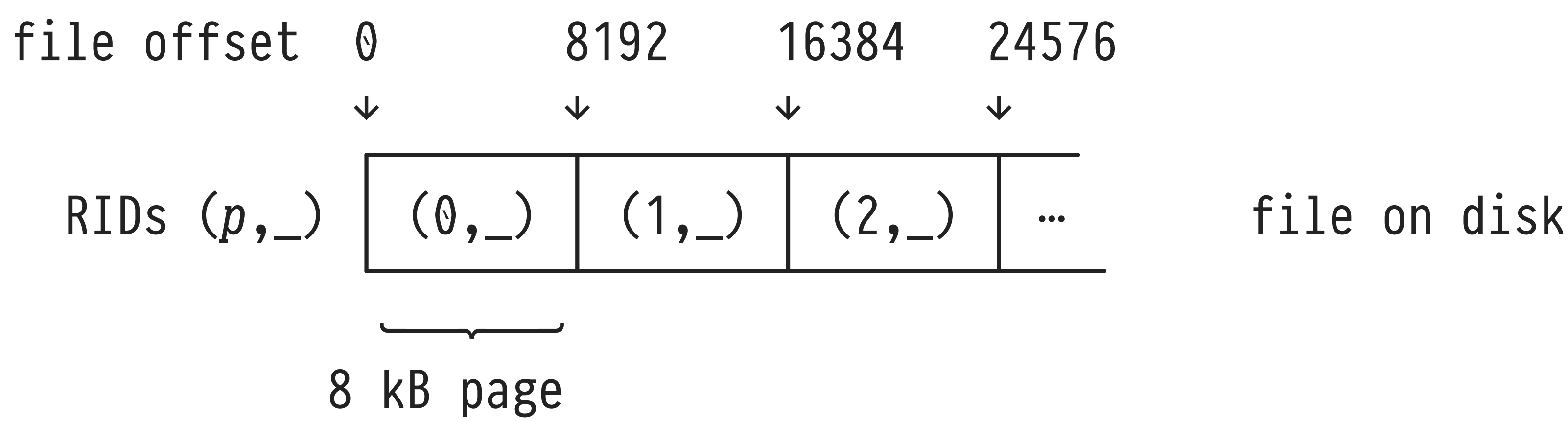
```
SELECT u.ctid, u.*
FROM   unary AS u;
```

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.

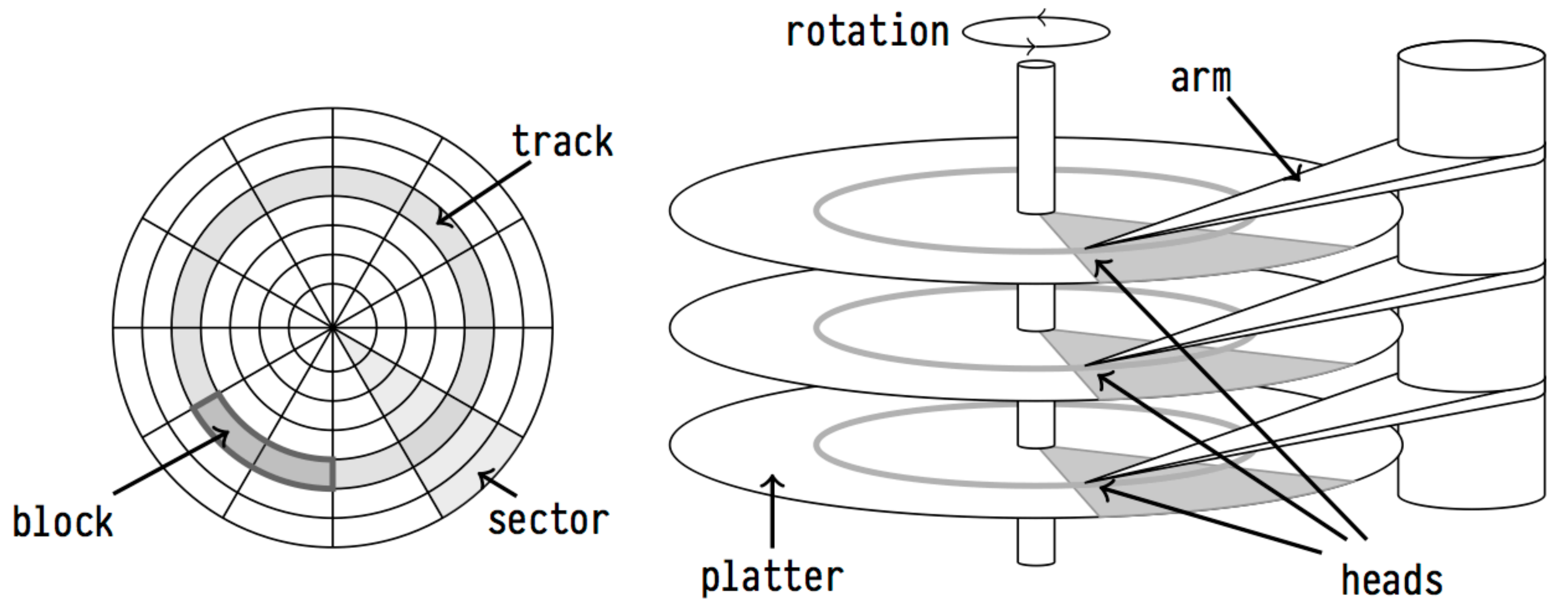
- This page-based access to heap files reflects the OS's mode of performing **disk input/output page-by-page.**
  - Terminology: DB🗨 **page** ≡ **block** 🗨OS

