The SQL++ Query Language: Configurable, Unifying and Semi-structured

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ABSTRACT

NoSQL databases support semi-structured data, typically modeled as JSON. They also provide limited (but expanding) query languages. Their idiomatic, non-SQL language constructs, the many variations, and the lack of formal semantics inhibit deep understanding of the query languages, and also impede progress towards clean, powerful, declarative query languages.

This paper specifies the syntax and semantics of SQL++, which is applicable to both JSON native stores and SQL databases. The SQL++ semi-structured data model is a superset of both JSON and the SQL data model. SQL++ offers powerful computational capabilities for processing semi-structured data akin to prior non-relational query languages, notably OQL and XQuery. Yet, SQL++ is SQL backwards compatible and is generalized towards JSON by introducing only a small number of query language extensions to SQL. Indeed, the SQL capabilities are most often extended by removing semantic restrictions of SQL, rather than inventing new features.

Recognizing that a query language standard is probably premature for the fast evolving area of NoSQL databases, SQL++ includes configuration options that formally itemize the semantics variations that language designers may choose from. The options often pertain to the treatment of semi-structuredness (missing attributes, heterogeneous types, etc), where more than one sensible approaches are possible.

SQL++ is unifying: By appropriate choices of configuration options, the SQL++ semantics can morph into the semantics of existing semi-structured database query languages. The extensive experimental validation shows how SQL and four semi-structured database query languages (MongoDB, Cassandra CQL, Couchbase N1QL and AsterixDB AQL) are formally described by appropriate settings of the configuration options.

Early adoption signs of SQL++ are positive: Version 4 of Couchbase’s N1QL is explained as syntactic sugar over SQL++. AsterixDB will soon support the full SQL++ and Apache Drill is in the process of aligning with SQL++.

1. INTRODUCTION

Numerous databases marketed as SQL-on-Hadoop, NewSQL and NoSQL support Big Data applications. These databases generally support the 3Vs. (i) Volume: amount of data (ii) Velocity: speed of data in and out (iii) Variety: semi-structured and heterogeneous data. Due to the Variety requirement, they have adopted semi-structured data models, which are generally different subsets of enriched JSON.

Their evolving query languages fall short of full-fledged semi-structured query language capabilities and have many variations. Some variations are due to superficial syntactic differences. However, other variations are genuine differences in query language capabilities and semantics. The lack of succinct, formal syntax and semantics inhibits a deep understanding of the various systems. It also impedes progress towards declarative languages for querying semi-structured data.

SQL++ is a semi-structured query language that is backwards compatible with SQL, in order to be easily understood and adopted by SQL programmers. The described semi-structured SQL++ data model is a superset of JSON and the SQL data model. The SQL++ model expands SQL with bags (as opposed to having JSON arrays only) and enriched values, i.e., atomic values that are not only numbers and strings (vendors have already adopted this extension). Vice versa, one may think of SQL++ as expanding SQL with JSON features: arrays, heterogeneity, and the possibility that any value may be an arbitrary composition of the array, bag and tuple constructors, hence enabling arbitrary nested structures, such as arrays of arrays. The SQL++ query language inputs and outputs SQL++ data. It makes the following contributions towards the evolution of query languages for JSON databases.

Full-fledged semi-structured language

Many commercial JSON databases started as key-value and document-oriented databases. Others started with SQL as their base. In either case, they grow towards full-fledged JSON databases. SQL++ provides a full-fledged target language whose semantics pick the salient features of past full-fledged declarative query languages for non-relational data models: OQL, the nested relational model and query languages and XQuery (and other XML-based query languages). Importantly, in the spirit of XQuery and OQL, SQL++ is a fully composable and semi-structured language, hence being able to input and output nested and heterogeneous

1 As explained below, the SQL data model itself is a subset of enriched JSON.

2 They also fall short of full-fledged SQL capabilities also.
structures. The cornerstones of achieving this while also being SQL compatible, are described next.

Removing restrictions of SQL semantics Instead of inventing (or re-inventing) many new features, the extension from SQL to SQL++ is most often achieved simply by removing semantic restrictions of SQL:

1. Unlike SQL’s FROM clause variables, which bind to tuples only, the FROM clause variables of SQL++ bind to any JSON element.
2. SQL++ is fully composable in the sense that subqueries can appear anywhere, potentially creating nested results when they appear in the SELECT clause.
3. While correlation of the subqueries in a FROM clause is not allowed in SQL, the SQL++ subqueries of a FROM clause may be correlated with (earlier defined) variables of the same FROM clause.
4. The groups created by the GROUP BY are directly usable in nested queries - as opposed to SQL’s approach where they may only participate in aggregate functions in very limited and particular ways. Interestingly, the SQL++ approach ends up explaining in a simpler way even plain SQL’s grouping and aggregation.
5. Unlike SQL, the SQL++ semantics do not require schema or any homogeneity on the input data.

Extensions: Variables binding to attribute/value pairs and array positions In addition to not requiring a schema, SQL++ can allow a pair of variables of the FROM clause to range over the attribute name and attribute value pairs of input tuples. Similarly, when a FROM clause ranges over an array, SQL++ allows a pair of variables to capture the data at an array position and the index of this position. In this way SQL++ seamlessly expands the logic of SQL to “schema” inspection and arrays.

As a result, the SQL++ syntax and semantics are short (as evidenced by this paper’s syntax and semantics definitions), despite adding functionality on SQL. A key methodology that led to short, succinct semantics is the staging: First we define an SQL++ core. Consequently, SQL compatibility is achieved as syntactic sugar over the core. Similarly, many JSON database query language constructs of various vendors, can also be reduced to syntactic sugar over the core. As a proof of concept, we coauthored with the Couchbase NiQL team a reduction of the NiQL v4 query language into the SQL++ core, by using simple rewriting rules that treat the NiQL v4 syntactic constructs as syntactic sugar over SQL++. Indeed the formal semantics of NiQL v4 are explained by this reduction [12]. (We had earlier collaborated with Couchbase to align NiQL v4 with SQL++.)

The simplicity and power of the language have led to positive early adoption signs: (a) the Couchbase NiQL - SQL++ alignment, (b) an SQL++ interface for AsterixDB captures the SELECT-FROM-WHERE language part and a full release of SQL++ for AsterixDB will soon follow, and (c) collaboration with MapR’s Apache Drill towards aligning the query language with SQL++. An earlier version of SQL++ has been used by the federated query processor of the FORWARD application development platform http://forward.ucsd.edu/sqlpp.

