DataCert

Data Centric Systems Deep Specification

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Verification of Algorithms, Languages and Systems

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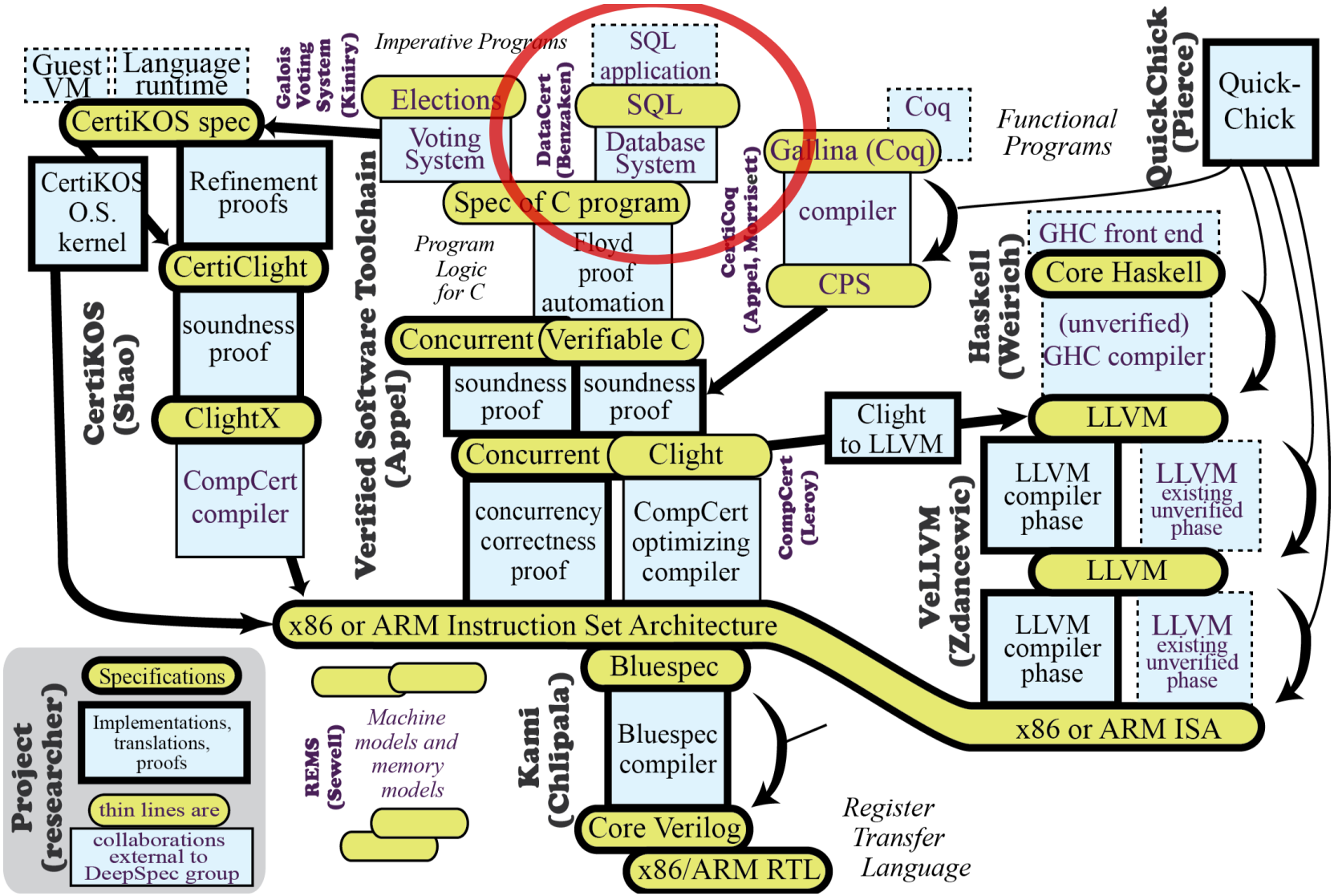
DeepSpec: The Big Project



Motivations

Data are pervasive and valuable ...

Little attention to guarantee systems are reliable and safe.

How to obtain strong guarantees?

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How to obtain strong guarantees? By using formal methods

Promising approach: use of proof assistants such as Coq or Isabelle (e.g., Compcert)

Seminal work by [Malecha et.al] POPL2010

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Promising approach: use of proof assistants such as Coq or Isabelle (e.g., Compcert)

Seminal work by [Malecha et.al] POPL2010 Let's do it!

Long term goal:

Data Centric Programming Languages and System's Coq formalization

Towards Data Centric Systems Deep Specification

First systems of interest: Relational ones

. . . **relational database systems** still play a central role

Beyond relational: NoSQL engines, XML, RDF . . .

