Language, Data, and Security

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joint work with:
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Semantics of SQL: quiz

\[
\text{SELECT R.A FROM R EXCEPT SELECT S.A FROM S} \equiv \?
\]

\[
\text{SELECT R.A FROM R WHERE R.A NOT IN ( SELECT S.A FROM S )}
\]
Three themes

- In roughly chronological order:
  - Language-integrated query
  - Systems provenance and security
  - Towards verified databases

- Common theme: *provenance*
  - that is, metadata about execution / how query results depend on inputs / rich auditable log data
  - (roughly; not really what this talk is about)
Language-integrated query
Databases and Queries

```
SELECT d.dpt, d.id
FROM depts d, emps e
```
The conventional (JDBC) approach

Queries constructed using strings
SQL injection attacks can subvert meaning of query
Language-integrated query

• "SQL-like comprehension operations increasingly adopted [in e.g. JavaScript, Python, ...]" - Eric Sedlar, Oracle (SIGMOD 2014 keynote)

• Microsoft's LINQ and other "language-integrated query" features now popular
Links example

query { for (x <-- employees) where (x.salary > 50000) [(name = x.name)] }

select name
from employees e
where e.salary > 50000

Language-integrated provenance

query { for (x <-- employees) where (x.salary > 50000) [(name = x.name)] }

Fehrenbach & Cheney (PPDP 2016/SCP)
Stolarek et al. (work in progress)
Language-integrated provenance

Fehrenbach & Cheney (PPDP 2016/SCP)
Stolarek et al. (work in progress)
Language-integrated view update

query { for (x <-- employees) 
   where (x.salary > 50000) 
   [(name = x.name)] }
Language-integrated query update

query { for (x <-- employees) where (x.salary > 50000) [(name = x.name)] }

Horn (work in progress)
Language-integrated view update

query { for (x <-- employees) where (x.salary > 50000) [(name = x.name)] }
Systems provenance & security
Massive Data Breach Puts 4 Million Federal Employees’ Records At Risk

June 4, 2015 · 7:22 PM ET

DARPA Transparent Computing ($60m, 2015-2019)
General idea

P1  P2  P3

Provenance recorder

Kernel

DB
Challenge

- The amount of "normal" system data is massive (up to GBs/day; graphs with millions or billions of nodes/edges)
  - while attacks are ~ 50 nodes/edges.
- We don't know what attacks "look like" in advance
  - We usually don't have annotated data
  - Nor can we expect future attacks to be similar to previously seen ones
- We need **unsupervised** techniques that can find **sparse** anomalies in **large property graphs**
  - this appears to be an open problem in general
- Currently exploring **pattern mining**

Berrada et al., work in progress
Provenance expressiveness benchmarking

- How do we know correct/sufficient information is recorded?
- How do different recording systems differ?
- Idea: Benchmarking recording systems to observe & classify their behavior automatically (at least for small examples)

Chan et al., TaPP 2017
High-level *configuration* languages are increasingly popular ("DevOps")

- Chef, Ansible, **Puppet**

Configuration errors can have be hard to spot, yet cause massive damage/losses

- (e.g. $150M cost for recent four hour Amazon outage)

First step: understanding *semantics* of configuration languages such as Puppet (Fu et al, ECOOP '17)

- Next: formalizing and implementing provenance tracking for such languages (MSR studentship)
Mechanizing the metatheory of SQL with nulls

Project funded by NCSC/VeTSS
August 2017-March 2018
W. Ricciotti and J. Cheney
Semantics of SQL with nulls: quiz

\[
\begin{align*}
\text{R} & \quad \text{S} \\
\begin{array}{c|c}
A & \ \text{A} \\
1 & \null \\
\text{null} & \null \\
\end{array} & \begin{array}{c|c}
A & \null \\
\end{array}
\end{align*}
\]

\[
\text{SELECT R.A FROM R EXCEPT SELECT S.A FROM S} \\
\equiv ? \\
\text{SELECT R.A FROM R WHERE R.A NOT IN (SELECT S.A FROM S)}
\]
Semantics of SQL with nulls: quiz

This is because "NOT IN" uses 3-valued semantics...
Semantics of SQL with nulls: quiz

This is because "NOT IN" uses 3-valued semantics...

This means DB query optimizers tend to be VERY conservative

X

\{\}

This is because "NOT IN" uses 3-valued semantics...
What is the semantics of SQL?

• It is one of the most widely used and successful "declarative" languages
  • There is even a standard!

• However, its "standard" semantics is (many many pages of) formal-ish English

• To date there is no formal semantics for all of SQL
  • Handling complications of "full" SQL such as multiset semantics, grouping, aggregation, nulls
  • The "awkward squad" of the database world.
Wouldn't it be nice to formalize that? (using homotopy type theory, obviously?)