Configurable At the same time, via communication with the vendors we recognize that a model and query language standard is probably premature for such a young and fast-evolving area. Yet, the language designers need to know now the options that are available, especially as it pertains to the handling of semi-structured aspects (semantics for missing attributes, heterogeneous types, etc), which are not captured by the SQL backwards compatibility.

To handle this requirement, SQL++ includes configuration options that describe
1. which features are supported and
2. (for the supported features) different options of language semantics that formally capture the variations of existing database query languages.

Unifying and Explanatory By appropriate choices of configuration options, the SQL++ semantics morph into the semantics of other SQL+JSON databases. The paper shows how the SQL standard and four well known (Cassandra CQL, MongoDB, Couchbase NiQL, AsterixDB AQL) semi-structured database query languages, are explained as particular settings of the configuration options. While SQL++ does not support the exact syntax of any of these four databases, it can be morphed by the configuration options to support equivalent queries. By understanding each database’s capabilities in terms of SQL++ configuration options, the reader can focus on the fundamental differences of the databases without being confused by syntactic idiosyncrasies of various query languages and superficial differences in the documented descriptions of their semantics. To further facilitate understanding of SQL++ and the effect of the various configuration options, we provide a web-accessible reference implementation of SQL++ at http://forward.ucsd.edu/sqlpp.

An earlier, extended version [13] shows how an additional six databases correspond to particular settings of the configuration options. We expect that some of the results listed in the feature matrices describing configuration options will change in the next years as the space evolves rapidly. Despite the forthcoming changes, we expect SQL++ to remain a standing contribution in
1. guiding towards formal, SQL backwards compatible, minimalistic syntax and semantics for a full-fledged semi-structured JSON language and
2. enable understanding of differences in this space and guide towards rational decisions via the configuration option mechanism.

2. DATA MODEL

The SQL++ data model is a superset of both SQL’s relational tables and JSON, based on the observation that they both use similar concepts: A SQL tuple corresponds to a JSON object literal and a SQL string/integer/boolean to the respective JSON scalar. A JSON array is similar to a SQL table (bag) with order.

Figure 1 shows the BNF grammar for SQL++ values, and Figure 2 shows an example SQL++ value. A SQL++ database generally contains one or more SQL++ top-level named values (BNF line 1). A name, such as the name sensors of Figure 2 is a string and is unique. A value is a scalar, complex, missing (explained below) or null. A complex value is either a tuple or a collection. A tuple is a set of attribute name/value pairs, where each name is a unique string within the tuple (as in SQL). Notice, SQL++
heterogeneous (1st and 3rd are numbers, 2nd is a tuple). Furthermore, unlike SQL where the values are tables that have homogeneous tuples that have scalars, SQL++ allows arbitrary composition of complex values. E.g., the top level value is a tuple, the array of lines 3-13 has two heterogeneous tuples, and the bag of line 11 has two scalars and one tuple.

SQL++ and many semi-structured databases also contain maps. A map contains mappings, where each mapping maps a left value to a right value, and each left value is unique within the map. In effect, both a map and a tuple are sets of name/value pairs where names are unique. Their only difference is that a map allows the left value of each mapping to be any arbitrary value, whereas a tuple restricts attribute names to strings (as in SQL). Therefore we do not further discuss maps, as they are essentially tuples without the string restriction.

3. QUERIES, ENVIRONMENTS AND BINDING TUPLES

A SQL++ query is either an SFW query (i.e. SELECT FROM WHERE, lines 5-16 of the grammar of Figure 3) or an expression query (or expression, lines 17-27). Unlike SQL expressions, which are restricted to outputting scalar and null values, SQL++ expression queries output arbitrary values, and are fully composable with SFW queries. Furthermore, SQL++ supports the top-level query to also be an expression query, not just a SFW query as in SQL.

A SQL++ (sub)query is evaluated within an environment, which provides variable bindings (as defined next) and optionally configuration options, defined in Section 4.

Environments and Variable Bindings: Each SQL++ (sub)query q is evaluated within an environment (for brevity, env) Π comprising a config env Πc and a variable

Figure 1: BNF Grammar for SQL++ Values

Figure 2: Example of a SQL++ Value

Figure 3: BNF Grammar for SQL++ Queries
When a query is submitted to a database, it is evaluated in the environment of reading names and their values are produced as follows:

1. A query is submitted to a database, it is evaluated in the environment of its variables $b$ and $b'$. In order to define variable scoping later, we require that if a variable $x$ is bound in both $b$ and $b'$, $b||b'$ retains only the binding of $x$ in $b$. Each variable remains unique within a binding tuple.

2. The FROM clause of a SFW query produces new environments by concatenating bindings of its variables to the environment of its SQL query, as explained below. Subqueries are evaluated in these new environments. (The GROUP BY clause also produces additional variable bindings, as explained in Section 5.3.)

SFW Query Clauses: Similar to SQL semantics, the clauses of a SQL++ SFW query are evaluated in the following order: FROM, WHERE, GROUP BY, HAVING, ORDER BY, LIMIT / OFFSET and SELECT. The FROM expression (readings in Figure 4) is evaluated in the environment of the query ($\Gamma$) in the example. Thereafter the FROM clause outputs the bag of binding tuples $B_{\text{FROM}}^\text{out}$ (which has 3 binding tuples in the example). In each binding tuple of $B_{\text{FROM}}^\text{out}$, each variable of the FROM clause is bound to a value. There are no restrictions that a variable binds to homogenous values across binding tuples. In the example, $r$ respectively binds to 3 values that are heterogeneous.

Each subsequent clause inputs a bag of binding tuples, evaluates the constituent expressions of the clause (which may themselves contain nested SFW queries), and outputs a bag of binding tuples that is in turn input by the next clause. For instance, the WHERE clause inputs the bag of binding tuples that have been output by FROM ($B_{\text{FROM}}^\text{out} = B_{\text{WHERE}}^\text{in}$), and outputs the subset thereof that satisfies the condition expression $e$ of the WHERE clause. Condition $e$ is evaluated once for each input binding tuple $b$ in the binding env $\Gamma$, where $\Gamma$ is the binding env of the SFW query. In the example, the condition $r.co < \text{max}$ is evaluated once for each of the 2 input binding tuples of $B_{\text{WHERE}}^\text{in}$. The binding env of the first evaluation is $\Gamma = \langle r: (\{r: (\text{co:2.2}), \text{readings} : \ldots, \text{max:2} \})\rangle$, thus the first binding tuple is not output.

