Can We Trust SQL as a Data Analytics Tool?

SQL

- **The** query language for relational databases
- International Standard since 1987
- Implemented in all systems (free and commercial)
- **$30B/year** business
- Most common tool used by data scientists

Main Questions

- Do we understand SQL queries, even simple ones?
- And if we think we do, do query results make sense?

Asking these questions now?

A bit of history:
before 1969, various ad-hoc database modes (network, hierarchical)

writing queries: a very elaborate task

All changed in 1969: Codd's relational model;
now dominates the world.

Query writing made easy: **SQL**

Relational Model

Orders

ORDER_ID	TITLE	PRICE
Ord1	“Big Data”	30
Ord2	“SQL”	35
Ord3	“Logic”	50

Pay

CUST_ID	ORDER
c1	Ord1
c2	Ord2

Customer

CUST_ID	NAME
c1	John
c2	Mary

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Language: **Relational Algebra (RA)**

- projection **π** (find book titles)
- selection **σ** (find books that cost at least £40)
- Cartesian product **×**
- union **U**
- difference **-**

Queries

Find ids of customers who buy all books:

$$\pi_{\text{cust\_id}}\,(\text{Pay})\;-$$

$$\pi_{\text{cust\_id}}\left((\pi_{\text{cust\_id}}(\text{Pay}) \times \pi_{\text{title}}(\text{Order})\right) -$$

$$\pi_{\text{cust\_id,title}}\left(\sigma_{\text{order\_id=order}}\,(\text{Order} \times \text{Pay})\right)\Big)$$

Queries

Find ids of customers who buy all books:

$$\pi_{\text{cust\_id}} (\text{Pay}) - \pi_{\text{cust\_id}} \Big((\pi_{\text{cust\_id}}(\text{Pay}) \times \pi_{\text{title}}(\text{Order})\Big) - \pi_{\text{cust\_id,title}} \Big(\sigma_{\text{order\_id=order}} (\text{Order} \times \text{Pay})\Big)\Big)$$

That's not pretty. But here is a better idea (1971): express queries in **logic**

Queries

Find ids of customers who buy all books:

$$\pi_{\text{cust\_id}}(\text{Pay}) - \pi_{\text{cust\_id}}\Big(\big(\pi_{\text{cust\_id}}(\text{Pay}) \times \pi_{\text{title}}(\text{Order})\big) - \pi_{\text{cust\_id,title}}\big(\sigma_{\text{order\_id=order}}(\text{Order} \times \text{Pay})\big)\Big)$$

That's not pretty. But here is a better idea (1971):
express queries in **logic**

$$\{c \mid \forall(o,t,p) \in \text{Order}\ \ \exists\,(o',t,p') \in \text{Order}: (c,o') \in \text{Pay}\}$$

Queries

Find ids of customers who buy all books:

π_{cust_id} (Pay) -

π_{cust_id} ((π $_{cust\_id}$(Pay) $\times$ π_{title}(Order)) -

$\pi_{cust\_id,title}$ ($\sigma_{order\_id=order}$ (Order $\times$ Pay)))

That's not pretty. But here is a better idea (1971):
express queries in **logic**

{c | ∀(o,t,p) ∊ Order ∃ (o',t,p') ∊ Order: (c,o') ∊ Pay}

This is *first-order logic* (FO).
Codd 1971: ***RA = FO***.

History continued

Of course programmers don't write logical sentences, they need a programming syntax. Enters **SQL:**

```
SELECT P.cust_id FROM P
WHERE NOT EXISTS
     (SELECT * FROM Order O
      WHERE NOT EXISTS
          (SELECT * FROM Order O1
           WHERE O1.title=O.title AND O1.order_id=P.order))
```

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- Take FO and turn into into programming syntax:
- Committee design!
- Then use RA to implement queries.

SQL development

- Standards: SQL-86, SQL-89, SQL-92, SQL:1999, SQL:2003, SQL:2008, SQL:2011, SQL:2016
  - The latest standard will make you $1000 poorer
- The core remains the same.
- And yet things are not as obvious as they should be.
- Now a few quiz-type slides….

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Compute R - S.

