Tabular Database Systems

⑦

More SQL (Subqueries + Embedded SQL)

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1 ¦ Compositionality (in Programming Languages)

> “*The meaning of a complex program is determined by the meanings of its constituent programs.*”
>
> —Principle of **Compositionality**

The following two (Python) programs are equivalent:

1. Uses literal 21:

   ```
   print(2 * 21)
   ```

2. Computes value 21:[1]

   ```
   def twenty_one():
     return (12 + 12*12 + 20) // (2*4) - 1
   print(2 * twenty_one())
   ```

[1] Based on a variation of a popular limerick: “*A dozen, a gross, and a score / divided by two times the four / decreased just by one / it gives twenty-one / (which is three times seven, no more).*”

2 ¦ SQL: Subqueries (Queries Inside Queries)

SQL queries may contain nested **subqueries** enclosed in (···).

1. **Scalar subquery:** Where a query accepts a scalar x, x may be replaced by a subquery (q) that returns a single-cell table:

   #036

   q evaluates to $\begin{array}{|c|}\hline \\ \hline x \\ \hline\end{array} \equiv x$

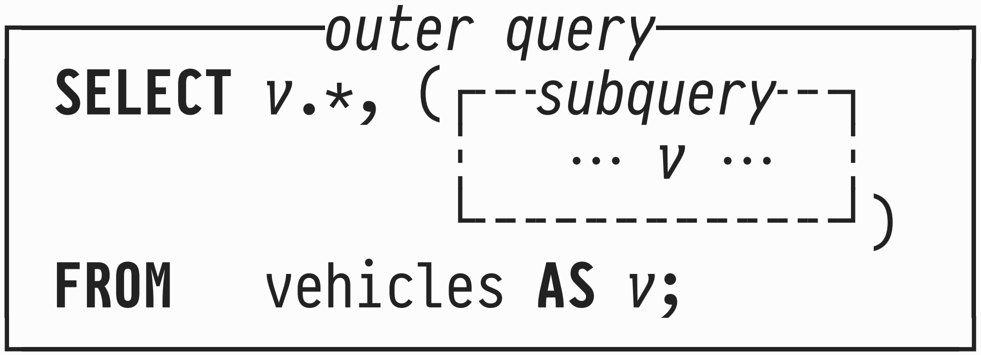
   NB. A scalar subquery q needs to return…

   ○ … a **single-column** table (column name irrelevant). Otherwise: error at query *compile time*. 👎

   ○ … **at most one row.**
   0 rows ≡ NULL, ⩾ 2 rows: error at query *run time*. 👎 👎

Subqueries Can Relate to Outer Queries: Correlation

- Row variables bound inside a subquery do not “escape”: their scope is local to the subquery (see var v1 in 🗎 #036).
- **But:** Subqueries may relate to row variables bound in the enclosing/outer query:



```
SELECT v.*, (… v …)
FROM   vehicles AS v;
```

The subquery can access the current row bound to *v* ✓

  - The subquery in ⬚ *cannot* be evaluated in isolation: depends on outer query □ to provide a binding for row variable *v*.
  - DB jargon: “The subquery is **correlated** (since it uses *v*).”[2]

[2] PL jargon: “Variable *v occurs free* in the subquery (but bound in the outer query).”

Correlated Subqueries ≡ Nested Loops? 🤓

NB. Due to correlation, the subquery *q* in ⬚ below acts like a function of type int → text (*q*(pid) maps vehicle to driver name):

```
-- Query Q: Pair vehicles with their driver (if any)
                ┌---------- q -----------┐
SELECT v.*, (   ¦ SELECT p.name          ¦
                ¦ FROM   peeps AS p      ¦
                ¦ WHERE  p.pid = v.pid   ¦) AS driver
                └------------------------┘
FROM   vehicles AS v;
```

- A “*nested loops*” evaluation strategy for *Q*:

```
for each v ∈ vehicles
│ driver ← q(v.pid)                         }  evaluated
└ result ← result ⊎ (v.*, driver)           }  |vehicles| times
```