Keeping in mind relevant database applications

Education aware: A first Coq formalised course in database systems

Relational model then **SQL**

- Information modeling:

  through relations and tuples

Structure: relation name and sort (finite set of attributes)

r(a, b) relation name **r** sort: {a,b}

- Information extraction:

  through query languages (relational algebra)

Relational Model Deep Specification

Two perspectives:

named vs unnamed

$\mathbf{r} = \{\mathsf{f1}; \mathsf{f2}; \mathsf{f3}\}$

$\mathsf{f1}(\mathsf{a}) = 1, \mathsf{f1}(\mathsf{b}) = 2$
$\mathsf{f2}(\mathsf{a}) = 3, \mathsf{f2}(\mathsf{b}) = 2$
$\mathsf{f3}(\mathsf{a}) = 1, \mathsf{f3}(\mathsf{b}) = 1$

$\mathbf{r} = \{(1, 2); (3, 2); (1, 1)\}$

Relational Model Deep Specification

named (SPJR)

$$q := r \mid \sigma_f(q) \mid \pi_W(q) \mid \rho_g(q) \mid q \bowtie q \mid q \cup q \mid q \cap q \mid q \setminus q$$

unamed (SPC)

$$q := r \mid \sigma_f(q) \mid \pi_W(q) \mid q \times q \mid q \cup q \mid q \cap q \mid q \setminus q$$

Relational Model Deep Specification

[Benzaken et.al] ESOP 2014

More than 20.000 Coq loc

Based on two textbooks:

Abiteboul, Hull, Vianu: Foundations of Databases. Addison-Wesley (1995)

Ullman: Principles of Database Systems, 2nd Edition. Computer Science Press (1982)

We learned a lot

- subtleties hidden in textbooks
- relevant hypotheses
- useless concepts
- sloppy definitions
- lack of formal specifications

SQL: a Simple Declarative Language

SQL "inter-galactic" dialect for manipulating (relational) data

Declarative DSL describe what opposed as how

With attribute's names as first-class citizens

$\Rightarrow$ name-based perspective

SQL: a Simple Declarative Language

Assuming `tbl1(a,b,c)` and `tbl2(d,e)`

```
select a, c from tbl1 where b>3;
```

$$\pi_{\{\mathtt{a},\mathtt{c}\}}(\sigma_{\mathtt{b}>3}(\mathtt{tbl1}))$$

```
select a as a1, c as c1 from tbl1 where b>3;
```

$$\rho_{\{\mathtt{a}\to\mathtt{a1};\mathtt{c}\to\mathtt{c1}\}}(\pi_{\{\mathtt{a},\mathtt{c}\}}(\sigma_{\mathtt{b}>3}(\mathtt{tbl1})))$$

```
select * from tbl1, tbl2 where b=d and c=e;
```

$$\sigma_{\mathtt{b}=\mathtt{d}\wedge\mathtt{c}=\mathtt{e}}(\mathtt{tbl1}\bowtie\mathtt{tbl2})$$

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SQL: a Simple Declarative Language

```
select b, 2*(a+c), sum(a)
from tbl1
where a+b = 7
group by b, a+c
having b > 6;
```

No algebraic semantics

SQL: a Simple Declarative Language

Declarative DSL = ... simple

But

Not so simple ...

SQL: a Simple Declarative Language

Based on relational algebra for the `select-from-where` part

Mixes two algebras: the name based SPJR and the unamed SPC

$\Longrightarrow$ strange behaviours

SQL: Examples

Some queries are rejected while they admit an equivalent algebraic semantics

```
select * from tbl, tbl;
```

Computes either an auto-join or a Cartesian product (up to attribute renaming)

SQL: Examples

Some queries are rejected while they admit an equivalent algebraic semantics

```
select * from tbl, tbl;
ERROR: table name "tbl" specified more than once
```

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Some are accepted but should not be

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select a as c, b as c from tbl;
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select c from (select a as c, b as c from tbl) as t
ERROR: column reference "c" is ambiguous
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Reformulation

```
select a as ca, b as cb from tbl;
```

SQL: Examples

Attributes' order matters

```
table tbl1;
```

```
 a1 | b1 | c1
----+----+---
 1  | 2  | 3
 4  | 5  | 7
(2 rows)
```

```
(select b1, a1, c1 from tbl1)
          intersect
(select a1, b1, c1 from tbl1);
```

```
 b1 | a1 | c1
----+----+---
(0 rows)
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(0 rows)
```

$\cap$ and $\cup$ are not idempotent neither are they associative nor commutative