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and that they can do it directly in SQL:

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select * from r except select * from s
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null

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A
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1
null

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select * from r  except  select * from s
```

A
1

SELECT * should be simple, no?

R

Q = SELECT R.A, R.A FROM R on

A
1

gives

A	A
1	1

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`Q = SELECT R.A, R.A FROM R` on

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Let’s use it as a subquery:

`Q’ = SELECT * FROM (Q) AS T`

SELECT * should be simple, no?

`Q = SELECT R.A, R.A FROM R` on

R

A
1

gives

A	A
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<u>Output:</u>

- Postgres: as above
- Oracle, MS SQL Server: compile-time error

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SELECT R.A FROM R WHERE EXISTS (Q')

SELECT * should be simple, no?

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gives

A	A
1	1

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`SELECT R.A FROM R WHERE EXISTS (Q')`

Answer:

A
1

SELECT * should be simple, no?

`Q = SELECT R.A, R.A FROM R` on

R

A
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gives

A	A
1	1

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- Postgres: as above
- Oracle, MS SQL Server: compile-time error

`SELECT R.A FROM R WHERE EXISTS (Q’ )`

Answer:

A
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Except in MySQL

Another example: Query equivalences

Q1(x) :- T(x,y)
Q2(x) :- T(x,y), T(u,v)

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In theory: equivalent; on

A	B
1	2
3	4

return

A
1
3

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Now the same in SQL:

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Now the same in SQL:

Q1 = `SELECT R.A FROM R` returns

A
1
3

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Q1(x) :- T(x,y)
Q2(x) :- T(x,y), T(u,v)

In theory: equivalent; on

A	B
1	2
3	4

return

A
1
3

Now the same in SQL:

Q1 = `SELECT R.A FROM R` returns

A
1
3

Q2 = `SELECT R1.A FROM R R1, R R2` returns

A
1
1
3
3

Why do we find these questions difficult?

- Reason 1: there is no formal semantics of SQL.
  - The Standard is rather vague, not written formally, and different vendors interpret it differently.
- Reason 2: theory works with a simplified model, no nulls, no duplicates, no repeated attributes.
  - Under these assumptions several semantics exist (1985 - 2017) but they do not model the real language.

