Tabular Database Systems

③

Reading Data at the Speed of ~~Light~~Memory

Summer 2025

Torsten Grust
Universität Tübingen, Germany

1 ¦ DBMSs Exploit Modern Computer Architecture[1]

The internals of DBMSs are carefully engineered to exploit the performance features of modern computer architecture:

- **CPUs** (and their multi-threading capabilities),
- **main memory** (DRAM) and its hierarchy of caches, and
- **secondary memory** (mass storage on SSDs / rotating disks).

Since database queries typically process millions of rows, the effect of even the tiniest performance tweaks/tricks played in the innermost loops of DBMS routines multiply.

Goal: Understand the performance spectrum for a simple “query.”

quick one-liner shell script	⟷	hand-written C program

[1] This chapter adapts and expands on a discussion found in Thomas Neumann's lecture “Foundations in Data Engineering” (TUM).

A Simple Benchmark Query

1. Read the CSV file for TPC-H table lineitem (scale factor SF = 1: 6+ million rows × 16 columns ≈ 720 MB of data) and
2. sum the quantity integer values in the 5th column:

lineitem.csv

```
1|155190|7706|1|17|21168.23|0.04|0.02|N|O|1996-03-13|…␤
1|67310|7311|2|36|45983.16|0.09|0.06|N|O|1996-04-12|…␤
1|63700|3701|3|8|13309.60|0.10|0.02|N|O|1996-01-29|…␤
 ⋮
 [6+ million more rows]
```

- Real TPC-H benchmark data and its queries are more complex but this suffices to demonstrate the effect of code optimizations.
- We will implement the query in awk, Python, C, and SQL.

2 ┆ Performance Limits

What is the fastest query time we can hope for in principle?

- Torsten's current computer (MacBook Pro M2 Max, 2023):

Memory (❷ Secondary/❶ Primary)	Read Bandwidth	⏱ Query Time
(Ethernet)	2.5 GB/s	0.28s
❷ External USB-C SSD (2 TB)	800 MB/s	0.90s
❷ NVMe SSD (2 TB)	5 GB/s	0.14s
❶ DRAM (64 GB)	21 GB/s	0.03s

- **NB.**
  - **Query Time** based on I/O speed, ignores CPU cost (less significant for secondary mem, very significant for DRAM).
  - ⟹ We will *not* reach these limits. Let us try to get close.

- Understand how DuckDB achieves 0.002s for our query. 🦆

3 ┆ Sum of Quantities ❶ — awk

- awk: interpreted text processing language popular on UNIX™.
  - Read input line by line, match each line against (regular) patterns in order, on a match invoke action {…} on line.

```
awk -F '|' \                            ┆  delimiter in CSV is |           #012
    'BEGIN { sum = 0 }                  ┆  match first line, reset sum
           { sum = sum + $5 }           ┆  match any line, sum 5th column
    END    { print sum }' \             ┆  match last line, output sum
    lineitem.csv                        ┆  input file
```

- Invoke the awk script, measure elapsed wall-clock time (s) ⏱:

```
$ time ./sum-quantity.awk lineitem.csv
153078795
        1.58 real         1.43 user         0.14 sys
```

Sum of Quantities ➊ — awk

- ⏱ Query time on Torsten's computer: ≈1.6s:

Output of time	Measurement
real	elapsed wall-clock time ⏱ (≈ user+sys+Δ)
user	time spent in application/library code
sys	time used by OS (system calls)

- The interpreted awk script cannot even keep up with secondary memory (SSD) read bandwidth:[2]
  - awk processes the CSV file with a throughput of 471 MB/s.
  - awk is **CPU-bound** for this query.
  - ⇒ The OS file system cache in DRAM does not help.

[2] Execution speed of awk variants vary greatly. We are using GNU awk (gawk) here. macOS awk is about 10 times slower for our benchmark query.

4 ¦ Sum of Quantities ❷ — Python

- Python: established scripting/programming language, mainly follows an imperative paradigm.
  - Translates to bytecode, then interprets.

```
sum = 0                                          ¦ reset sum            #013
                                                 ¦
with open(sys.argv[1], 'r') as file:             ¦ open file (reading)
    for line in file:                            ¦ read line by line
        sum = sum + int(line.split('|')[4])      ¦ | extract 5th col,
                                                 ¦ ⌊ cast to int, add
print(sum)                                       ¦ output
```

- ⏱ Query time on Torsten's computer: ≈2.75s.
  - Python processes the CSV file with a throughput of 275 MB/s.
  - Python is **CPU-bound** for this query.