The pattern of “input bag, evaluate constituent expressions, output bag” has a few exceptions, each of them exemplified in the example: First, the ORDER BY clause inputs a bag of binding tuples and outputs an array of binding tuples. Second, a LIMIT / OFFSET clause need not evaluate its constituent expression for each input binding tuple. Finally, the SELECT ELEMENT clause inputs a bag (resp. array, if ORDER BY is present) of binding tuples, and outputs the SFW query’s result, which is a bag (resp. array) with exactly one element for each input binding tuple. In the example, the SELECT ELEMENT expression $r.no2$ is evaluated once for each of the 2 input binding tuples of $B_{\text{SELECT}}^\text{in}$. The first evaluation is within the binding env $\langle r: (\{r: (\text{co:1.8, no2:0.7})\})\rangle\};$, and outputs the element $0.7$.

Finally, notice that the above discussion of SFW queries did not capture the set operators UNION, INTERSECT and EXCEPT. As is the case with SQL semantics too, the coordination of ORDER BY with the set operators is treated as a special case, which is described in the extended version.

Generalizing Variable Bindings: Assume that readings in Figure 4 were a SQL table (i.e. a bag of homogeneous tuples) with number attributes $co$ and $no2$. SQL semantics dictate that FROM readings AS $r$ outputs homogeneous tuples with attributes $co$ and $no2$. In contrast, the SQL++ FROM clause outputs binding tuples, each of which binds the single variable $r$ to a potentially heterogeneous tuple. In the example, $r$ binds to tuples containing $co$ and $no2$ attributes. This additional level of nesting generalizes SQL++ variable bindings beyond SQL’s homogeneous tuples, to encompass arbitrary readings elements that are heterogeneous (as shown in the example), including a mixture of scalars, tuples and/or collections.

Composability: Notice that query evaluation treats each value named $n$ identically to a variable named $n$. For example, the query of Figure 4 could be a nested query where readings and max are variables defined in the FROM clause.

SQL++ also supports a syntax improvement where SELECT is optionally written as the last clause.
of the parent query. This property serves the composability of the language. **Heterogeneity**: SQL++ supports named values, query results and variables to be arbitrary values. This is in contrast to SQL which restricts named values to flat homogeneous tables (created by CREATE TABLE, CREATE VIEW and WITH), query results to flat homogeneous tables, and tuple variable bindings to homogeneous flat tuples.

The combination of composability and heterogeneity are needed to input and output arbitrarily structured SQL++ values.

## 4. Configuration Options

Config options enable SQL++ to be instantiated to different capabilities and semantics. In effect, they represent the choices that language designers may consider. Some options specify whether a syntactic feature is supported or not. For example, GROUP BY is supported by MongoDB, but not Cassandra. Other options specify variations in the semantics of a syntactic feature. For example, given a tuple \( t \) with a single attribute \( a \), AsterixDB evaluates the path step \( t.b \) to return null (effectively losing the difference between a missing \( b \) attribute and a \( b \) attribute with null value), Couchbase returns missing (which behaves differently from null), and SQL throws an error.

Config options are extensively utilized throughout SQL++. This section presents the formality, a simple use case in path navigation (Section 4.2) and a complex use case in equality (Section 4.3). The support/non-support of query features described in Section 5 are also specified by config options. Section 6 experimentally validates these config options by using them to systematically (a) describe the features of the surveyed databases as a subset of SQL++ and (b) describe their semantics as a specific instantiation of SQL++ semantics.

### 4.1 Config Env(s), Parameters and Options

A config annotation \( @g(p:o) \) (Figure 5) lines 4, 28-34) configures (sub)query \( q \) with parameter group \( g \), parameter name \( p \) and option \( o \)\(^{4}\). The config annotation is statically specified: it cannot be the result of another query. A query is evaluated in the configuration env(ironment) created by its config annotation. A config env \( \Gamma \) is a config tuple \( (p_1:o_1), \ldots, (p_m:o_m) \), where each parameter \( p_i \) maps to an option \( o_i \).

Using config options, language designers have the flexibility for very fine-grained customization of language semantics. To assist designers in choosing sets of options that are compatible with each other a macro config annotation \( \#g(p:o) \) expands to a set of coordinated config annotations \( @g(p_1:o_1) \ldots @g(p_m:o_m) \). For example, a macro config annotation may dictate that the semantics of WHERE in the presence of null and missing are identical to SQL’s 3-valued logic, whereas missing is treated as null. Alternatively, the annotation may dictate another form of semantics where the distinction between null (i.e., unknown) and missing (i.e. inapplicable) is retained.

The utility of configuration override in federated query processing: A query’s configuration environment may be overridden by annotations that apply to its subqueries. Suppose \( @g(p:o) \) is evaluated in env \( \Gamma = (\Gamma_a, \Gamma_b) \). (The query \( q \) may be a subquery of an enclosing query.) Then \( q \) is evaluated in env \( \Gamma' = (\Gamma_a, @g(p:o)|\Gamma_b) \). That is, \( q \) is evaluated in a context where \( p \) is set to \( o \), regardless of whether it could have been configured differently in an enclosing query. Similar to binding tuples, given two config tuples \( c \) and \( c' \), their concatenation \( c||c' \) retains the mapping of \( c \) if parameter \( p \) is mapped in both \( c \) and \( c' \). Therefore, two different parts of a query may correspond to configurations of different databases.

The ability to configure subqueries with different annotations becomes handy when SQL++ is used as a federated query language. In such case, if a subquery that is pushed to a certain database is configured according to the options of such database then it can indeed be pushed. In effect, the task of a federated query processor (such as FORWARD) is to rewrite the user query into one where all subqueries that are pushed to an underlying database have been configured according to the configuration options of such database.