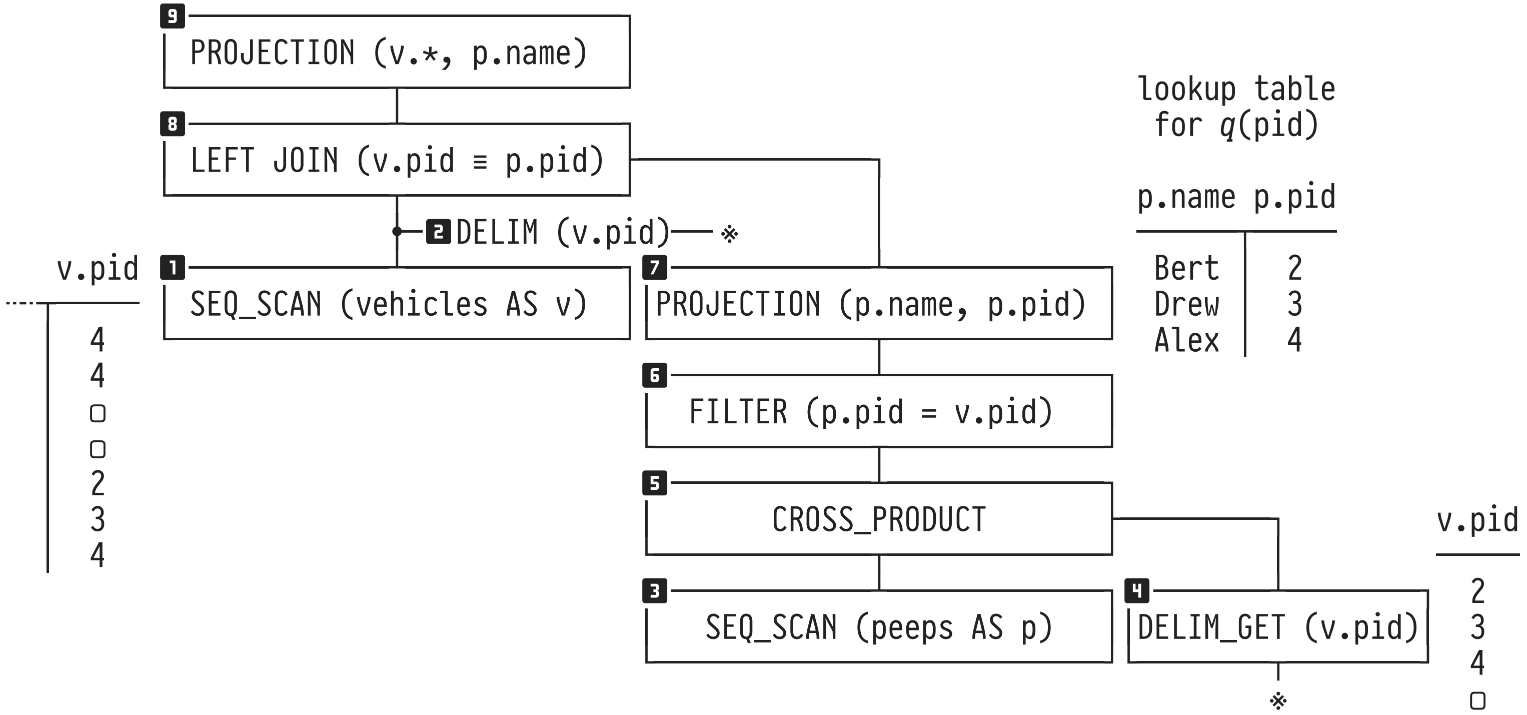
  - If vehicles.pid is not unique, this will evaluate subquery *q*(pid) repeatedly with identical arguments. 👎

DuckDB's Query Optimizer Removes Correlation

Query optimization **decorrelates** the subquery (plan for *Q*):[3]

1. ❷,❹: Compute the set of *distinct arguments* for subquery *q*.
2. ❸–❼: Build a lookup table for “function” *q*(pid).
3. ❽: For each vehicle v, perform a lookup to evaluate *q*(v.pid).