5 ¦ Sum of Quantities ❸ — C

- Switch to compiled programming language C. Start out with a direct transcription of the Python code:
  - Read CSV file line by line using getline(3).[3]
  - Use strchr(3) to search for delimiter '|' in line (4×).
  - Convert string (up to next '|') into integer using atoi(3).

#014

```c
while (getline(&line, &linecap, file) > 0) {
  delim = line;

  for (column = 1; column < 5; column++) {
    delim = strchr(delim, '|');
    delim++;
  }

  sum = sum + atoi(delim);
}
```

[3] The (3) suffix in getline(3) refers to Section 3 of the UNIX™ manual which describes the function in the C Standard Library.

Sum of Quantities ③ — C

- ⏱ Query time on Torsten's computer: ≈0.5s.
  - C processes the CSV file with a throughput of 1.5 GB/s.
  - Yet, C still is **CPU-bound** for this query. Getting closer to SSD read bandwidth, though.

- But where does time go?
  - **Profile** the running program, identify code portions consuming the most CPU time (UNIX™: perf, macOS: Instruments).

C library routine	% of CPU time
(all other C code)	*(16%)*
getdelim (≡ getline)	58%
atoi	14%
memchr (≡ strchr)	12%

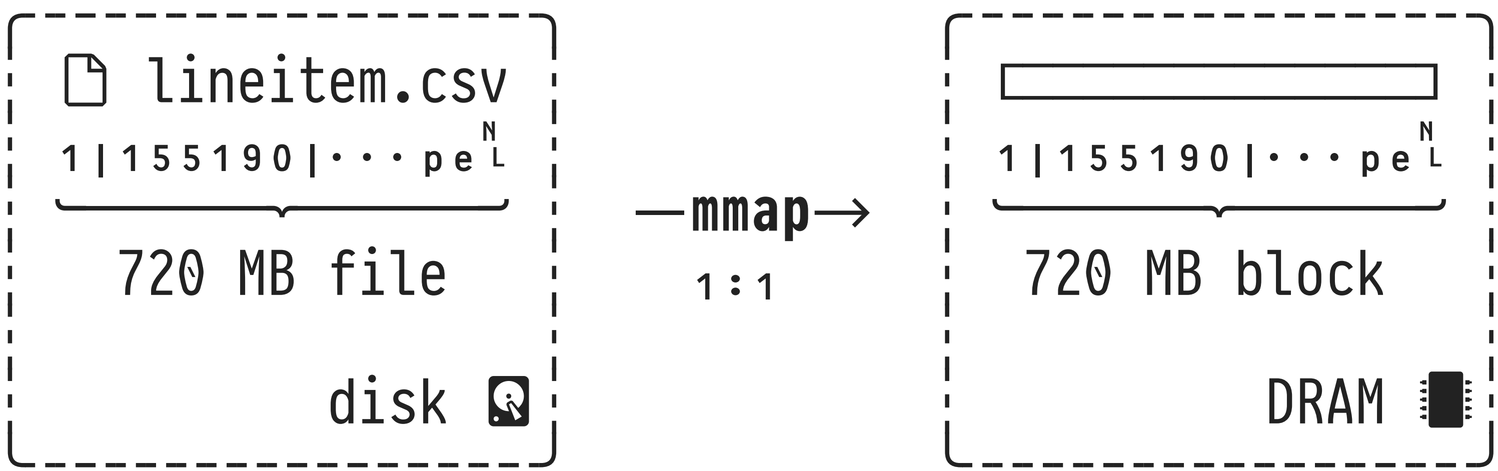
- Reading the CSV file line by line is too slow.
  - 💡 Read entire file at once, impose line structure ourselves.