### 4.2 Path Navigation

A tuple path navigation \( t.a \) from the tuple \( t \) to its attribute \( a \) (Figure 3) line 21) returns the value of \( a \). An array path navigation \( a[1] \) returns the 1-th element of the array \( a \) (line 22). Notice that consecutive tuple/array navigations (e.g. \( r.no[1] \)) navigate deeply into complex values, and each navigation evaluates to a unique value. This is identical to SQL’s behavior, but different from XQuery/XPath’s behavior where each path step may return a set of one or more nodes.

Since SQL++ does not assume a schema, the semantics must also specify the return value when \( t \) is not a tuple or when it is a tuple that does not have an \( a \) attribute. Multi-

<table>
<thead>
<tr>
<th>path_param</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v ) if ( t ) is a tuple that maps ( a ) to ( v )</td>
</tr>
<tr>
<td>( v ) if ( t ) is a tuple that does not map ( a )</td>
</tr>
<tr>
<td>otherwise</td>
</tr>
</tbody>
</table>

| t.a | \( @tuple_nav.absent \) |
|----------|
| \( @tuple_nav.type.mismatch \) if \( t \) is a tuple that maps \( a \) to \( v \) |
| \( @tuple_nav.type.mismatch \) otherwise |

\( a[1] \) to

| array_nav.absent | \( @array_nav.absent \) |
|----------|
| \( @array_nav.type.mismatch \) if \( a \) is an array with \( 1 \) elements |
| \( @array_nav.type.mismatch \) otherwise |

| \( v \) | if \( a \) is an array with \( n \) elements |
|----------|
| \( i < 1 \lor i > n \) |

\( | \) is evaluated in env \( \Gamma = (\Gamma_a, \Gamma_b) \).

Figure 5: BNF Grammar for Path Parameters/Options

Figure 6: Path Evaluation Functions for \( t.a \) and \( a[i] \)

Figure 7: Configuring Tuple/Array Navigation
4.3 Equality

Selection and join queries prominently use the equality function. Since SQL++ variables bind to arbitrary heterogeneous values and missing information is prevalent, the evaluation function for the equality comparison $x = y$

must specify the semantics of comparing specified (i.e., non-null, non-missing), null and missing values. Furthermore, the lack of schema may lead to comparing mismatched types. For instance, a type mismatch can evaluate to false/null/missing or an error. A language designer can also choose whether to follow SQL’s 3-valued logic in which $x = \text{null} \rightarrow \text{null}$. Analogous decisions apply for missing. Moreover, if deep equality is supported between complex values, there are further options for combining the results of shallow equality, which go beyond true/false to include null and missing.

Figure 9 shows the parameters and options of the equality parameter group, which are utilized in the equality evaluation function of Figure 9. For deep equality compar-
isons between complex values in farray, fbag and ftuple, additional subtleties are introduced by null and missing elements/attributes. Consider farray using two arrays $x$ and $y$ that each has $n$ elements, and all elements are either scalar or complex values. Then, each pairwise comparison $x[i]=y[i]$ evaluates to true/false, and array equality is simply the result of the operator $\ominus$, which returns the conjunction of these true/false values. However, $x[i]=y[i]$ can also evaluate to null/missing $\ominus$ and must be configured to also produce a result for the logical conjunction between null/missing/true/false. This configuration is achieved by the five parameters in Figure 10, which extend SQL's 3-valued logic.

Figure 10 shows two different configurations and the different results that the same query $r = r$ has for each configuration. The left example follows languages (such as Javascript) which consider null a sentinel value that is equal to itself. null = null evaluates to true, thus the array $r$ deep equals itself. The right example follows SQL's 3-valued logic, which uses null to represent an unknown value. Since the array contains an unknown value, the result of deep equality is also unknown. Therefore, to support equality that behaves reasonably with respect to null, we recommend language designers utilize the macro config annotation @unknown.value. In the case of databases that support null and do not support missing, the two sensible options are sentinel and logic. If a language designer chooses the 3-valued, she has implicitly chosen that null=Null is null but also that null$\ominus$true is null.

In the presence of missing, the @unknown.value must specify its behavior in comparison. In the sentinel approach, the missing will behave as yet another sentinel value. In the logic-based approach, we recall that missing is introduced as “inapplicable”, while null stands for the currently unknown. In such case, the logic approach is expanded as shown in Table 2. Notice that Table 2 provides a pure sentinel approach and an unknown/inapplicable logic approach. One may still consider other possibilities and this is why macro operate as guidelines, rather than definitive options.

<table>
<thead>
<tr>
<th>@unknown.value :</th>
<th>Logic</th>
<th>sentinel</th>
</tr>
</thead>
<tbody>
<tr>
<td>eq.null_eq_null</td>
<td>null</td>
<td>true</td>
</tr>
<tr>
<td>eq.null_eq_missing</td>
<td>missing</td>
<td>false</td>
</tr>
<tr>
<td>eq.null_eq_value</td>
<td>null</td>
<td>false</td>
</tr>
<tr>
<td>eq.missing_eq_missing</td>
<td>missing</td>
<td>true</td>
</tr>
<tr>
<td>eq.missing_eq_value</td>
<td>missing</td>
<td>false</td>
</tr>
<tr>
<td>eq.null_and_true</td>
<td>null</td>
<td>false</td>
</tr>
<tr>
<td>eq.null_and_null</td>
<td>null</td>
<td>true</td>
</tr>
<tr>
<td>eq.null_and_missing</td>
<td>missing</td>
<td>false</td>
</tr>
<tr>
<td>eq.missing_and_true</td>
<td>missing</td>
<td>false</td>
</tr>
<tr>
<td>eq.missing_and_null</td>
<td>missing</td>
<td>true</td>
</tr>
<tr>
<td>eq.missing_and_missing</td>
<td>missing</td>
<td>true</td>
</tr>
</tbody>
</table>

Table 2: @unknown.value Macro Expansion

Figure 11: BNF Grammar for FROM Clause and @from Config Parameters

5. SFW QUERY CLAUSES

5.1 FROM clause

The SQL++ FROM clause allows variables to range over any data, unlike SQL FROM clause tuple variables that range over tuples only. The SQL++ variables can range over heterogeneous elements, over nested collections, and over the attribute/value pairs of tuples (a feature reminiscent of SQL extensions for dynamic schema introspection [9]). Furthermore, FROM variables can register the order of input elements in arrays, which is useful for order-aware queries.