#038



❾ PROJECTION (v.*, p.name)

❽ LEFT JOIN (v.pid ≡ p.pid)

❷ DELIM (v.pid) ※

❶ SEQ_SCAN (vehicles AS v)

❼ PROJECTION (p.name, p.pid)

❻ FILTER (p.pid = v.pid)

❺ CROSS_PRODUCT

❸ SEQ_SCAN (peeps AS p)

❹ DELIM_GET (v.pid) ※

v.pid
4
4
□
□
2
3
4

lookup table for *q*(pid)

p.name	p.pid
Bert	2
Drew	3
Alex	4

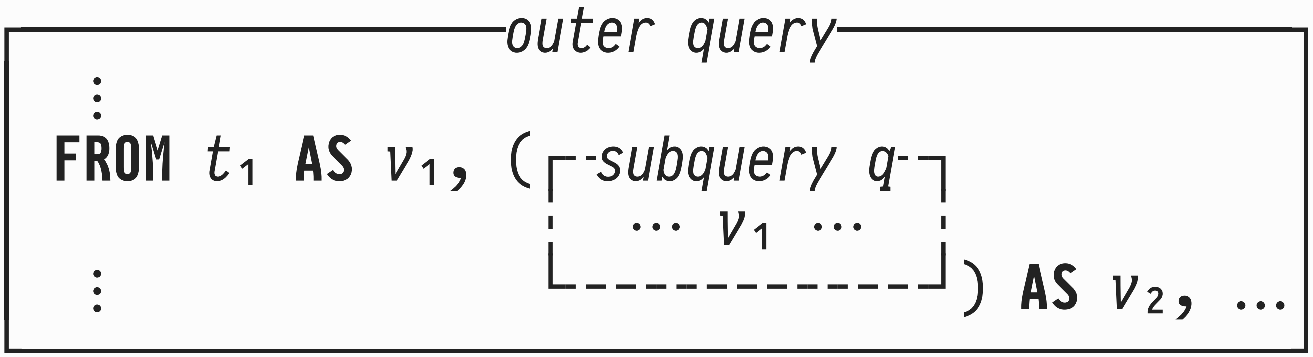
v.pid
2
3
4
□

[3] Plan has been simplified. Use `PRAGMA explain_output = 'all';` to see the above Unoptimized Logical Plan. In these plans, the `LEFT (OUTER) JOIN/DELIM` pair is represented as `DELIM_JOIN`.

Scalar vs. Table-Valued Subqueries

SQL interprets subqueries (q) based on their *usage context*:

1. **Scalar:** q returns single-cell table □ that holds one scalar.
2. **Table-valued** (e.g., in **FROM** clause): q returns any table ▦:



outer query

⋮

FROM t_1 **AS** v_1, (*subquery q* … v_1 …) **AS** v_2, …

⋮

#039

Subquery q in table-valued context

- Correlation: row variable v_1 may occur free[4] in subquery q. In this case, ⬚ acts like a table-valued function $q(v_1)$. (DBMS will decorrelate to avoid $|t_1|$ evaluations of q).
- If q is uncorrelated: ⬚ acts like a (computed) table.

[4] Some SQL implementations require the keyword **LATERAL** (“sideways”) to allow q to refer to v_1 (and thus depend on the evaluation of t_1): **FROM** t_1 AS v_1, **LATERAL** (q) AS v_2, …. (DuckDB infers whether **LATERAL** is required.)

SQL uses table-valued subqueries (*q*) to compactly formulate **existentially or universally quantified comparisons:**[5]

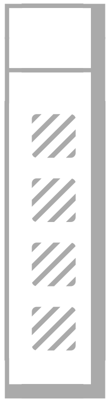
EXISTS (*q*) does *q* return ⩾ 1 rows (is *q* non-empty)?
NOT EXISTS (*q*) does *q* return no row at all (is *q* empty)?

---

expr = **ANY** (*q*) does *expr* equal any value in ▨?
expr = **ALL** (*q*) does *expr* equal all values in ▨?

also: <> < <= >= >

q evaluates to a single-column table:



#040 + #041

[5] The SQL keywords **ANY** and **SOME** are synonyms. Syntactic sugar: *expr* = **ANY** (*q*) is equivalent to *expr* **IN** (*q*) (think of ∊ or "*is element **in***").

4 ¦ Embedding SQL in Python Programs

- The DuckDB CLI >_ enables interactive experimentation and the execution of ad-hoc/one-short querying. Definitely valuable.