SQL: Foundational Mismatch

Attribute names are first class citizens

$\Rightarrow$ **name based algebra**

but **unamed** algebra is used

Under database programmer responsability to **manage names in an unamed setting**

Clean name-based formal specification and mechanised semantics are missing

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$\Longrightarrow$ **SQLCert**

Formal Framework: SQLCert

Based on attributes names

Conforming to theoretical foundations

Allow to detect and manage such queries

Define SQL_{Coq}: a formal SQL-friendly grammar

Notion of well-formed queries

`select-from-where-` `group-by-having` with function symbols, aggregates and nested queries

Formal Framework: SQLCert

Define $[\![\_]\!]_{\mathrm{SQL}_{\mathrm{coq}}}$ (`eval_sql_query`) a mechanised semantics for $\mathrm{SQL}_{\mathrm{Coq}}$.

Accepts all well-formed queries

Slight bias between SQL and $\mathrm{SQL}_{\mathrm{Coq}}$ compensated thanks to a reformulation

$\mathrm{SQL}_{\mathrm{Coq}}$: Syntax

```
Inductive sql_query : Type :=
  | Sql_Table : relname → sql_query
  | Sql_Set : set_op → sql_query → sql_query → sql_query
  | Sql_Select :
      (* select *) select_item →
      (* from *) list from_item →
      (* where *) sql_formula →
      (* group by *) group_by →
      (* having *) sql_formula → sql_query
with from_item : Type := [...]
with sql_formula : Type := [...]
with sql_atom : Type :=
  | Sql_True : sql_atom
  | Sql_Pred : predicate → list aggterm → sql_atom
  | Sql_Quant :
    quantifier -> predicate -> list aggterm -> sql_query -> sql_atom
  | Sql_In :  select_item -> sql_query -> sql_atom.
```

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```

SQL_{Coq}: Semantics

```
Fixpoint eval_sql_query (sq : sql_query) {struct sq} : setT :=
  match sq with
  | Sql_Table tbl => instance tbl
  | Sql_Set o sq1 sq2 =>
     if sql_sort sq1 =S?= sql_sort sq2 then [...] else emptySE
  | Sql_Select s lsq w gby h =>
     let elsq := (* evaluation of the from part [lsq] *)
         map eval_from_item lsq in
     let cc := (* selection of the from part by the where formula [w]
                  (with old names) *)
         filter (fun t => eval_sql_formula w (Tpl t))
                (plain_product elsq) in
     let lg1 := (* computation of the groups grouped according to [gby] *)
         make_groups cc gby in
     let lg2 := (* discarding groups according the having clause [h] *)
         filter (fun g => eval_sql_formula h (Grp g)) lg1 in
       (* applying the outermost projection and renaming,
          the select part [s] *)
       Set.map (fun g => projection s (Grp g)) lg2
  end with [...]
```

Formal Framework: SQLCert

Related to an (extended) relational algebra (`eval_equery`)

Coq mechanised parser $\mathscr{T}$ (`sql_to_alg`), of $\mathsf{SQL}_{\mathsf{Coq}}$ to our, name-based algebra with its Coq adequation proof and its Ocaml extraction