6 ¦ Sum of Quantities ❹ — C with mmap(2)

Aim to *read the CSV file* into DRAM using a *single OS system call*:

- mmap(2) returns a pointer data to a contiguous block of memory that holds the contents of an entire disk file:

```
data = (char*)mmap(NULL, size, PROT_READ, MAP_SHARED, file, 0);
```



  - If file size exceeds available DRAM, OS pages in file contents on demand.

Sum of Quantities ❹ — C with mmap(2)

- Cannot use strchr() to find '|' (next column) ❶.
- No getline(): need to locate ␤ ('\n') ❷ on our own now:

#015

`column = 1;`	start in column 1
`while (data < end) {`	scan memory block, byte by byte
`  switch (*data) {`	
`    case '|' : column++; break;`	❶ found |: next column begins
`    case '\n': …`	error: line has too few columns
`  }`	
`  data++;`	proceed through memory block
`  if (column < 5)`	reached column 5 already?
`    continue;`	no, keep scanning
`  sum = sum + atoi(data);`	convert to int (up to |,␤), add
`  column = 1;`	next line starts with column 1
`  while (*data++ != '\n');`	❷ skip rest of line until ␤
`}`	

Sum of Quantities ❹ — C with mmap(2)

- ⏱ Query time on Torsten's computer:
  - Once the OS caches the file in DRAM, mmap() directly maps the file system cache into the program's address space.

OS file system cache	Query time ⏱	Throughput
cold	1.6s	471 MB/s
warm	0.42s	1.8 GB/s

- **NB.** The C program's profile has changed:

C code fragment/function	% of CPU time
(all other C code)	*(25.5%)*
atoi	21.4%
while (*data++ ≠ '\n')	👎 53.1%

- Search for ␤ ❷ dominates. 💡 Use strchr(data, '\n') instead.
  - ⏱ Query time: 0.27s (throughput 2.8 GB/s).
  - How can strchr() be so efficient?

#015

7 ┆ Sum of Quantities ❺ — C with mmap(2) + Block-Wise ␤ Search

Avoid byte-wise search for ␤. Modern CPUs operate on 64-bit words.

- 💡 Load **8 bytes (64 bits) at a time,** search for ␤ ('\n' = 0x0a) in this block. Advance pointer data in strides of 8 bytes.

```
/* HAS_NL(x): find ␤ in 64 bit-wide character block x */
#define HAS_ZERO(x) (((x) - 0x0101010101010101) &
                     ~(x) & 0x8080808080808080)
#define HAS_NL(x)   (HAS_ZERO(x ^ 0x0a0a0a0a0a0a0a0a))

    HAS_NL(0x0a42440a6b637544)  ≡  "Duck␤DB␤" reversed ⚠️
  =        0x8000008000000000      (ARM CPUs: little endian)
             ↑     ↑
 high bit set: found ␤ at offsets 4 and 7
```

- How do C macros HAS_ZERO() and HAS_NL() work?[4] #016

[4] See the Stanford Bit Twiddling Hacks (section “Determine if a word has a byte equal to n”) for a discussion of these C macros.

Sum of Quantities ❺ — C with mmap(2) + Block-Wise ␤ Search

#017

```
while (data < end) {
  ⋮
  sum = sum + atoi(data);

  column = 1;

  block = (uint64_t*)data;
  while (!(nl = HAS_NL(*block)))
    block++;  /* advance by one 8-byte-block (64 bits) */

  data = (char*)block;
  if (nl & 0x0000000000000080ULL) { data += 1; continue; }
  if (nl & 0x0000000000008000ULL) { data += 2; continue; }
  if (nl & 0x0000000000800000ULL) { data += 3; continue; }
  if (nl & 0x0000000080000000ULL) { data += 4; continue; }
  if (nl & 0x0000008000000000ULL) { data += 5; continue; }
  if (nl & 0x0000800000000000ULL) { data += 6; continue; }
  if (nl & 0x0080000000000000ULL) { data += 7; continue; }
  data += 8;
}
```