- **Database-supported applications** embed SQL statements directly in the program source instead:
  - Programs can connect to/disconnect from selected databases.
  - Program flow controls which/how often SQL queries execute.
    - Queries may be constructed/parameterized on the fly.
  - Query results may be consumed by the program:
    - Map SQL data types to programming language's type system.
    - Receive *all* rows at once? *Iterate* over result row-by-row?

Q: Which parts of the app logic are performed by the DBMS?
Which parts are implemented by program code? ¯\_(ツ)_/¯

Here ● ↔ 🐍: Use DuckDB's API to **embed SQL queries into Python.**

Embdedding SQL in Python: General Setup

Application code mixes SQL query strings 🛢 with program code 🐍:

```
import duckdb   # requires: pip install duckdb                          #042
 ⋮
 # ❶ connect to database (in ▮ or on 🖴)
 with duckdb.connect(database) as con:
 │  # ❷ construct SQL query, submit to DuckDB
 │  rel = con.sql("""
 │    ┌------------🛢  ⎫ • embed SQL query as literal multi-line
 │    ¦  SQL query  ¦  ⎬   string between """…"""
 │    └-------------┘  ⎭ • sent to DuckDB (not executed yet)
 │    """)
 │  # ❸ DuckDB executes query, retrieve all result rows
 │  result = rel.fetchall()
 │  # ❹ iterate over list of rows
 │  for row in result:
 │  │ ┌------------🐍  ⎫ • Python code operates on a result row
 │  │ ¦    code     ¦  ⎬   represented as a tuple (…,…,…)
 └  └ └-------------┘  ⎭ • DuckDB not involved
```

DuckDB's Python DB API (Overview[6])

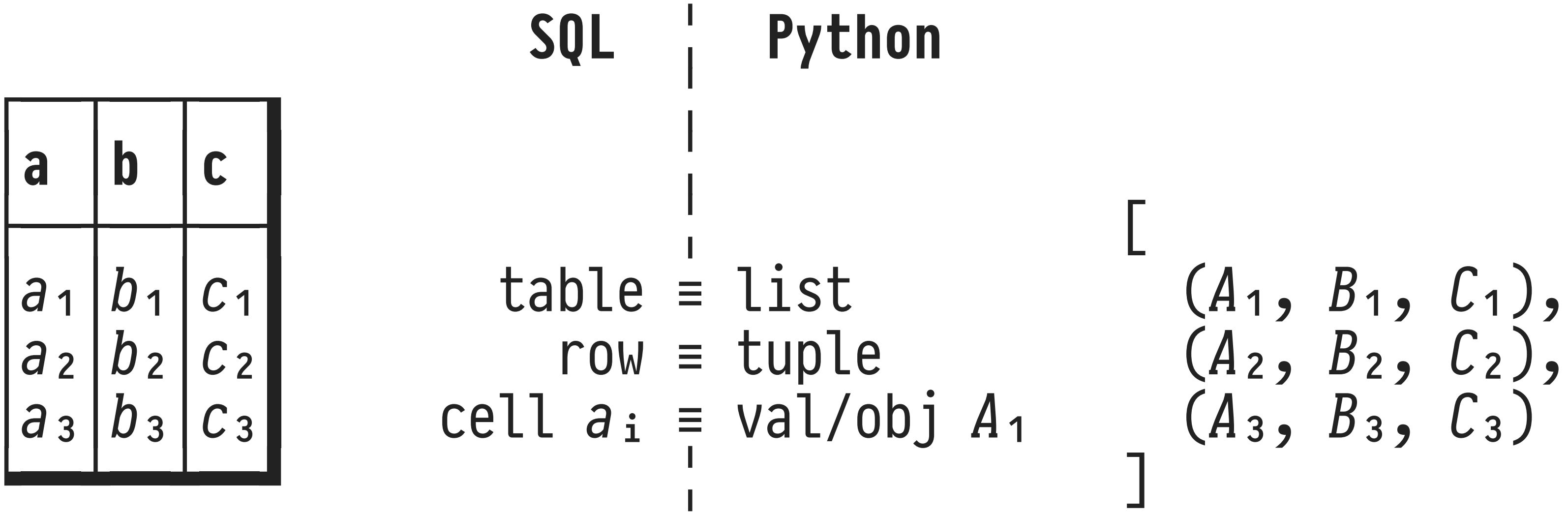
DuckDB Python API Call	Python Result
❶ con = duckdb.connect(":memory:")	DuckDB connection object
con = duckdb.connect(*database file*)	
❷ rel = con.sql(*sql*)	effect on DB or DuckDB relation object[7]
rel = con.sql(*sql*, params = […])	*sql* may contain parameters $1, $2, …
❸ rel.fetchall()	list of all result tuples in table rel
rel.fetchmany(*n*)	list of next *n* result tuples
rel.fetchone()	next result tuple or None
rel.columns	list of column names for table rel
rel.types	list of column types
rel.show()	None + printed table output (▦)