Some semi-structured query languages have introduced unnesting constructs (following the nested relational algebra [6,15]) that essentially specify how the variables of the FROM clause range over nested data. The SQL++ core semantics show that these constructs can be fused with SQL and be expressed succinctly by the combination of (a) allowing correlated queries in SQL's FROM clause, and (b) a distinction of how variable bindings of the correlated queries combine, which is akin to the distinction between JOIN versus LEFT OUTER JOIN in SQL. The combination of these two simple features, allows the SQL++ core to directly express queries that could only be expressed in cumbersome ways (involving intermediate results) even in advanced prior languages, such as XQuery and the nested relational algebra.

Figure 11 shows the BNF grammar for the SQL++ FROM clause and corresponding config parameters. The syntax and semantics of FROM is defined inductively with three cases. (1) Lines 4-5: the SQL++ core base case where the FROM item ranges over a single collection or tuple (2) Lines 6-7: the SQL++ core inductive case where the FROM item comprises correlation between two other FROM items (3) Lines 8-12: the “syntactic sugar” cases, where the grammar introduces well known SQL constructs (e.g., joins, outer joins) as well as the unnesting constructs of NoSQL databases. The semantics of the “syntactic sugar” constructs are explained by reduction to the SQL++ core constructs of #1 and #2.

3a) SQL++ Core, Ranging over Collection Elements: FROM e AS x (AT y)? supports ranging over elements of a collection (line 4). x is an element variable, and y is an optional position variable. As in SQL, expression e can be any SFW subquery or named value (Figure 8 lines 18-19). SQL++ extends beyond SQL towards full compositability, as e can also be a variable, path, function call,
Figure 12: Using AT (Position Variable) to Obtain Ordinal Positions for Input Order

```
\[ \{ \text{(readings: [0.7, [0.5, 2]], } \text{"repair" } \text{)} \} \]
```

Figure 13: Using AS \( \{x:y\} \) to Range Over Tuple Attributes

```
\[ \{ \text{(reading: [no2: 0.7, co: [0.5, 2]])} \} \]
```

Figure 14: Using INNER CORRELATE to Correlate FROM Items

tuple with 2 attributes no2 and co. The FROM clause defines variables \( g \) and \( v \), and outputs 2 binding tuples where \( g \) is bound to the attribute name and \( v \) is bound to the attribute value. The SELECT ELEMENT clause outputs a bag with 2 elements, one for each input tuple attribute. In SQL’s parlance, the SQL++ query has transposed/pivoted the tuple’s attributes (columns) into the collection’s elements (rows).

If \( t \) evaluates into a value that is not a tuple, coercion may be activated by the configuration options of Figure 11 (lines 18-19): When \( t \) evaluates to null or missing, the language designer may elect to coerce \( t \) into the empty tuple \( {} \), instead of producing an error.

(2a) Core, INNER CORRELATE: The first inductive step case is \( \text{FROM } l \text{ INNER CORRELATE } r \) (Figure 11 line 6). (For brevity, also written as \( \text{FROM } l \text{ INNER } r \)). The FROM item \( r \) can utilize variables defined by FROM item \( l \). Suppose the SFW query is evaluated in binding env \( \Gamma \). Let \( B^l \) be the bag of binding tuples that would result from the clause \( FROM l \). Then, \( \text{FROM } l \text{ INNER CORRELATE } r \) outputs all binding tuples \( B^l \parallel B^r \), where \( B^l \subseteq B^l \parallel B^r \subseteq B^r \), and \( B^r \parallel \) is the bag of binding tuples that would result from evaluating \( r \) within the binding env \( \Gamma \).

For example, Figure 14 shows a SQL++ query that ranges over attribute/value pairs, thereafter ranges over the array of each attribute value. From reading AS \( \{g:a\} \) would result in binding tuples \( b^1_1, b^1_2, b^1_3 \) each with variables \( g \) and \( a \). Evaluating the right hand side \( a \text{ AS } v \) in the context of \( B^l = \{ (g: \text{"co"}, a: [0.7, [0.5, 2]]) \} \) results into \( B^r = \{ (v: 0.7), (v: [0.5, 2]) \} \). Consequently the FROM clause outputs the first 2 binding tuples of Figure 13. Likewise \( B^2 = \{ (g: \text{no2}, a: [\text{"repair" }]) \} \) leads to \( B^r_2 = \{ (v: \text{"repair"}) \} \) which leads to \( \text{FROM } \) outputting the 3rd binding tuple. Since \( b^3 = \{ (g: \text{so2}, a: [\text{\{}]) \} \) results in an empty \( B^r_3 \), there is no binding tuple that corresponds to \( \text{so2} \).

Notice that correlated queries are akin to nested for-loops of imperative languages, where the left subquery \( l \) and the right subquery \( r \) are respectively the outer and inner loops. While this example has a simple expression \( r \) (i.e. the expression \( a \text{ AS } v \)), in general \( r \) can be a complex SFW query. For example, we could replace the \( a \text{ AS } v \) in Figure 14 with the following subquery, which would correlate each \( g \text{ AS } a \) pair only with the top-1 element of each collection.

(2b) Core, LEFT OUTER CORRELATE: In \( \text{FROM } l \text{ LEFT OUTER CORRELATE } r \) (Figure 11 line 6), \( r \) can again utilize vari-
ables defined by \( l \). (For brevity one may simply write \( l \) \( \text{LEFT} \) \( r \), omitting either or both of the \( \text{OUTER} \) and \( \text{CORRELATE} \) keywords.) Similar to SQL’s \( \text{LEFT JOIN} \), the \( \text{LEFT} \) outputs binding tuples derived from \( l \), even if there are no matching binding tuples from \( r \). Formally, let \( B' \) be the bag of binding tuples that results from the clause FROM \( l \). Then, FROM \( l \) \( \text{LEFT} \) \( r \) outputs all binding tuples that FROM \( l \) \( \text{INNER} \) \( r \) would output. In addition, for each \( b'_i \in B' \) such that \( B'_i \) is an empty bag, LEFT also outputs a binding tuple \( b'_i |\{x'_1, \ldots, x'_m\} : @from.no_match, \ldots, x'_n : @from.no_match\} \), where \( x'_1, x'_2, \ldots, x'_n \) are variables defined by \( r \), and each variable is bound to the value configured by \( @from.no_match \) (line 20). Since \( \text{LEFT} \) generalizes SQL’s \( \text{LEFT JOIN} \) (as discussed below), achieving SQL compatibility requires configuring \( @from.no_match \) to null. Alternatively, a language designer may also choose to configure \( @from.no_match \) to null.