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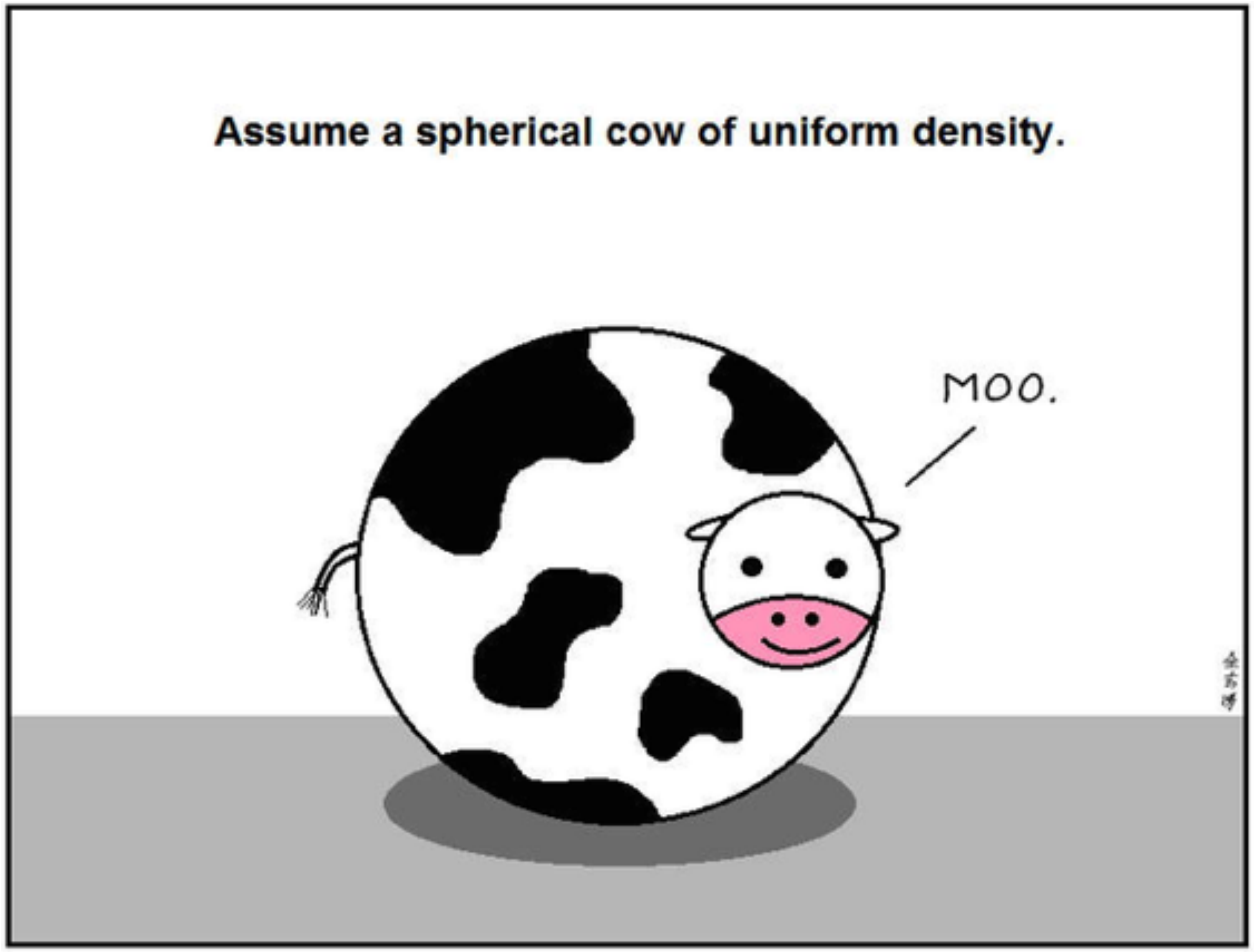
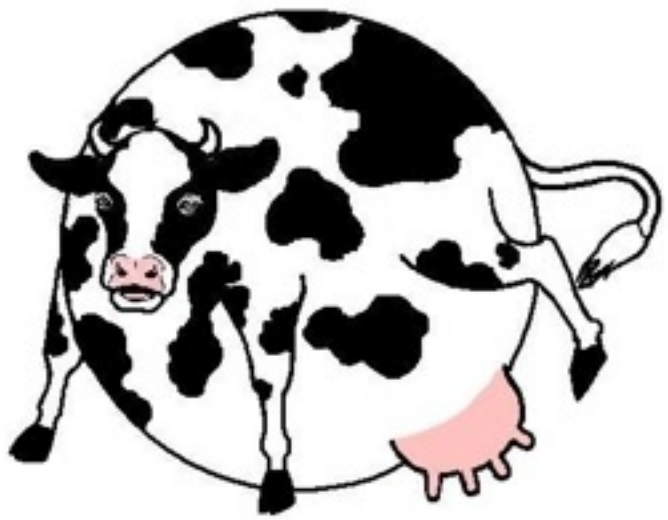


From spherical to real cows



- We do it for the basic fragment of SQL:
    - `SELECT-FROM-WHERE` without aggregation
    - but with pretty much everything else

[G.,L. *A Formal Semantics of SQL Queries, its Validation and Applications*. PVLDB 2017]

Syntax

$$\tau : \beta \;:=\; T_1 \;\texttt{AS}\; N_1,\; \ldots,\; T_k \;\texttt{AS}\; N_k \quad \text{for } \tau = (T_1, \ldots, T_k),\; \beta = (N_1, \ldots, N_k), \quad k > 0$$

$$\alpha : \beta' \;:=\; t_1 \;\texttt{AS}\; N'_1,\; \ldots,\; t_m \;\texttt{AS}\; N'_k \quad \text{for } \alpha = (t_1, \ldots, t_m),\; \beta' = (N'_1, \ldots, N'_m),\; m > 0$$

QUERIES:

$$\begin{aligned} Q \;:=\;& \texttt{SELECT}\; [\texttt{DISTINCT}]\; \alpha : \beta' \;\texttt{FROM}\; \tau : \beta \;\texttt{WHERE}\; \theta \\ \mid\;& \texttt{SELECT}\; [\texttt{DISTINCT}]\; * \;\texttt{FROM}\; \tau : \beta \;\texttt{WHERE}\; \theta \\ \mid\;& Q\; (\texttt{UNION} \mid \texttt{INTERSECT} \mid \texttt{EXCEPT})\; [\texttt{ALL}]\; Q \end{aligned}$$

CONDITIONS:

$$\begin{aligned} \theta \;:=\;& \texttt{TRUE} \mid \texttt{FALSE} \mid P(t_1, \ldots, t_k),\; P \in \mathcal{P} \\ \mid\;& t \;\texttt{IS}\; [\texttt{NOT}]\; \texttt{NULL} \\ \mid\;& \bar{t}\; [\texttt{NOT}]\; \texttt{IN}\; Q \mid \texttt{EXISTS}\; Q \\ \mid\;& \theta \;\texttt{AND}\; \theta \mid \theta \;\texttt{OR}\; \theta \mid \texttt{NOT}\; \theta \end{aligned}$$

Names: either simple (R, A) or composite (R.A)

Terms t: constants, nulls, or composite names

Predicates: anything you want on constants

Semantics: labels

$$\ell(R) = \text{tuple of names provided by the schema}$$

$$\ell(\tau) = \ell(T_1)\cdots\ell(T_k) \quad \text{for } \tau = (T_1,\ldots,T_k)$$

$$\ell\begin{pmatrix} \texttt{SELECT}\ [\texttt{DISTINCT}]\ \alpha : \beta' \\ \texttt{FROM}\ \tau : \beta\ \texttt{WHERE}\ \theta \end{pmatrix} = \beta'$$

$$\ell\big(\texttt{SELECT}\ [\texttt{DISTINCT}] * \texttt{FROM}\ \tau : \beta\ \texttt{WHERE}\ \theta\big) = \ell(\tau)$$

$$\ell\big(Q_1\ (\texttt{UNION} \mid \texttt{INTERSECT} \mid \texttt{EXCEPT})\ [\texttt{ALL}]\ Q_2\big) = \ell(Q_1)$$

Semantics

$$[\![Q]\!]_{D,\eta,x}$$

Q: query

D: database

η: environment (values for composite names)

x: Boolean switch to account for non-compositional nature of SELECT * (to show where we are in the query)

Semantics of terms

$$\llbracket t \rrbracket_\eta = \begin{cases} \eta(A) & \text{if } t = A \\ c & \text{if } t = c \in \mathsf{C} \\ \texttt{NULL} & \text{if } t = \texttt{NULL} \end{cases}$$

$$\llbracket (t_1, \ldots, t_n) \rrbracket_\eta = \big(\llbracket t_1 \rrbracket_\eta, \ldots, \llbracket t_n \rrbracket_\eta \big)$$

Semantics: queries

