Incomplete Information
SQL’s handling of incompleteness is problematic

“... this topic cannot be described in a manner that is simultaneously both comprehensive and comprehensible”

“Those SQL features are ... fundamentally at odds with the way the world behaves”

C. Date & H. Darwen, ‘A Guide to SQL Standard’

“If you have any nulls in your database, you’re getting wrong answers to some of your queries. What’s more, you have no way of knowing, in general, just which queries you’re getting wrong answers to; all results become suspect. You can never trust the answers you get from a database with nulls”

C. Date, ‘Database in Depth’
But it must be handled...

- Incomplete data is everywhere.
- Represented by nulls in relational databases.
- The more data we accumulate, the more incomplete data we accumulate.
- Sources:
  - Traditional (missing data, wrong entries, etc)
  - The Web
  - Integration/translation/exchange of data, etc
- The importance of it was recognized early
  - Codd, “Understanding relations (installment #7)”, 1975.
- And yet the state is very poor.
## Company database – orders, customers, payments

<table>
<thead>
<tr>
<th>Order ID</th>
<th>Title</th>
<th>Price</th>
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<tbody>
<tr>
<td>Ord1</td>
<td>“Big Data”</td>
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<tr>
<td>Ord2</td>
<td>“SQL”</td>
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<tr>
<td>Ord3</td>
<td>“Logic”</td>
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<tr>
<th>Cust ID</th>
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<td>Ord1</td>
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### Queries, as we teach students to write them:

**Unpaid orders (Customers without an order):**

```sql
SELECT O.order_id 
FROM Orders O 
WHERE NOT EXISTS ( 
  SELECT * FROM Pay P, Customer C 
  WHERE C.cust_id = P.cust_id AND P.order_id = O.order_id
)
```

**Answer:** Ord3

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**Topics in FD 2017:** Incomplete and inconsistent data
Company database – orders, customers, payments

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<tr>
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Queries, as we teach students to write them:

Unpaid orders
SELECT O.order_id
FROM Orders O
where O.order_id not in
(select order from Pay)

Customers without an order
select Ccust_id from Customer C
where not exists
(SELECT * from Orders O, Pay P
where Ccust_id=Pcust_id
and P.order=O.order_id)
## Company database – orders, customers, payments

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### Queries, as we teach students to write them:

#### Unpaid orders

**SELECT** 0.order_id  
**FROM** Orders 0  
**WHERE** 0.order_id not in (select order from Pay)  

**Answer:** Ord3

#### Customers without an order

**SELECT** C.cust_id from Customer C  
**WHERE** not exists (SELECT * from Orders O, Pay P  
where C.cust_id=P.cust_id  
and P.order=0.order_id)  

**Answer:** none
Company database – orders, customers, payments

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Queries, as we teach students to write them:

Unpaid orders

SELECT O.order_id
FROM Orders O
where O.order_id not in
(select order from Pay)

Customers without an order

select C.cust_id from Customer C
where not exists
(SELECT * from Orders O, Pay P
where C.cust_id=P.cust_id
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Company database – orders, customers, payments

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Queries, as we teach students to write them:

Unpaid orders

```sql
SELECT O.order_id
FROM Orders O
where O.order_id not in
    (select order from Pay)

Answer: Ø/none
```

Customers without an order

```sql
SELECT C.cust_id from Customer C
where not exists
    (SELECT * from Orders O, Pay P
    where C.cust_id=P.cust_id
    and P.order=O.order_id)

Answer: none c2
```
What it’s blamed on: 3-valued logic

SQL used 3-valued logic, or 3VL, for databases with nulls.

Normally we have two truth values: true $t$, false $f$. But comparisons involving nulls evaluate to unknown ($u$): for instance, $5 = \text{null}$ is $u$.

They are propagated using 3VL rules:

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<thead>
<tr>
<th>$\land$</th>
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> Committee design from 30 years ago, leads to many problems,
> but is efficient and used everywhere
What does theory have to offer?