For example, suppose Figure 11 uses \( \text{LEFT} \) instead of \( \text{INNER} \). Assuming \( @from.no_match \) is configured to null, the query will output the additional tuple: \{gas:"so2", val:0.7\}

(Figure 11, line 7) resembles SQL’s \( \text{LEFT JOIN} \), which is core SQL++.

(3c) Syntactic Sugar, Flattening: Flattening (aka unnesting) is commonly used within SQL-on-Hadoop and NoSQL databases to range over nested collections. SQL++ supports INNER FLATTEN (lines 11-12) as a special case of the core \( \text{INNER} \), in which \( r \) must be a path expression \( x.p \) that starts from the left hand side variable \( x \), as follows. Analogously, OUTER FLATTEN is syntactic sugar for \( \text{LEFT} \).

(3b) Syntactic Sugar, SQL’s Join: Similarly, SQL++ supports SQL joins (lines 9-10) as a special case of \( \text{CORRELATE} \). \( \text{LEFT JOIN} \) is syntactic sugar for the core \( \text{LEFT CORRELATE} \) as follows, and analogously, \( \text{INNER JOIN} \) is syntactic sugar for \( \text{INNER CORRELATE} \). Finally, \( \text{RIGHT JOIN} \) is syntactic sugar for \( \text{LEFT JOIN} \), and \( \text{FULL JOIN} \) is identical to \( \text{FULL CORRELATE} \).

(1) SQL++ Core, Outputting a Collection: SELECT \( e \) (Figure 15, line 2) is core SQL++ that outputs a collection of arbitrary elements (both tuples and non-tuples). Notice that the keywords are different from SQL’s plain \( \text{SELECT} \), which is subsequently explained as syntactic sugar for outputting specifically a collection of tuples. The \( \text{SELECT} \) clause inputs a bag (resp. array, if \( \text{ORDER BY} \) is present) of binding tuples \( B'_{\text{SELECT}} \), and outputs a bag (resp. array) of values. Let \( \Gamma \) be the binding env of the enclosing SFW query. For each input binding tuple \( b \in B'_{\text{SELECT}} \), \( \text{SELECT} \) output a value \( v \), where \( b |\Gamma \vdash e \rightarrow v \).

5.2 \text{SELECT} clause

The SELECT clause of SQL++ can output more than SQL’s collections of flat tuples. First, an output tuple can contain other nested collections. Second, an output collection can directly contain (i.e. without intervening tuples) any arbitrary value, including scalars, collections, null and missing. Finally, output tuples can be heterogeneous: Missing attributes in the input can reflect to missing attributes in the output. Indeed, an output tuple can have a data-dependent number of attributes, where both the attribute names and their values are provided by variables.

Figure 15: BNF Grammar for SELECT Clause

Figure 16: Using SELECT ATTRIBUTE to Output a Variable-Width Tuple

supports INNER FLATTEN (lines 11-12) as a special case of the core \( \text{INNER} \). IN a general expression, a plain variable and a tuple constructor within \( \text{SELECT} \).

When a \( \text{missing} \) is provided as an attribute value in a constructor then the particular attribute/value pair is omitted. Therefore, particular attribute omissions and heterogeneities in the input can easily propagate to corresponding attribute omissions and heterogeneities in the output. For example, consider the query FROM readings AS \( r \) SELECT \( e \) ("co":r.co, "no2":r.no2) evaluated on the readings heterogeneous collection of tuples of Figure 14. The query output is identical to readings.
since the absence of the attribute no2 in the first tuple of the input will lead to a respective absence of no2 in the first tuple of the output.

(2) SQL++ Core, Outputting a Variable-Width Tuple: SELECT ATTRIBUTE \(e_0, \ldots, e_m\) (Figure 13 line 3) outputs a tuple where the attribute name-value pairs are determined by the input bindings. For each input binding tuple \(b\) of \(B^1_{\text{rel}}\), the output tuple contains an attribute \(n: v\), where \(b[i] \rightarrow e_i \rightarrow n\) and \(b[j] \rightarrow e_j \rightarrow v\). An error occurs if \(n\) is not a string. The attribute/value pair is omitted if \(v\) is missing.

Figure 16 shows another example, where \(\text{SELECT}\) \(\text{GROUP}\) \(\text{BY}\) is used. The query output tuple contains an attribute \(\text{GROUP}\) \(\text{BY}\) \(\text{gas}\), \(\text{as}\) \(\text{no2}\) \(\text{count}\) \(\text{avg}\). The explicit presence of groups in SQL++, more general than SQL, also leads to simpler semantics than those of SQL, since the \(\text{GROUP}\) \(\text{BY}\) clause semantics are independent of the presence of subsequent functions in \(\text{HAVING}\), \(\text{ORDER}\) \(\text{BY}\) and \(\text{SELECT}\) clauses.

For example, Figure 15 shows a SQL++ query for counting and averaging the readings of each gas. The \(\text{GROUP}\) \(\text{BY}\) clause inputs 3 binding tuples, and uses \(r.gas\) to partition them into 2 groups. Within \(\text{SELECT}\) \(\text{ELEMENT}\), the count function counts the elements in each group, whereas \(\text{avg}\) outputs the average \(r.num\) in each group. The \(\text{GROUP}\) \(\text{BY}\) clause is independent of \(\text{count}\) and \(\text{avg}\), since both are general-purpose functions that can input arbitrary collections (i.e. not just group).

(2) Syntactic Sugar, SQL’s \text{GROUP BY}: For SQL compatibility, SQL++ supports using a grouping expression \(e_i\) in \text{HAVING}, \text{ORDER BY} and \text{SELECT} clauses, and omitting its corresponding grouping variable. Let \(\Gamma e\) be the binding env of the enclosing SFW query. The bag of input binding tuples \(B^i_{\text{inp}}\) are partitioned into the minimal number of equivalence groups \(B_1, \ldots, B_m\), such that any two binding tuples \(b, b’ \in B^i_{\text{inp}}\) are in the same equivalence group if and only if every grouping expression \(e_i\) evaluates to the identical value \(v_i\), i.e., \(b[i] \rightarrow e_i \rightarrow v_i\) and \(b’[i] \rightarrow e_i \rightarrow v_i\). For each group \(B_j\) \((1 \leq j \leq m)\), the \(\text{GROUP}\) \(\text{BY}\) clause outputs a binding tuple \(b_j = (x_1: v_1, \ldots, x_m: v_m, \text{group}: B_j)\).