$$[\![R]\!]_{D,\eta,x} = R^D$$

$$[\![\tau:\beta]\!]_{D,\eta,x} = [\![T_1]\!]_{D,\eta,0} \times \cdots \times [\![T_k]\!]_{D,\eta,0} \quad \text{for } \tau = (T_1,\ldots,T_k)$$

$$\left[\!\!\left[\begin{array}{rl} \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,x} = \left\{ \underbrace{\bar r,\ldots,\bar r}_{k \text{ times}} \;\middle|\; \bar r \in_k [\![\tau:\beta]\!]_{D,\eta,0},\ \ [\![\theta]\!]_{D,\eta'} = \mathbf{t},\ \ \eta' = \eta \overset{\bar r}{\oplus} \ell(\tau:\beta) \right\}$$

$$\left[\!\!\left[\begin{array}{rl} \textbf{SELECT} & \alpha:\beta' \\ \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,x} = \left\{ \underbrace{[\![\alpha]\!]_{\eta'},\ldots,[\![\alpha]\!]_{\eta'}}_{k \text{ times}} \;\middle|\; \eta' = \eta \overset{\bar r}{\oplus} \ell(\tau:\beta),\ \ \bar r \in_k \left[\!\!\left[\begin{array}{rl} \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,x} \right\}$$

$$\left[\!\!\left[\begin{array}{rl} \textbf{SELECT} & * \\ \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,0} = \left[\!\!\left[\begin{array}{rl} \textbf{SELECT} & \ell(\tau:\beta):\ell(\tau) \\ \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,0}$$

$$\left[\!\!\left[\begin{array}{rl} \textbf{SELECT} & * \\ \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,1} = \left[\!\!\left[\begin{array}{rl} \textbf{SELECT} & c \ \textbf{AS} \ N \\ \textbf{FROM} & \tau:\beta \\ \textbf{WHERE} & \theta \end{array}\right]\!\!\right]_{D,\eta,1} \quad \text{for arbitrary } c \in \mathsf{C} \text{ and } N \in \mathsf{N}$$

$$\left[\!\!\left[\begin{array}{l} \textbf{SELECT DISTINCT } \alpha:\beta' \mid * \\ \textbf{FROM } \tau:\beta \textbf{ WHERE } \theta \end{array}\right]\!\!\right]_{D,\eta,x} = \varepsilon\left(\left[\!\!\left[\begin{array}{l} \textbf{SELECT } \alpha:\beta' \mid * \\ \textbf{FROM } \tau:\beta \textbf{ WHERE } \theta \end{array}\right]\!\!\right]_{D,\eta,x} \right)$$

Semantics: conditions

$$[\![P(t_1,\ldots,t_k)]\!]_{D,\eta} = \begin{cases} \mathbf{t} & \text{if } P\big([\![t_1]\!]_\eta,\ldots,[\![t_k]\!]_\eta\big) \text{ holds and } [\![t_i]\!]_\eta \neq \texttt{NULL} \text{ for all } i \in \{1,\ldots,k\} \\ \mathbf{f} & \text{if } P\big([\![t_1]\!]_\eta,\ldots,[\![t_k]\!]_\eta\big) \text{ does not hold and } [\![t_i]\!]_\eta \neq \texttt{NULL} \text{ for all } i \in \{1,\ldots,k\} \\ \mathbf{u} & \text{if } [\![t_i]\!]_\eta = \texttt{NULL} \text{ for some } i \in \{1,\ldots,k\} \end{cases}$$

$$[\![t \texttt{ IS NULL}]\!]_{D,\eta} = \begin{cases} \mathbf{t} & \text{if } [\![t]\!]_\eta = \texttt{NULL} \\ \mathbf{f} & \text{if } [\![t]\!]_\eta \neq \texttt{NULL} \end{cases}$$

$$[\![t \texttt{ IS NOT NULL}]\!]_{D,\eta} = \neg[\![t \texttt{ IS NULL}]\!]_{D,\eta}$$