- ⚠️ 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:

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

- 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: $\frac{1}{2} \times (1/15000\ \text{min}^{-1}) = 2$ ms
  - Transfer time t_{tr}: 8 kB / (163 MB/s) = 0.0491 ms
  - $\Rightarrow t_s + t_r + t_{tr}$ = 3.4 ms + 2 ms + 0.05 ms = <u>5.45 ms</u>

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:
  - $1000 \times t = 5.45$ s 👎
- **Sequential access time** for 1000 adjacent blocks of 8 kB:
  - 512 kB per track: 1000 blocks will span 16 tracks
  - $\Rightarrow t_s + t_r + 1000 \times t_{tr} + 15 \times 0.2$ ms = <u>58.4 ms</u>

- Once we need to read more than 58.4 ms / 5450 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 ⇒ 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 AP2048R

- **Random access time** for 1000 blocks of 8 kB:
  - Transfer time t_{tr}: 128 kB / (7.0 GB/s) = 0.02 ms
  - 1000 × t_{tr} = <u>20 ms</u>
- **Sequential access time** for 1000 adjacent blocks of 8 kB:
  - $\lceil(1000 \times 8\text{ kB}) / 128\text{ kB}\rceil \times t_{tr}$ = <u>1.25 ms</u>

⚠️ 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 0.731123 secs

                  ≈ 5.6 GB/s
```

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

- **DRAM transfer speed test** (sequentially write 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: 1550931µs
```

$\underbrace{\texttt{time: 1550931µs}}_{\approx\ 41.2\ \mathrm{GB/s}}$

- 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 ⌛	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	≈ 100 ns	4 min
SSD I/O	50–150 µs	1.5–4 days
HDD I/O	1–10 ms	1–9 months
Internet roundtrip (DE ↔ 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

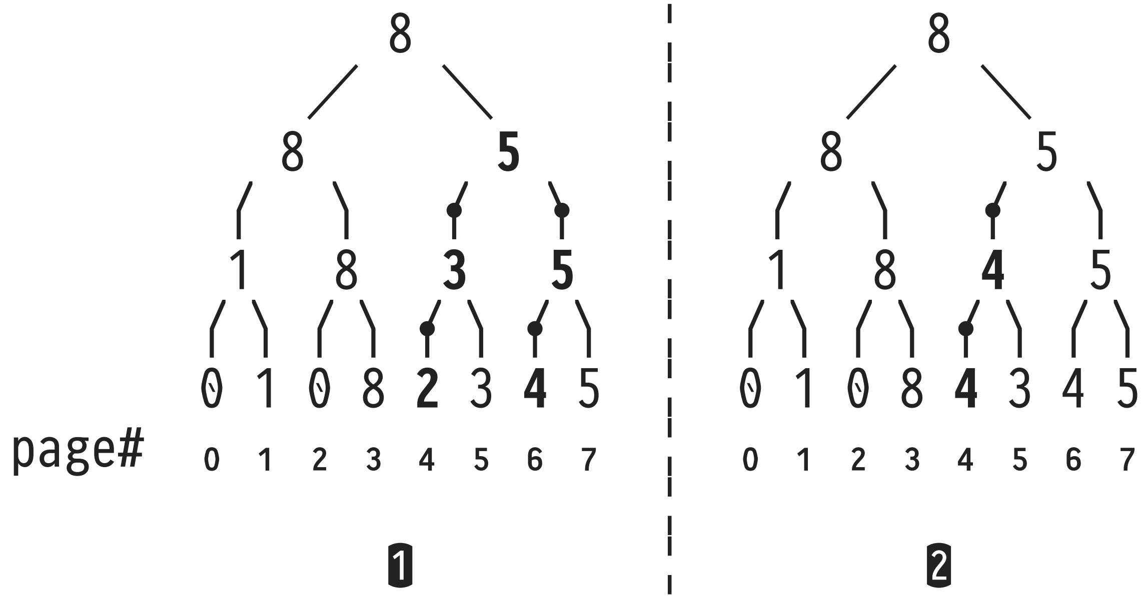
PostgreSQL maintains a **tree-shaped FSM** for each heap file:

```
                 8
               /   \
            8         5
          /   \     /   \
         1     8   3     5   ← maximal space available in subtree
        / \   / \ / \   / \
       0  1  0  8 2  3  4  5  ← space available on page #7
page#  0  1  2  3 4  5  6  7
```

- 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↑3↑5↓5↓4** along).