[6] DuckDB's Python DB API (documentation)

[7] If *sql* is a **SELECT** query, returns a DuckDB relation object rel. Otherwise, applies the effect of the DDL or DML statement to the database represented by DuckDB connection object con.

How SQL Data Maps to Python Values/Objects

The type systems of SQL and Python—indeed most PLs—differ.[8] SQL data (tables, rows, cell values) needs to be **mapped** to Python values and objects:



SQL | **Python**

a	b	c
a_1	b_1	c_1
a_2	b_2	c_2
a_3	b_3	c_3

table ≡ list

row ≡ tuple

cell a_i ≡ val/obj A_1

$$\begin{array}{l} [\\ \quad (A_1,\ B_1,\ C_1), \\ \quad (A_2,\ B_2,\ C_2), \\ \quad (A_3,\ B_3,\ C_3) \\ ] \end{array}$$

Data and Type Mapping in DuckDB's Python DB API

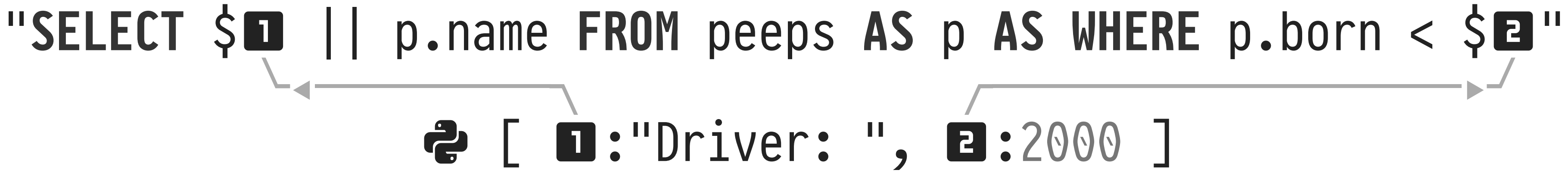
- DuckDB implements a best-effort mapping from cell values a_i (of types int, text, …) to Python's value and objects A_i. #043

[8] This tension—not only regarding types—between SQL as a query language and programming languages (PLs) is known as the **impedance mismatch**.

Constructing SQL Queries at Program Run Time

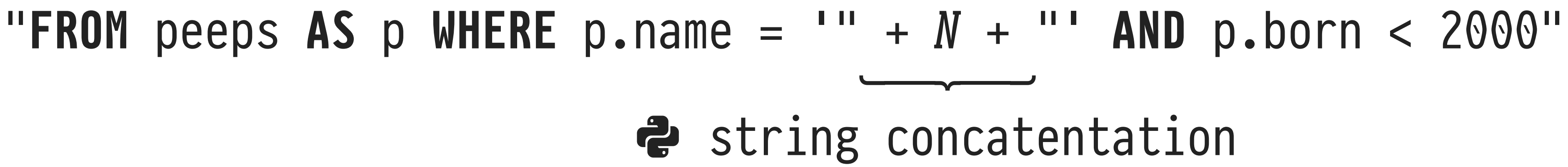
Embedded SQL queries are regular strings: **programs can construct queries at run time** by interpolation 👍 or concatenation 👎.

1. **Interpolation** (Python values replace parameterized SQL values $❶, $❷, … in a template query):



```
"SELECT $❶ || p.name FROM peeps AS p AS WHERE p.born < $❷"
🐍 [ ❶:"Driver: ", ❷:2000 ]
```

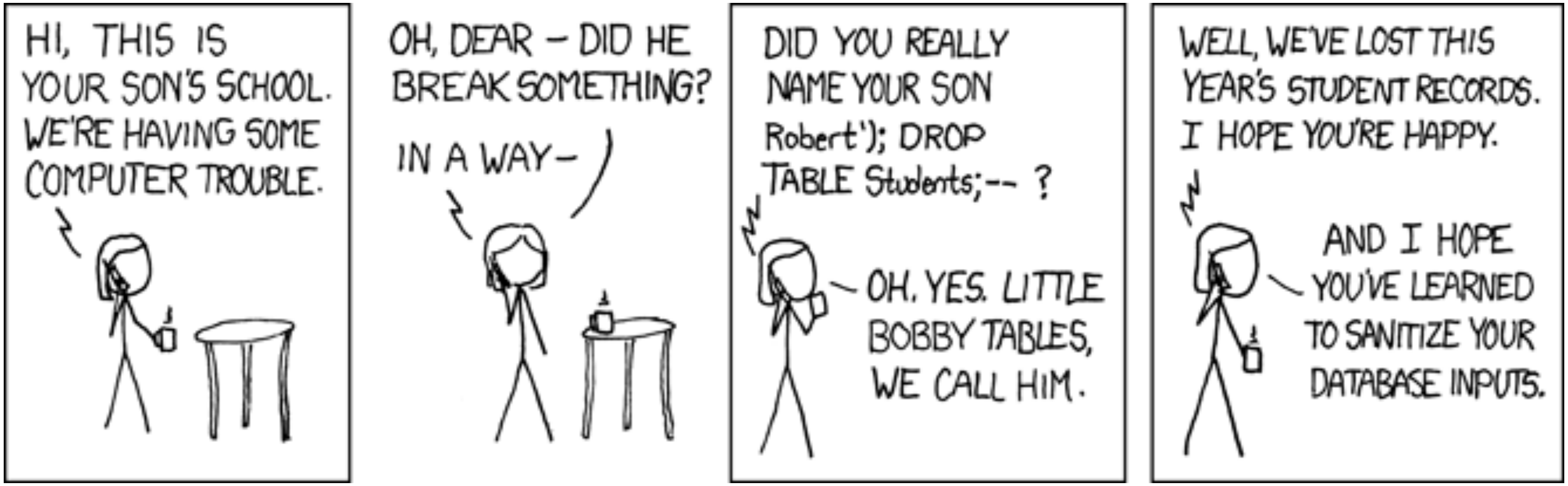
2. String concatenation (⚠️ Risk of SQL injection):



```
"FROM peeps AS p WHERE p.name = '" + N + "' AND p.born < 2000"
🐍 string concatentation
```

If an attacker controls the value of Python string variable *N*, the DBMS may be tricked into executing arbitrary queries.

Parameterized Queries Protect Against Little Bobby's Mom


HI, THIS IS YOUR SON'S SCHOOL. WE'RE HAVING SOME COMPUTER TROUBLE.
OH, DEAR – DID HE BREAK SOMETHING?
IN A WAY–
DID YOU REALLY NAME YOUR SON Robert'); DROP TABLE Students;-- ?
OH. YES. LITTLE BOBBY TABLES, WE CALL HIM.
WELL, WE'VE LOST THIS YEAR'S STUDENT RECORDS. I HOPE YOU'RE HAPPY.
AND I HOPE YOU'VE LEARNED TO SANITIZE YOUR DATABASE INPUTS.

"Exploits of a Mom", © xkcd

#044 + #045

Move Your Computation Close to the Data!

A rule of thumb 👍: *If you can, express data-related computation using SQL.*[9] *Do not demote the DBMS to a dumb table storage.*

- Filter/aggregate tables to **reduce result set sizes** before you transport data from the DBMS to the program.
- Common anti-pattern (the “***n+1 query problem***”):

```
outer = con.sql("SELECT …")     # yields n rows                    #046
for row in outer.fetchall():
  inner = con.sql("SELECT … $1 …", params = [… row …])
  ⋮
```

  - The above issues *n+1 separate queries* all of which need to be interpolated, parsed, optimized, executed, and fetched. 👎
  - Reformulate using a join or a correlated subquery (which the query optimizer will decorrelate). Issues a *single query*. 👍

[9] Indeed, with SQL:1999 and the introduction of *recursive common table expressions*, the query language has become Turing-complete. We explore the consequences of this jump in expressivness in the course *Advanced SQL*.