$$[\![(t_1,\ldots t_n) = (t'_1,\ldots,t'_n)]\!]_{D,\eta} = \bigwedge_{i=1}^{n} [\![t_i = t'_i]\!]_{D,\eta} \qquad [\![(t_1,\ldots t_n) \neq (t'_1,\ldots,t'_n)]\!]_{D,\eta} = \bigvee_{i=1}^{n} [\![t_i \neq t'_i]\!]_{D,\eta}$$

$$[\![\bar{t} \texttt{ IN } Q]\!]_{D,\eta} = \begin{cases} \mathbf{t} & \text{if } \exists \bar{r} \in [\![Q]\!]_{D,\eta,0} \text{ s.t. } [\![\bar{t} = \bar{r}]\!]_{D,\eta} = \mathbf{t} \\ \mathbf{f} & \text{if } \forall \bar{r} \in [\![Q]\!]_{D,\eta,0} \text{ s.t. } [\![\bar{t} = \bar{r}]\!]_{D,\eta} = \mathbf{f} \\ \mathbf{u} & \text{if } \nexists \bar{r} \in [\![Q]\!]_{D,\eta,0} \text{ s.t. } [\![\bar{t} = \bar{r}]\!]_{D,\eta} = \mathbf{t} \text{ and } \exists \bar{r} \in [\![Q]\!]_{D,\eta,0} \text{ s.t. } [\![\bar{t} = \bar{r}]\!]_{D,\eta} \neq \mathbf{f} \end{cases}$$

$$[\![\bar{t} \texttt{ NOT IN } Q]\!]_{D,\eta} = \neg[\![\bar{t} \texttt{ IN } Q]\!]_{D,\eta}$$

$$[\![\texttt{EXISTS } Q]\!]_{D,\eta} = \begin{cases} \mathbf{t} & \text{if } [\![Q]\!]_{D,\eta,1} \neq \varnothing \\ \mathbf{f} & \text{if } [\![Q]\!]_{D,\eta,1} = \varnothing \end{cases}$$

$$[\![\texttt{TRUE}]\!]_{D,\eta} = \mathbf{t} \qquad [\![\theta_1 \texttt{ AND } \theta_2]\!]_{D,\eta} = [\![\theta_1]\!]_{D,\eta} \wedge [\![\theta_2]\!]_{D,\eta} \qquad [\![\texttt{NOT } \theta]\!]_{D,\eta} = \neg[\![\theta]\!]_{D,\eta}$$

$$[\![\texttt{FALSE}]\!]_{D,\eta} = \mathbf{f} \qquad [\![\theta_1 \texttt{ OR } \theta_2]\!]_{D,\eta} = [\![\theta_1]\!]_{D,\eta} \vee [\![\theta_2]\!]_{D,\eta}$$

Truth Tables:

$\wedge$	t	f	u
t	**t**	**f**	**u**
f	**f**	**f**	**f**
u	**u**	**f**	**u**

$\vee$	t	f	u
t	**t**	**t**	**t**
f	**t**	**f**	**u**
u	**t**	**u**	**u**

	$\neg$
t	**f**
f	**t**
u	**u**

Semantics: operations

$$
\begin{aligned}
[\![Q_1 \ \textbf{UNION ALL}\ Q_2]\!]_{D,\eta,x} &= [\![Q_1]\!]_{D,\eta,0} \cup [\![Q_2]\!]_{D,\eta,0} \\
[\![Q_1 \ \textbf{INTERSECT ALL}\ Q_2]\!]_{D,\eta,x} &= [\![Q_1]\!]_{D,\eta,0} \cap [\![Q_2]\!]_{D,\eta,0} \\
[\![Q_1 \ \textbf{EXCEPT ALL}\ Q_2]\!]_{D,\eta,x} &= [\![Q_1]\!]_{D,\eta,0} - [\![Q_2]\!]_{D,\eta,0} \\
[\![Q_1 \ \textbf{UNION}\ Q_2]\!]_{D,\eta,x} &= \varepsilon\big([\![Q_1 \ \textbf{UNION ALL}\ Q_2]\!]_{D,\eta,x}\big) \\
[\![Q_1 \ \textbf{INTERSECT}\ Q_2]\!]_{D,\eta,x} &= \varepsilon\big([\![Q_1 \ \textbf{INTERSECT ALL}\ Q_2]\!]_{D,\eta,x}\big) \\
[\![Q_1 \ \textbf{EXCEPT}\ Q_2]\!]_{D,\eta,x} &= \varepsilon\big([\![Q_1]\!]_{D,\eta,0}\big) - [\![Q_2]\!]_{D,\eta,0}
\end{aligned}
$$

Bag interpretation of operations; ϵ is duplicate elimination

Looks simple, no?

- It does not. Such basic things as variable binding changed several times till we got them right.

- The meaning of the new environment:

$$\left[\!\!\left[\begin{array}{ll} \mathbf{FROM} & \tau : \beta \\ \mathbf{WHERE} & \theta \end{array} \right]\!\!\right]_{D,\eta,x} = \left\{ \underbrace{\bar{r},\ldots,\bar{r}}_{k \text{ times}} \;\middle|\; \bar{r} \in_k [\![\tau : \beta]\!]_{D,\eta,0},\;\; [\![\theta]\!]_{D,\eta'} = \mathbf{t},\; \boxed{\eta' = \eta \overset{\bar{r}}{\oplus} \ell(\tau : \beta)} \right\}$$

  - in η, unbind every name that occurs among labels of the FROM clause

  - then bind non-repeated names among those to values taken from record r

How do we know we this is correct?

- Since the Standard is rather vague, there is only one way — **experiments.**
- But what kind of benchmark can we use?
- For performance studies there are standard benchmarks like TPC-H. But they won’t work for us: not enough queries.

Experimental Validation

- Benchmarks have rather few queries (22 in TPC-H). Validating on 22 queries is not a good evidence.
- But we can look at benchmarks, and then generate lots of queries that look the same.
- In TPC-H:
  - 8 tables,
  - maximum nesting depth = 3,
  - average number of tables per query = 3.2,
  - at most 8 conditions in WHERE (except two queries)

Validation: results

- Small adjustments of the Standard semantics (for Postgres and Oracle)
- Random query generator
- Naive implementation of the semantics
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- Random query generator
- Naive implementation of the semantics
- Finally: experiments on 100,000 random queries
- **Yes, it is correct!**

What can we do with this?

- Equivalence of basic SQL and Relational Algebra: formally proved for the first time
    - Previous attempts (Ceri and Gottlob, Van den Bussche and Vansummeren restricted the language severely: no nulls, for example).
- 3-valued logic of SQL vs the usual Boolean logic: 3-valued logic does not add expressiveness.
    - Although it does not mean we should get rid of it now…

Does it matter which DBMS we use?

- We already saw it does. In fact in our experiments we adjusted things a bit for Postgres and Oracle.
- But how much of a difference does it make?
- We have a random query generator, so let's experiment:
  - generate lots of queries (over 150K)
  - send to standard DBMSs (Oracle, MySQL, MS SQL Server, PostgreSQL, IBM DB2)
  - and see what happens…

Discrepancies between RDBMSs

- About 2% of queries do not behave the same way on different DBMSs
    - and they come from the most basic fragment
- Lots of issues are minor and syntactic
    - different syntax for set operations (eg `EXCEPT` vs `MINUS`) or functions (eg `%` vs `MOD`, or `substring` vs `substr`)
- But some are serious - and surprise even people with good SQL knowledge. Four of the most surprising examples to follow…

Is empty string equal to itself?