Notice that unlike SQL, the output binding tuple provides the partitioned input binding tuples in the special variable \text{group}, which can be explicitly utilized in subsequent \text{HAVING}, \text{ORDER BY} and \text{SELECT} clauses. Thus, a SQL++ query can perform complex computations on the groups, leading to results of any type (e.g. collections nested within collections). The explicit presence of groups in SQL++, while more general than SQL, also leads to simpler semantics than those of SQL, since the \(\text{GROUP}\) \(\text{BY}\) clause semantics are independent of the presence of subsequent functions in \text{HAVING}, \text{ORDER BY} and \text{SELECT}.

For example, Figure 15 shows a SQL++ query for counting and averaging the readings of each gas. The \(\text{GROUP}\) \(\text{BY}\) clause inputs 3 binding tuples, and uses \(r.gas\) to partition them into 2 groups. Within \(\text{SELECT}\) \(\text{ELEMENT}\), the count function counts the elements in each group, whereas \(\text{avg}\) outputs the average \(r.num\) in each group. The \(\text{GROUP}\) \(\text{BY}\) clause is independent of \(\text{count}\) and \(\text{avg}\), since both are general-purpose functions that can input arbitrary collections (i.e. not just group).

(3) Syntactic Sugar, SQL’s \text{GROUP} \text{BY} \text{Clauses}: For SQL compatibility, SQL++ supports using a grouping expression \(e_i\) in \text{HAVING}, \text{ORDER BY} and \text{SELECT} clauses, and omitting its corresponding grouping variable (i.e. \(\text{AS} x_i\)) in the \text{GROUP} \text{BY} clause. Thus, \(e_i\) becomes syntactic sugar for \(x_i\) within \text{HAVING}, \text{ORDER BY} and \text{SELECT}. For example, Figure 15 can equivalently use: \(\text{SELECT}\) \(\{\text{gas} : \text{r.gas}\ldots\}\).

(3) Syntactic Sugar, SQL’s \text{Aggregation Functions}:

SQL++ also supports syntactic sugar for aggregation functions. Suppose any of the \text{SELECT}, \text{HAVING} and \text{ORDER BY} clauses contains a function call \(f(e)\), where \(f\) is a SQL aggregation function such as \text{SUM} and \text{AVG}, and expression \(e\) utilizes variables \(v_1, \ldots, v_n\) that are defined in the \text{FROM} clause. Then, \(f(e)\) is syntactic sugar for \(f(\text{SELECT} e' \text{FROM} \text{GROUP AS} p)\), where \(e'\) results from sub-
6. SQL++ AS AN EXPRESSIVENESS BENCHMARK OF DATABASES

To evaluate SQL++’s effectiveness as a configurable and unifying language, we utilize SQL++ config options as a formal expressiveness benchmark of five databases:

A. SQL as implemented in MySQL 5.6
B. CQL 3.2.0 of Apache Cassandra 2.1.2
C. the Aggregation Pipeline API of MongoDB 2.6.5
D. N1QL DP4 of Couchbase Server 3.0.1
E. AQL of AsterixDB 0.8.6.

All feature matrices have been empirically validated as follows. Classifying a feature as supported (✓) requires exemplary queries to return results consistent with both SQL++ semantics and the database’s documentation. Non-support of a feature (✗) is substantiated by (i) explicit documentation of the restriction (ii) documentation that illustrates the lack of a feature (e.g. the absence of arrays among supported data types), and/or (iii) a query that throws an error. A feature that is partially supported (⊙) requires respective substantiation for both supported and unsupported parts. The full benchmark comprising sample data, queries and results, as well as links to supporting documentation and bug reports, is available at [http://forward.ucsd.edu/sqlpp](http://forward.ucsd.edu/sqlpp).

Table 3 presents feature matrices that classify the data model of the surveyed databases. We focus on named values that are stored within databases for two main reasons: (i) Since stored values are input by queries, they prominently affect whether query features interact with complex values, heterogeneity etc. (ii) Stored values are independent of query features (subsequently classified in Table 4), unlike the values of named views and query results. Parameters in substituting each $v_i$ in $e$ with $p.v_i$. For the special case where an aggregation function $f$ (such as $\text{count}$) needs the entire group as-is, $f(*)$ is syntactic sugar for $f(\text{group})$. For example, Figure 18 can equivalently use: $\text{count(*)}$ and $\text{avg(r.num)}$.

![Table 3: Data Model Feature Matrices](http://forward.ucsd.edu/sqlpp)

Table 4: Query Language Feature Matrices

@stored_named (lines 1-6) classify whether a stored named value can be an array, bag, tuple, scalar, null or missing. For all stored bags, independently of whether they are named or nested, @stored_bag (lines 7-13) classifies whether each type of element, as well as heterogeneous elements, are supported. @stored_array and @stored_tuple are analogously defined. Collectively, the parameters classify the values that a stored named value can recursively contain, wherein unsupported features indicate a lack of composability.

@stored_named: Following SQL, all databases restrict stored named values to bags (i.e. a SQL table). @stored_bag: CQL, MongoDB and N1QL follow SQL in restricting bags to only comprise tuples. AQL is classified with partial support, as the restriction applies to named bags but not nested bags. Unlike SQL and CQL, bags can be heterogeneous in MongoDB, N1QL and AQL. @stored_array: SQL does not support arrays. A CQL array supports up to 65k scalar elements of the same type (e.g. strings). MongoDB/N1QL arrays are heterogeneous and contain arrays, tuples, scalars and nulls. An AQL array further supports bag elements.

@stored_tuple: Tuple attributes can be scalars or nulls in SQL. In addition, CQL supports arrays, MongoDB and
N1QL also support tuples, and AQL further supports supports bags. Table 4 classify query language features, and show how databases are more restrictive than SQL in some ways, but extend beyond SQL in others. We illustrate the classification convention using @tuple nav and @array nav (lines 1-6). Parameter support classifies whether tuple/array navigation is supported (✓), unsupported (✗) or partially supported (●). Parameters absent and type_mismatch are as defined in Figures 5 and 6. For brevity, the options of Figure 5 are abbreviated: null (n), missing (m) and error (×).