HoTTSQL: Proving Query Rewrites with Univalent SQL Semantics

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Abstract
Every database system contains a query optimizer that performs query rewrites. Unfortunately, developing query optimizers remains a highly challenging task. Part of the challenges comes from the intricacies and rich features of query languages, which makes reasoning about rewrite rules difficult. In this paper, we propose a machine-checkable denotational semantics for SQL, the de facto language for interacting with relational databases, for rigorously validating rewrite rules. Unlike previously proposed semantics that are either non-mechanized or only cover a small amount of SQL language features, our semantics covers all major features of SQL, including bags, correlated subqueries, aggregation, and indexes. Our mechanized semantics, called HoTTSQL, is based on K-Relations and homotopy type theory, where univalence holds. We have implemented HoTTSQL using Coq, an implementation of homotopy type theory, and have proven its correctness. In addition, while query equivalence is generally undecidable, we have implemented an automated decision procedure using homotopy type theory, obviously?

Keywords SQL, Formal Semantics, Homotopy Types, Equivalence

1. Introduction
From purchasing plane tickets to browsing social networking websites, we interact with database systems on a daily basis. Every database system consists of a query optimizer that takes in an input query and determines the best program, also called a query plan, to execute in order to retrieve the desired data. Query optimizers typically consist of two components: a query plan enumerator that generates query plans, and a plan selector that chooses the optimal plan from the enumerated plans. Unfortunately designing such rules remains a highly challenging task. For one, rewrite rules need to be proven correct. In addition, while query equivalence is generally undecidable, we have implemented an automated decision procedure using homotopy type theory, obviously? 

Every database system contains a query optimizer that performs query rewrites. Unfortunately, developing query optimizers remains a highly challenging task. Part of the challenges comes from the intricacies and rich features of query languages, which makes reasoning about rewrite rules difficult. In this paper, we propose a machine-checkable denotational semantics for SQL, the de facto language for interacting with relational databases, for rigorously validating rewrite rules. Unlike previously proposed semantics that are either non-mechanized or only cover a small amount of SQL language features, our semantics covers all major features of SQL, including bags, correlated subqueries, aggregation, and indexes.

Our mechanized semantics, called HoTTSQL, is based on K-Relations and homotopy type theory, where univalence holds. We have implemented HoTTSQL using Coq, an implementation of homotopy type theory, and have proven its correctness. In addition, while query equivalence is generally undecidable, we have implemented an automated decision procedure using homotopy type theory, obviously?
Handles most of the "SQL awkward squad"

- "our semantics covers all major features of SQL, including bags, correlated subqueries, aggregation, and indexes"
- combines HoTT with K-relation semantics used for DB provenance, to dramatically simplify query equivalence proofs
- BUT WAIT....

3.5 Limitations

*HoTT*SQL does not currently support ORDER BY. ORDER BY is usually used with LIMIT $n$, e.g., output the first $n$ tuples in a sorted relation. In addition, we currently do not support NULLs (i.e., 3-valued logic), and leave them as future work.
Meanwhile, back at the ranch...

A Formal Semantics of SQL Queries, Its Validation, and Applications

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ABSTRACT

While formal semantics of theoretical languages underlying SQL have been provided in the past, they all made simplifying assumptions ranging from changes in the syntax to omitting bag semantics and nulls. This situation is reminiscent of what happens in the field of programming languages, where semantics of formal calculi underlying main features of languages are abundant, but formal semantics of real languages that people use are few and far between.

We take the basic class of SQL queries – essentially SELECT-FROM-WHERE queries with subqueries, set/bag operations, and nulls – and define a formal semantics for it, without any departures from the real language. Already this fragment requires decisions related to the data model and handling variables that are normally disregarded.

We prove however that this is not so, as three-valued logic that is universally assumed to be necessary to handle nulls.

Using a reconstruction of the language, thus not accounting of conditions.

We give two applications of the semantics. One is the first formal proof of the equivalence of basic SQL and relational algebra that extends to bag semantics and nulls. The other application looks at the 3-valued logic employed by SQL.

As it needs to account for all its idiosyncrasies. This has been done for several languages [1, 13, 18, 25, 28, 29]; the difference is that to describe such a formal semantics one needs a book, rather than a paper (or sometimes even a book to explain what the first book said [24]).

When it comes to the main query language used by relational DBMSs – SQL – we have the Standard [20], but it cannot serve as a formal semantics, as it is written in natural language. In fact, it is well known that different vendors of RDBMSs interpret various points of the Standard differently (see, e.g., [4, 21]). A natural language description does not lend itself to proper formal reasoning that is necessary to derive language equivalences and optimization rules.

Given the problems of using the Standard as the definition of formal semantics, there have been attempts to formalize
Our project

- Formalize Guagliardo & Libkin semantics of (subset of) SQL with nulls...
  - using "conventional" Coq formalization approach, at least initially
- Try to reconcile with Chu et al.'s HoTTSQL approach
  - also: consider the "adequacy" of HoTT / K-relation interpretation of SQL
- Goal: first full formalization of "real" SQL with nulls
  - + verification or counterexamples to equivalences
Conclusion

- My (group's) research covers a range of topics
  - Programming languages + DB = language integrated query
  - Security + DB = provenance mining
  - Verification + DB = mechanizing metatheory of SQL

- Long-term vision: **verified trustworthy database systems**
  - that provide answers that are **correct** (queries executed correctly)
  - and **trustworthy** (provenance/explanation of how results were derived)