```
SELECT *
FROM   R
WHERE  ''=''
```

Is empty string equal to itself?

```
SELECT *
FROM   R
WHERE ‘’=‘’
```

- Usually it is, but not in Oracle: the above query always returns the empty table.
- Because Oracle implements NULL as ‘’
- Madness? Yes. With a string operation that produces ‘’ you deal with 3-valued logic before you realize it!

Can you divide by zero?

```
SELECT  R.A/S.B
FROM    R, S

R={1},  S={0}
```

Can you divide by zero?

```
SELECT R.A/S.B
FROM   R, S

R={1},  S={0}
```

- Usually not except in MySQL 5.6
- It returns NULL
- OK, they realized it in MySQL 5.7 and now by default it's a warning. But one can go back to the 5.6 mode if one wishes…

Is equality transitive?

`x=y and y=z imply x=z, right?`

Is equality transitive?

`x=y and y=z imply x=z, right?`

- Usually yes, but not in MySQL
- x=’1a’, y=1, z=‘1b’
- Why is this a problem? SQL books teach programmers to overspecify join conditions: to `R.A=S.A AND S.A=T.A` add explicitly `R.A=T.A`
- But now it can turn a true condition into false!

Can you compare tuples in IN subqueries?

```
SELECT  *
FROM    R
WHERE  (R.A, R.B) IN SELECT (S.A, S.B FROM S)
```

Can you compare tuples in IN subqueries?

```
SELECT  *
FROM    R
WHERE  (R.A, R.B) IN SELECT (S.A, S.B FROM S)
```

- Usually yes, except in MS SQL Server.
- Why? No clue…

- Also SQL Server has UNION but no UNION ALL.
- Please explain this.

A simple tool

- We actually have a tool that lets you:
  - specify parameters of a query workload
  - generate lots of random queries, and
  - run against DBMSs you want to compare
- Have fun with results… at least you know what to expect.