The notion of correctness — certain answers.

- Answers independent of the interpretation of missing information.
- Typically defined as

$$\text{certain}(Q, D) = \bigcap Q(D')$$

over all possible worlds $D'$ described by $D$

- Standard approach, used in all applications: data integration and exchange, inconsistent data, querying with ontologies, data cleaning, etc.
- First need to define what an incomplete database can represent.
The model

Marked (aka labeled or naive) nulls. Idea: missing values, that can repeat.

Semantics: closed world

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<td>2</td>
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The model

**Marked** (aka labeled or naive) nulls. Idea: missing values, that can repeat.

**Semantics: closed world**

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<tr>
<td>1</td>
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<td>(\perp_1)</td>
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<td>(\perp_2)</td>
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\[ h(\perp_1) = 4 \]
\[ h(\perp_2) = 3 \]
\[ h(\perp_3) = 5 \]

\[ \Rightarrow \]

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SQL model: a special case when all nulls are distinct.
The model

Marked (aka labeled or naive) nulls. Idea: missing values, that can repeat.

Semantics: closed world

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\[ h(⊥₁) = 4 \]
\[ h(⊥₂) = 3 \]
\[ h(⊥₃) = 5 \]

\[ \implies \]

<table>
<thead>
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SQL model: a special case when all nulls are distinct.
Open worlds semantics

\[ h(\bot_1) = 4 \]
\[ h(\bot_2) = 3 \]
\[ h(\bot_3) = 5 \]

\[ \implies \]

\begin{array}{ccc}
A & B & C \\
1 & 2 & \bot_1 \\
\bot_2 & \bot_1 & 3 \\
\bot_3 & 5 & 1 \\
2 & \bot_3 & 3 \\
\end{array}

\begin{array}{ccc}
A & B & C \\
1 & 2 & 4 \\
3 & 4 & 3 \\
5 & 5 & 1 \\
2 & 5 & 3 \\
7 & 9 & 12 \\
11 & 8 & 10 \\
\end{array}
Semantics via homomorphisms/valuations

Maps $h$ are homomorphisms whose range does not include nulls. They are called valuation. A normal homomorphism:

- $h(c) = c$ for every constant value $c$
- $h(\bot)$ could be a null or a constant value

In a valuation,

- $h(c) = c$ for every constant value $c$
- $h(\bot)$ must be a constant value

They define open world semantics $\llbracket D \rrbracket_\text{owa}$ and closed world semantics $\llbracket D \rrbracket_\text{cwa}$

- semantics under open world and closed world assumptions
Semantics via homomorphisms/valuations

\[ [D]_{\text{cwa}} = \{ h(D) \mid h \text{ is a valuation} \} \]

\[ [D]_{\text{owa}} = \{ \text{complete } D' \mid \exists \text{ valuation } h : D \rightarrow D' \} \]

Alternatively:

\[ [D]_{\text{owa}} = \{ h(D) \cup D_0 \mid h \text{ is a valuation, } D_0 \text{ does not have nulls} \} \]
**Certain answers**

Tuples present in query answers in all possible world:

\[
\text{certain}_{CWA}(Q, D) = \bigcap \{ Q(D') \mid D' \in [D]_{cwa} \}
\]

\[
\text{certain}_{OWA}(Q, D) = \bigcap \{ Q(D') \mid D' \in [D]_{owa} \}
\]

Note that tuples in certain answers cannot have nulls, i.e. they only have constant values.
Can SQL evaluation and certain answers be the same?

No!

Complexity argument:
- Finding certain answers for relational calculus queries in coNP-hard
- SQL is very efficient (DLOGSPACE; even AC$^0$)
Complexity of certain answers

Query $Q$ from relational calculus/algebra, i.e., first-order logic. Assume it is a sentence (yes/no query).