Sum of Quantities ❺ — C with mmap(2) + Block-Wise ␊ Search

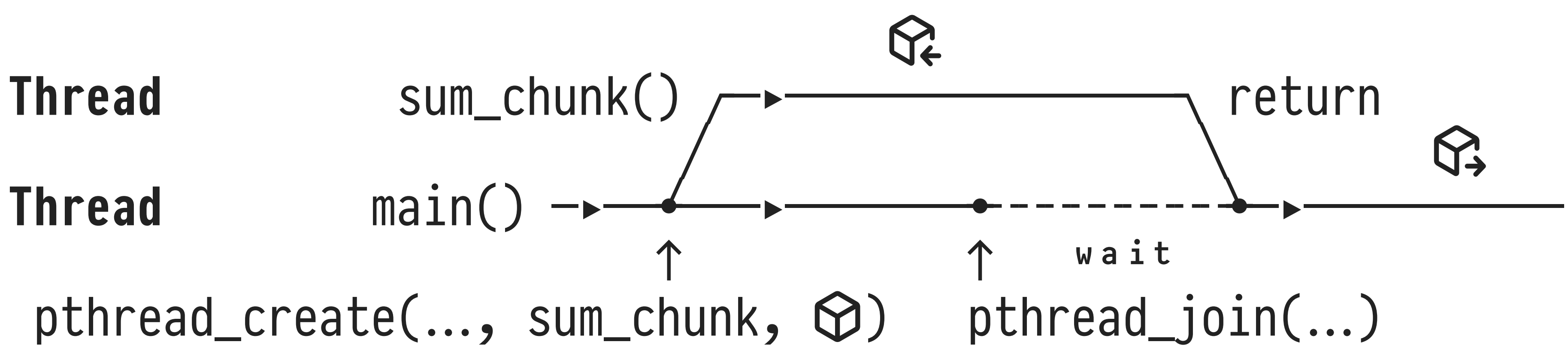
- ⏱ Query time on Torsten's computer (warm cache): ≈0.28s.
  - C with mmap() and block-wise search for ␊ processes the CSV file with a throughput of 2.8 GB/s.
  - We match the performance of the built-in strchr() function.

- Our code definitely got more complex and fiddly.
  - Slowly getting an impression of how much careful performance engineering is required to build a DBMS kernel.

8 ┊ Sum of Quantities ❻ — C with mmap(2) + Threads

CPUs feature **multiple cores** that can execute code in parallel. The CPU (M2 Max) in Torsten's computer features *T* = 12 such cores.

- 💡 Split CSV file at ␤ boundaries into *T* **partitions (chunks).**
- Spawn *T* **parallel threads,** each summing column 5 in one partition. Add thread-local partial sums to obtain overall sum.



- Threads use shared memory area to exchange data (*e.g.*, thread ID, pointers to chunk start/end, thread-local sum).

Sum of Quantities ❻ — C with mmap(2) + Threads

- C declaration of shared memory area 📦:

```
struct chunk {
  pthread_t thread;  /* thread ID */
  char      *data;   /* pointers to chunk start/end */
  char      *end;
  int       sum;     /* sum of partition */
};
typedef struct chunk chunk_t;
```

- Code for a thread (sums a chunk):

#018

```
void *sum_chunk(void *arg)
{
  chunk_t *chunk = (chunk_t*) arg;  /* this is the 📦 */

  char *data = chunk->data;  /* extract relevant arguments */
  char *end  = chunk->end;

  ⋮        /* sum chunk, just like sum-quantity-mmap.c did */

  chunk->sum = sum;           /* put return value into 📦 */
  return NULL;                /* NULL ≡ 👍 */
}
```

Sum of Quantities ❻ — C with mmap(2) + Threads

- ⏱ Query time on Torsten's computer (T = 12 threads spawned, warm cache): ≈0.04s.
  - Jointly, the threads process the CSV file with a throughput of 18.8 GB/s. This approaches DRAM read bandwidth.

- Profile shows that each `sum_chunk()` + `main()` use about the same chunk summing time. 👍
  - Creating chunk sizes (and thus thread-local work) of roughly equal size has worked well.
  - Wait time after `pthread_join(…)` expected to be small.

Sum of Quantities — Summary so Far

Query Implementation	Query Time ⏱	Throughput
awk	1.60s	471 MB/s
Python	2.75s	275 MB/s
C with getline	0.50s	1.5 GB/s
C with mmap	0.27s	2.8 GB/s
C with mmap + block-wise scan	0.28s	2.8 GB/s
C with mmap + 12 threads	0.04s	18.8 GB/s

- Implementation language and techniques matter **a lot.**
  - 50+ years after the inception of the relational model, database query optimization is a lively field of research.