In cases where a feature’s semantics vary under different circumstances, it is classified as inconsistent (§). Finally, a feature is irrelevant (-) if it depends on other unsupported features. For example, since arrays are unsupported in SQL, array navigation is irrelevant.

@tuple nav: All databases support tuple navigation, but behave differently for absent attributes or navigation from non-tuples. MongoDB has inconsistent semantics: navigating from scalars return missing, yet navigating from arrays return other arrays. Notably, even though missing cannot be stored in MongoDB and N1QL (Table 3, lines 6,12,19,26), it can be an intermediate result during query processing.

@array nav: CQL supports arrays, but not array navigation. MongoDB only supports array navigation in the WHERE clause, in which an expression language different from that of other clauses has been implemented. In both N1QL and AQL, the contrary, array navigation is fully supported and behaves symmetrically with tuple navigation.

@named_value: All databases follow SQL such that a named value (which is always a bag) is restricted to being ranged over within the FROM clause, instead of being usable in arbitrary expressions (such as table1 = table2).

@eq: The parameters are defined in Figures 8 and 9. In SQL, (i) complex equality is irrelevant due to the named value restriction above (ii) 1=null→null (iii) null=null→null (iv) 1='a'→false, a peculiarity of MySQL unlike other SQL databases. All other features are irrelevant as complex equality and missing are unsupported. In CQL, 1=null→false (unlike SQL), and null=null is precluded by other limitations (details in the extended version). In MongoDB, equality is cleanly supported through identity comparisons of null/missing. In N1QL, equality on null/missing is broadly inconsistent, as N1QL violates the equivalence x<y ⇔ [x]≠[y]. For example, null_eq scalar is inconsistent because 1=null (null like SQL), whereas {1}={null}→false. Finally, AQL follows SQL equality. Notice that four-valued logic parameters are irrelevant in the 5 databases and have thus been omitted: either complex equality is unsupported, or it is supported but shallow equality does not return null/missing (see N1QL inconsistency above).

@from: The parameters classify FROM clause features (Section 5.1), and options for bag_order, no_match, coerce null to collection etc. are as specified in Figure 11. SQL supports ranging over a named collection, over a subquery, Cartesian product, INNER JOIN, and LEFT JOIN. MySQL also supports a counter for the iteration order over a bag (lines 20-21). CQL, MongoDB and N1QL are less composable. CQL only supports ranging over a named collection. Likewise for MongoDB, but with the addition of INNER FLATTEN. N1QL further supports joins, but, unlike SQL, restricts them to between primary/foreign keys, and uses missing for no-matches. Notably, AQL exceeds SQL by supporting the more general INNER CORRELATE. However, AQL does not support LEFT/FULL JOIN. No database supports yet coercions, ranging over tuple attributes, LEFT CORRELATE, or OUTER FLATTEN.

@select: SQL and CQL can neither output nor store heterogeneous values. Conversely, MongoDB, N1QL and AQL can both output and store heterogeneous values. All databases follow SQL in supporting paths and functions within SELECT. However, many CQL functions (e.g. =, AND) are supported only in WHERE but not SELECT. Only N1QL and AQL support SELECT ELEMENT to output a collection of non-tuples, and only AQL fully supports subqueries to output nested collections. A SQL subquery must output scalars, and a N1QL subquery must be correlated with the outer query by primary/foreign keys. No database supports yet SELECT ATTRIBUTE to output a tuple of variable-width.

@group by: CQL does not support GROUP BY. All other databases support grouping all values in their data models. MongoDB, N1QL and AQL also extend beyond SQL to support the group variable. Counterintuitively, MongoDB groups null and missing together as if they were identical, which is contrary to @eq null_eq_missing=false (line 13).

7. CONCLUSIONS AND FUTURE WORK

We described the FROM, WHERE, GROUP BY and SELECT of the configurable, unifying and semi-structured SQL++ query language. SQL++ has picked salient features (composability, semantics without need for schema) from prior query languages - most notably XQuery and OQL. Unlike XQuery’s data model, JSON is simple and easily adjusted for ranging over various patterns of JSON data and/or abstracting away superficial syntactic differences. However, many CQL functions (e.g. =, AND) are supported only in WHERE but not SELECT. Only N1QL and AQL support SELECT ELEMENT to output a collection of non-tuples, and only AQL fully supports subqueries to output nested collections. A SQL subquery must output scalars, and a N1QL subquery must be correlated with the outer query by primary/foreign keys. No database supports yet SELECT ATTRIBUTE to output a tuple of variable-width.

@group by: CQL does not support GROUP BY. All other databases support grouping all values in their data models. MongoDB, N1QL and AQL also extend beyond SQL to support the group variable. Counterintuitively, MongoDB groups null and missing together as if they were identical, which is contrary to @eq null_eq_missing=false (line 13).

We also showed how appropriate settings of the configuration options morph SQL++ into SQL or any of four NoSQL query languages. The extended version provides the syntax and semantics of ORDER BY, LIMIT, set operators (UNION etc) and schemas. Furthermore, it provides a SQL++ algebra that (in the spirit of SQL++) is highly compatible with the set-at-a-time processing that SQL engines (based on SQL algebras) use. An earlier extended version provides the configuration options for an additional six semi-structured databases.

While the NoSQL space is bound to change, the configuration options technique (including the proposed macro options) provides a standing contribution in (a) itemizing and rationalizing the options of a language designer and (b) describing the capabilities and semantics of NoSQL databases, while abstracting away superficial syntactic differences.

The extended version will be expanded to describe (using the configuration options technique) the capabilities of selected SQL databases that have recently introduced JSON columns (e.g., and respective UDFs). Instead of forcing users to learn multiple new primitives (via UDF’s) for ranging over various patterns of JSON data and/or constructing various patterns of JSON data, SQL++ lets FROM variables to freely range over any type of data: attribute/value pairs, array elements and index positions in either correlated or uncorrelated fashion, and based on this
freedom delivers high expressive power. Similarly, SQL++ allows the `SELECT` clause to seamlessly create heterogenous and semi-structured JSON by the mere reuse of nested queries.

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8. REFERENCES