Adequation Theorem

Theorem

Let sq be a well-formed SQL_{Coq} query then

$$[\![sq]\!]_{SQL_{coq}} = [\![\mathscr{T}(sq)]\!]_{ALG_{Ext}}$$

```
Lemma sql_to_alg_is_sound :
∀ ip is ia I, well_sorted_instance I →
  ∀ n q sq, sql_to_alg n sq = Translation q →
     well_formed_sql_query sq = true →
      eval_sql_query ip is ia I sq =SE=
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```

Adequation Theorem

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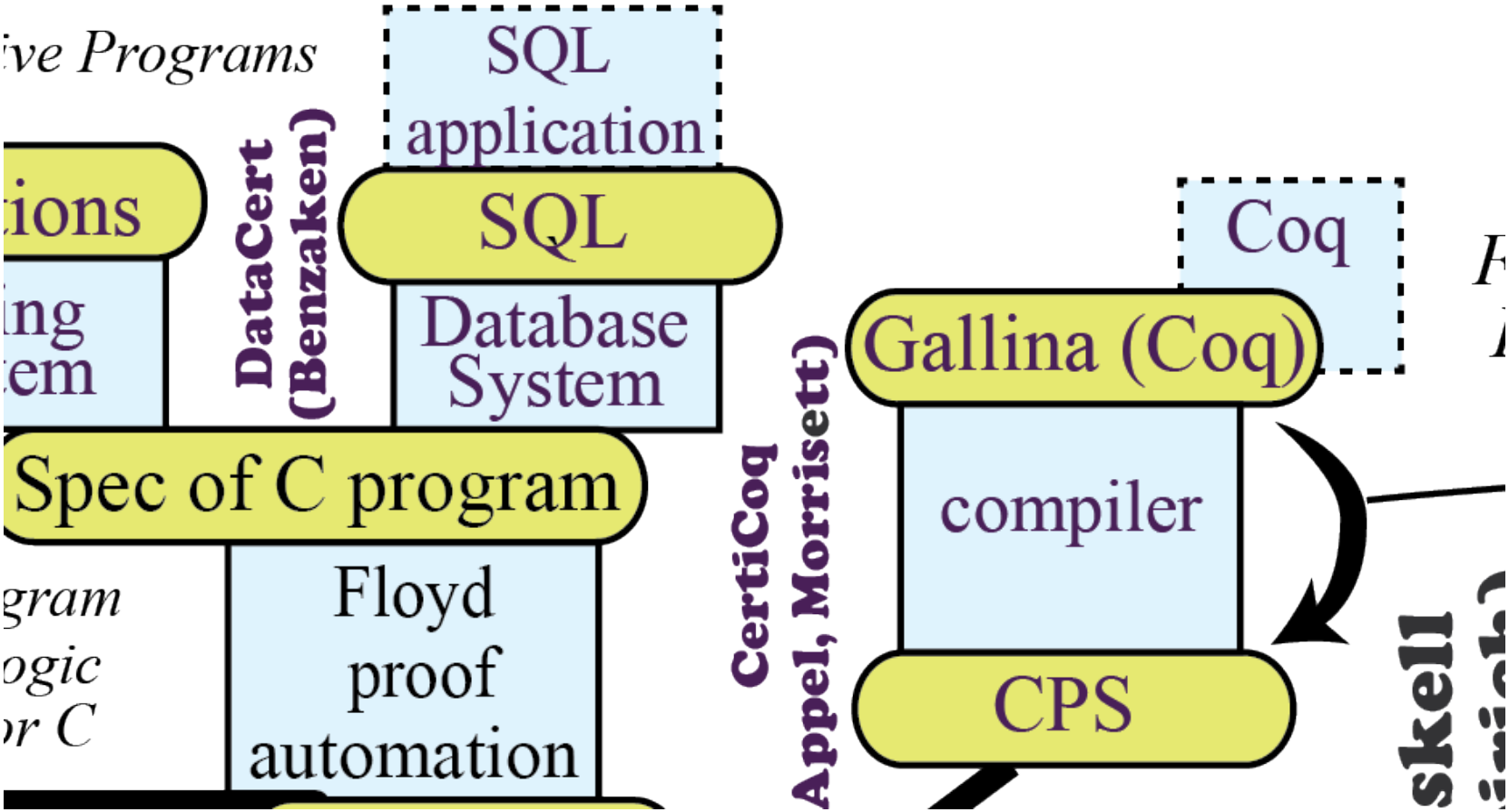
DataCert and DeepSpec

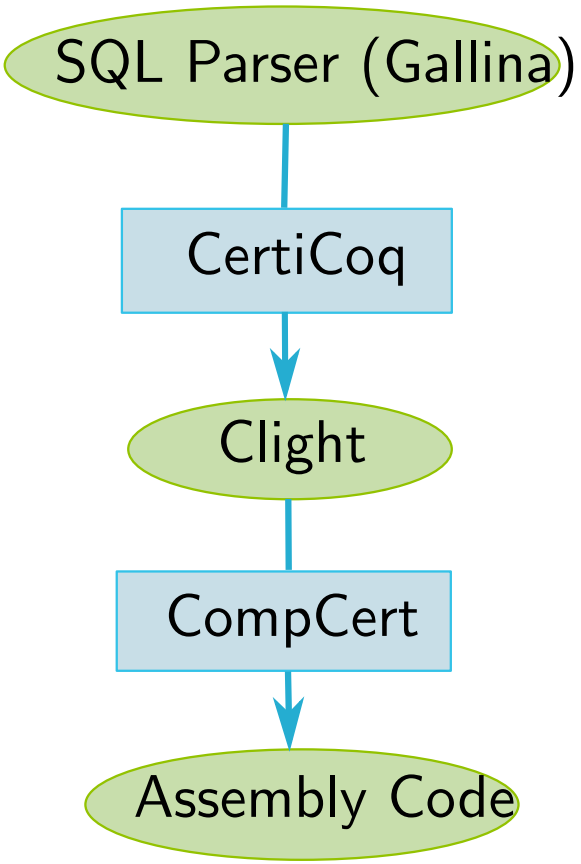


Short Term: Certified SQL Query Evaluation

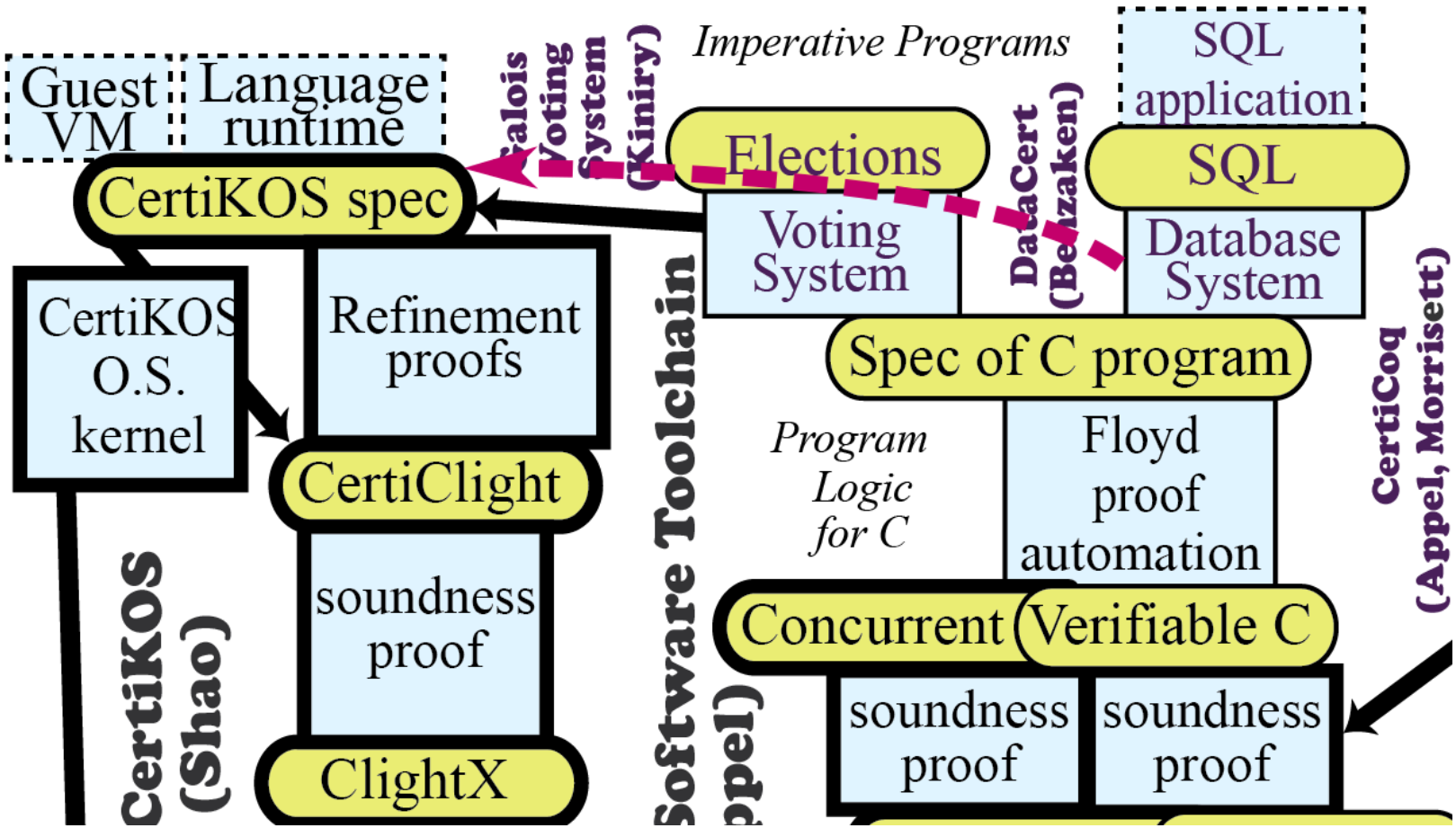
Use CertiCoq

SQL_{Coq} queries translated into Clight

Compare its execution times on various DB instances



Long Term: A Minimal Realistic Relational Engine



Long Term: A Minimal Realistic Relational Engine

Real SQL engines/relational databases' implementations are very involved and have a long-standing history

Their code is not modular at all

Formally verifying them could be a painful task

Rather: deeply specify a small, realistic database based on mCertiKOS Hypervisor.

Conclusions

SQLCert a realistic formalisation of SQL

Based on attributes names

Conforming to theoretical foundations

Around 32.000 Coq loc

Next step: query planner

Also: updates + data integrity and privacy