- Even your laptop can read and process multiple GB/s.
  - Here we saturate everything (but DRAM).
  - Do we always need “big iron” or server clusters? (🦆: “*No!*”)

SQL aggregates[5] condense a bag of rows into a *single* value:

vehicles

vehicle	kind	seats	wheels?
	car	5	true
	SUV	3	true
	bus	42	true
	bus	7	true
	bike	1	true
	tank	▢	false
	cabrio	2	true

- Most aggregates ignore (= skip) NULL (▢) values.
  - An optional **FILTER** clause can control value inclusion.
- Order-aware aggregates use clause **ORDER BY** to be deterministic:

  list(vehicle **ORDER BY** seats)

bool_and("wheels?") ≡ false
max(seats) ≡ 42
arg_max(kind, seats) ≡ 'bus'
count(vehicle) ≡ 7

[5] DuckDB's SQL dialect features an extensive list of built-in aggregate functions.

Interlude: SQL Aggregate Functions

- Let us use annotations to explain SQL constructs (here: query clause **row cardinality**, ❶❷❸: clause processing order[6]):

```
SELECT expr,…,expr    ┤ ❸ m
FROM   t              ┤ ❶ n (= |t|, cardinality of t)
WHERE  p              ┤ ❷ m (⩽ n)
                      └── # rows returned by query clause
```

- SQL aggregates reduce row cardinality to 1:

```
SELECT agg,…,agg      ┤ ❸ 1
FROM   t              ┤ ❶ n (= |t|)
WHERE  p              ┤ ❷ m (⩽ n)
                      └── # rows
```

  - ⇒ **SELECT** clause *cannot mix* scalar *expr* and aggregates *agg*.

#019

[6] SQL clause processing order ≠ SQL syntactic order. DuckDB implements a “friendly SQL dialect” to partly rectify this (e.g., allowing FROM-SELECT queries). We'll use such DuckDB-specific features sparingly.

10 ┆ Sum of Quantities ❼ — SQL

Aggregate function sum() is what we need to formulate a SQL variant of the benchmark query over the CSV file:[7]

```
#020
D .timer on
D SELECT sum(l_quantity)
  FROM   read_csv('lineitem.csv',
                  header = false,
                  names = [ ..., 'l_quantity', ... ])
┌─────────────────┐
│ sum(l_quantity) │
├─────────────────┤
│    153078795    │
└─────────────────┘
                    ⏱     used CPU time
                   ↙            ↓
Run Time (s): real 0.448 user 3.322090 sys 0.133819
```

- ⏱ Query time on Torsten's computer: ~0.45s.
  - Overall CPU time is >3s: DuckDB uses **parallel processing.**

[7] Command .timer on instructs the DuckDB CLI to report query times for all subsequent SQL commands. The DuckDB documentation contains a complete list of such commands.

Interlude: SQL EXPLAIN

SQL DBMSs typically implement an **EXPLAIN facility**[8] that exposes details of the system's **query evaluation plans:**

- Supports query and performance debugging.
- **Shows order of query operations** explicitly, making effects of query optimization visible (e.g., projection pushdown).
- **Measures query behavior during execution,** annotates plan with:
  - breakdown of how query operations use time,
  - # of rows processed,
  - size of intermediate results (in bytes), …