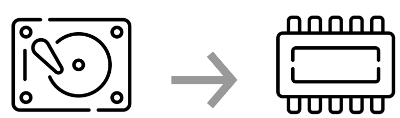
❷ Update page #4 to provide 4 available slots (traverses , updates **3** to max(3,4) = **4**, stops when max(4,5) = 5).

5 ¦ Q_1 — The Simplest SQL Probe Query

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

```
SELECT u.*           -- * ≡ 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.*                 --  } Q₁ 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 ≡ 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 ≡ 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
bit	1:bit	bit
bte, sht, <u>int</u>, lng, hge	42:τ	signed {8,16,32,64,128}-bit value
oid	42@0	32-bit row ID (≡ table offset)
<u>flt</u>, dbl	4.2	{32,64}-bit floating point
str	"42"	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 <u>underlined</u> type.

Columns (BATs)

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

densely ascending sequence of row IDs of type oid (row at offset *i* has oid *i*@0)

head	tail
0@0	42
1@0	42
2@0	0
3@0	-1
4@0	nil

scalars of type τ (≡ int) (BAT “payload”)

- **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 2@0) has been deleted (BAT unary reflects this update, thus no 2@0 in its tail):

algebra.projection(unary:bat[:oid] , a:bat[:int]) = result:bat[:int]

unary:bat[:oid]

head	tail
0@0	0@0
1@0	1@0
2@0	3@0
3@0	4@0
4@0	5@0
⋮	⋮
98@0	99@0

a:bat[:int]

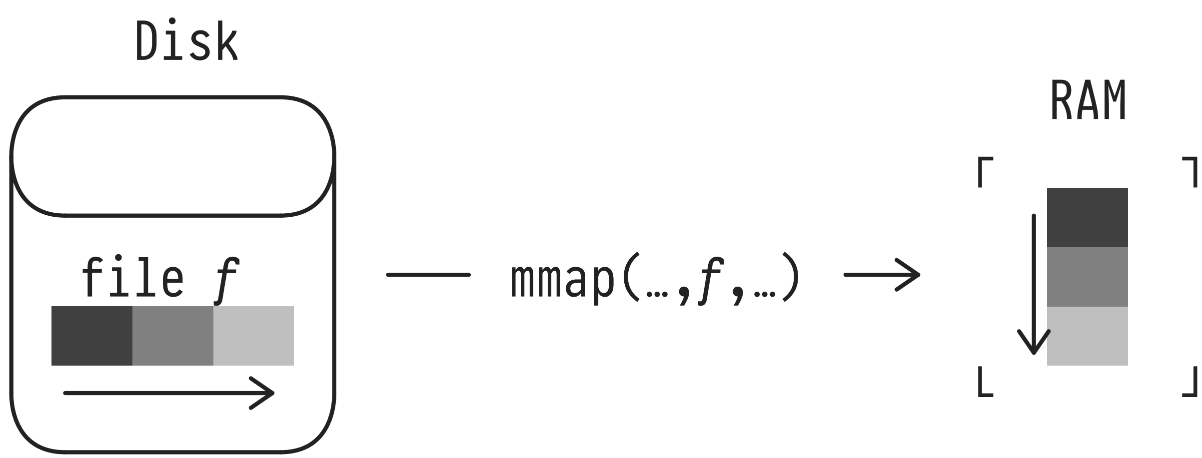
head	tail
0@0	1
1@0	2
2@0	3
3@0	4
4@0	5
⋮	⋮
98@0	99
99@0	100

result:bat[:int]

head	tail
0@0	1
1@0	2
2@0	4
3@0	5
4@0	6
⋮	⋮
98@0	100

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:

```
msql> a := sql.bind(sql, "sys", "unary", "a", …);
msql> (i1,i2) := bat.info(a);
msql> 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 τ ≡ `int`, width is 4 bytes).

- Runtime representation of **tail column as a C array**, say `a`. Access entry with oid i@0 simply via

$$\underbrace{\texttt{a[}i\texttt{ - hseqbase]}}_{\text{effective address: a + (}i\text{ - hseqbase) × size of }\tau}$$

- ⇒ 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: