Do Programming Languages need Query Languages?

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Do Programming Languages need Query Languages?

(spoiler alert)

Yes they do!
Programming and data processing

Claims

1. Data processing plays a central role in programming.
Programming and data processing

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Examples: standard support libraries

1. *Collections* to store data
   - binary search trees, hash tables, tuples, dynamic arrays, ….

2. *Algorithms* to operate on data
   - sorting, filtering, transforming, set operations, ….
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Working Draft of the C++ standard
(Document Number: N4964, Date 2023-10-15.)

C++ standard

2005 pages
Programming and data processing

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- standard support libraries
  - 1443 pages (71%)

- 2005 pages
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collections & algorithms

658 pages (33%)

1443 pages (71%)

2005 pages

Not counting: numeric, time, formatting, IO, threads, ...
An example: How to *program* relational algebra in C++

- **Data storage:** `std::tuple` (single row), `std::set` (rows).

- **Projection** ($\pi$ columns): `std::transform`.

- **Selection** ($\sigma$ conditions): `std::copy_if`, `std::views::filter`.

- **Joins** ($\times$, $\bowtie$, $\Join$): loops, `std::views::cartesian_product`.

- **Set operations** ($\cap$, $\cup$, $\setminus$): `std::set_union`, . . . .

- **Sorting**: `std::sort`, `std::stable_sort`.

- **Deduplication**: `std::unique_copy`.

- **Aggregation**: `std::accumulate` and `std::reduce`, `std::ranges::fold_left`.

- **Parallelization**: execution policies (algorithms), `std::async` (evaluation), . . . .

- **Pipelined execution**: `std::ranges`, coroutines using `std::generator`, . . . .
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\[ \pi_{R \text{.parent}}(\sigma_{R \text{.child}=S \text{.name}}(\rho_{R}(\text{parentOf}) \times \sigma_{S \text{.place}=\text{"Hamilton"}}(\rho_{S}(\text{person})))) \]
An example: How to *program* relational algebra in C++

\[
\pi_R.\text{parent}(\sigma_{R.\text{child}=S.\text{name}}(\rho_R(\text{parentOf}) \times \sigma_{S.\text{place}=\text{"Hamilton"}}(\rho_S(\text{person}))))
\]

```cpp
using namespace std::views;

auto where_pred = [](auto l) {
    return l.place == "Hamilton";
};

auto product_pred = [](auto t) {
    auto [po, p] = t;
    return po.child == p.name;
};

auto join = cartesian_product(parents, persons | filter(where_pred));
for (auto [po, p] : join | filter(product_pred)) {
    std::cout << po.parent << std::endl;
}
```
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Efficient data processing

“*Complex*” data processing algorithms even for *simple* data processing tasks.
E.g., join algorithms, join ordering, index usage, selection push down, ….

This complexity is delegated to the programmer.
An example: A *more-efficient* query in C++

```cpp
/* parents is a set, ordered on (parent, child).
 * persons is a set, ordered on (name, place). */

auto where_pred = [](auto l) { return l.place == "Hamilton"; };
auto filtered = persons | filter(where_pred)
    | std::ranges::to<std::vector>();

for (auto& [pname, cname] : parents) {
    person_t pcname, "Hamilton";
    bool has_child = std::binary_search(filtered.begin(),
                                          filtered.end(), p);
    if (has_child) {
        std::cout << pname << std::endl;
    }
}
```
An example: A *more-efficient* query in C++

```cpp
/* parents is a set, ordered on (parent, child).
 * persons is a set, ordered on (name, place). */

for (auto& [pname, cname] : parents) {
    person_t pcname, "Hamilton";
    bool has_child = persons.contains(p);
    if (has_child) {
        std::cout << pname << std::endl;
    }
}
```
An example: A *more-efficient* query in C++

<table>
<thead>
<tr>
<th></th>
<th>Runtime complexity</th>
<th>Memory usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>$\Theta(</td>
<td>\text{parents}</td>
</tr>
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<td>First variant</td>
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Both “improved” versions can be significantly improved to reduce overheads!
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Both “improved” versions can be significantly improved to reduce overheads!

What if we want *unique* parents?
An example: A *more-efficient* query in SQL

```sql
SELECT pname
FROM parents R, persons S
WHERE R.child = S.name AND S.place = "Hamilton";
```
An example: A *more-efficient* query in SQL

```
SELECT DISTINCT pname
FROM parents R, persons S
WHERE R.child = S.name AND S.place = "Hamilton";
```
An example: A *more-efficient* query in SQL

```
SELECT DISTINCT pname
FROM parents R, persons S
WHERE R.child = S.name AND S.place = "Hamilton";
```

Some database systems need a helping hand...

```
SELECT DISTINCT pname
FROM parents
WHERE child IN (SELECT name
                  FROM persons
                  WHERE place = "Hamilton");
```
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3. We need database technology in our programming languages.

Potential solution?
Programming and data processing

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Potential solution?

![Diagram showing produce data, database engine for data processing ("complex" queries), and consume results.](image-url)
Database systems are *not* the solution

What if we use a database system

For example, PostgreSQL (is free!)
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  ▶ There might not be a database system.
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- There might not be a database system.
- Inserting data into and reading data from the system is not free: Data transfers, necessary code to “translate” between types, ….
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Not all data is always in a database system.
- There might not be a database system.
- Inserting data into and reading data from the system is *not free*:
  Data transfers, necessary code to “translate” between types, ….
- Conceptual mismatches: database code does not mix well with other code!
  For example, type safety (program) versus no type safety (query results).
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For example, PostgreSQL SQLite (is free!)

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Proposed solution

What if... 

query<"%(parent) :- parents(parent, c),"
  "persons(c, 'Hamilton')(dataset);"

is valid C++ code in which query implements an optimized C++ algorithm.
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How to do so
Create a C++ library that

▶ Provides a domain specific query language for C++.
▶ At C++ compile time, the library compiles these queries into C++ algorithms: derive result types, derive query evaluation strategy, …. 
▶ At runtime: these queries are normal C++ functions.
Proposed solution: Feasibility and status

- C++ compile-time support for *domain specific languages*: Almost feature complete (optimistic: publication in 2024?).
- C++ compile-time query compiler: Proof-of-concept complete → we can turn high-level Datalog into algorithms.
- Compile-time query planner and query optimizer: *more work needed.*
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Challenges

```cpp
std::set<my_fancy_type, my_fancy_ordering> my_fancy_dataset;
```

- Which fields does `my_fancy_type` define?
- What ordering does `my_fancy_ordering` provide? Keys? Index?
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Solution. Sensible defaults where possible, else provide such information via traits classes.
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*Solution.* Sensible defaults where possible, else provide such information via *traits classes.*

Reflection (potential future C++ standards) might partly help.
Proposed solution: Feasibility and status

Source: https://xkcd.com/303/ by Randall Munroe.
Query compilation and evaluation

We can use a database-style query planner and query optimizer. *A compile time environment is different, however.*

Zero-cost principle

Our *abstraction* of a domain specific query language should not introduce costs (when compared to a handwritten algorithm).
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Zero-cost principle
Our abstraction of a domain specific query language should not introduce costs (when compared to a handwritten algorithm).

- Only-once query optimization (one compile time, many executions).
- Query optimization without access to the data.
- At runtime: algorithms can make choices (e.g., if–else), But there is only limited information: C++ containers do not have heuristics.
Demonstration—If time allows

Base relations

- \texttt{person}(id, name) assigns names to nodes.
- \texttt{parentOf}\,(parent, child) relates persons.

Example dataset

- Alice
- Bo
- Celeste
- Faythe
- Dafni
- Eva
- Greta
Demonstration—If time allows

Example queries

grandparentOf(0, 1) :- parentOf(0, 2), parentOf(2, 1);

grandparentOnly(0) :- parentOf(0, 1), parentOf(1, 2);

ancestorOf(0, 1) :- parentOf(0, 1);
ancestorOf(0, 1) :- parentOf(0, 2), ancestorOf(2, 1);

ancestorNamed(0, 1) :- ancestorOf(2, 3), person(2, 0), person(3, 1);

siblingOf(0, 1) :- parentOf(2, 0), parentOf(2, 1);
Evaluation: Two perspectives

First perspective: How do we compare with existing database products.
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Second perspective: How do we compare with (C++) programmers?

- Performance?
- Readability?
- Ease-of-use?
Evaluation: Two perspectives

First perspective: How do we compare with existing database products.

Second perspective: How do we compare with (C++) programmers?
  ▶ Performance?
  ▶ Readability?
  ▶ Ease-of-use?

Central question
  Should we switch to declarative languages even in traditional procedural source code?
Research Volunteers Needed

To evaluate our research, we will compare with data processing programs written in C++. You can provide these C++ programs via an online questionnaire.

▶ Questionnaire at https://jhellings.nl/q/.

The questionnaire takes 30min–120min and participation is entirely voluntarily.

This study has been reviewed by and received ethics clearance from the McMaster Research Ethics Board (#6885).
Programming Languages do need Query Languages!

Questionnaire at https://jhellings.nl/q/.