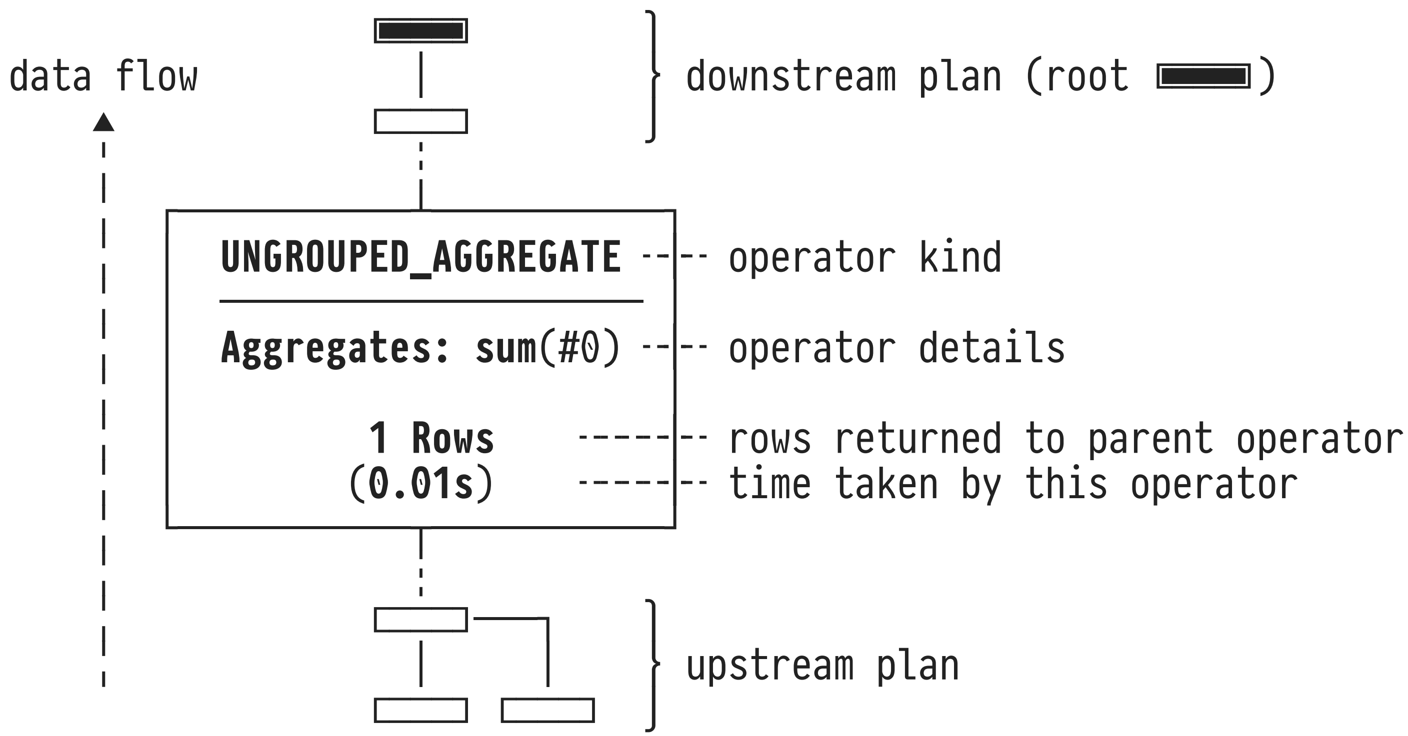
EXPLAIN *query*;	**EXPLAIN ANALYZE** *query*;
Do *not* run query. Show query plan and estimated row count.	*Actually run* query. Measure times/rows, annotate plan.

[8] DuckDB's EXPLAIN facililty is extensive. Can see even more plan details via EXPLAIN (FORMAT json) *query*.

Interlude: SQL EXPLAIN

Query evaluation plans visualize bottom-up **data flow:**[9]

- Data sources (e.g., TABLE_SCAN) reside at the leaves.
- Query result is produced by the root (top-most operator).



[9] U Tübingen has developed the DuckDB Execution Plan Visualizer which can render and inspect plans in the web browser (use EXPLAIN (ANALYZE, FORMAT json) *query* to produce plans that the visualizer can render).

Sum of Quantities ⑦ — SQL

```
D SELECT SUM(l_quantity)
  FROM   lineitem;
┌─────────────────┐
│ sum(l_quantity) │
├─────────────────┤
│    153078795    │
└─────────────────┘
Run Time (s): real 0.002 user 0.007288 sys 0.000294
```

#020

A ⏱ query time of 0.002s for the benchmark indicates that

- the DBMS uses multiple cores (threads) to evaluate SQL queries,
- the query plan does *not* scan—or skip over—all 16 columns of table `lineitem` (projection pushdown focuses on `l_quantity`),
- column values are *not* stored as text and thus do *not* have to be parsed again and again, and that
- the data for table `lineitem` does reside in DRAM (not in secondary storage).