Look at OWA first.

$$\text{certain}_{\text{OWA}}(Q, D) = t \iff \forall D' \in [D]_{\text{owa}} : D' \models Q$$

But: $[\emptyset]_{\text{owa}} = \text{all databases}$!

Therefore:

$$\text{certain}_{\text{OWA}}(Q, \emptyset) = t \iff \forall D' : D' \models Q$$

or $Q'$ is a valid sentence.
Validity and certain answers

What do we know about validity of first-order sentences? It is **undecidable**!

This is a classical result in logic. But here we are in a different world, all databases are finite. Does it help?

No! It is even worse, not even recursively enumerable (even infinite time does not help!)
Does CWA help? Somewhat....

\[
certain_{\text{CWA}}(Q, D) = \mathbf{t} \iff \forall \text{ valuations } h : h(D) \models Q
\]

There are still infinitely many valuations, but actually only finitely many suffice (blackboard).

This means checking whether \( certain_{\text{CWA}}(Q, D) = \mathbf{f} \) is in NP:

- guess a valuation \( h \)
- check if \( h(D) \models \neg Q \) (in PTIME in data complexity)

Thus checking whether \( certain_{\text{CWA}}(Q, D) = \mathbf{t} \) is in \( \text{coNP} \).
CWA: can we do better? No...

Checking whether $\text{certain}_{\text{CWA}}(Q, D) = t$ is coNP-complete.

Reduction from 3-colorability.

Take a graph $G = (V, E)$ and create a database $D_G$ with nulls $\bot_v$ for each $v \in V$ and edges $(\bot_v, \bot_{v'})$ whenever $(v, v') \in E$.

$Q = 4$ different vertices $\lor \exists x E(x, x)$

where 4 different vertices is $\exists x, y, z, u (x \neq y \land y \neq z \land \ldots)$

Then $\text{certain}_{\text{CWA}}(Q, D_G) = t$ iff $G$ is 3-colorable.
The bottom line

SQL is very efficient (for the relational calculus fragment, AC$^0$) Certain answers range from coNP-complete to undecidable for different semantics.
Hence provably SQL cannot compute certain answers.
Wrong behaviors: false negatives and false positives

False negatives: missing some of the certain answers

False positives: giving answers which are not certain

Complexity tells us:

SQL query evaluation cannot avoid both!

False positives are worse: they tell you something blatantly false rather than hide part of the truth

And we have seen SQL generates both.
What to do?

We now analyze evaluation procedures.

Goal: to see when we can effectively

- compute or
- approximate
certain answers.

So first we need to define evaluation procedures.
Evaluation procedures for first-order queries

Given a database $D$, a query $Q(\overline{x})$, a tuple $\overline{a}$

$\text{Eval}(D, Q(\overline{a})) \in \text{set of truth values}$

- 2-valued logic: truth values are $t$ (true) and $f$ (false)
- 3-valued logic: $t$, $f$, and $u$ (unknown)

Meaning: if $\text{Eval}(D, Q(\overline{a}))$ evaluates to

- $t$, we know $\overline{a} \in Q(D)$
- $f$, we know $\overline{a} \notin Q(D)$
- $u$, we don’t know whether $\overline{a} \in Q(D)$ or $\overline{a} \notin Q(D)$
Evaluation procedures and queries results

A procedure defines the result of evaluation:

\[ \text{Eval}(Q, D) = \{ \bar{a} \mid \text{Eval}(D, Q(\bar{a})) = t \} \]

Think of the *WHERE* clause in SQL: we only look at values that make it true (and discard those that make it false or unknown).
Standard semantics for logical connectives

All evaluation procedures are completely standard for $\lor$, $\land$, $\neg$, $\forall$, $\exists$:

$$
\begin{align*}
\text{Eval}(D, Q \lor Q') &= \text{Eval}(D, Q) \lor \text{Eval}(D, Q') \\
\text{Eval}(Q \land Q', D) &= \text{Eval}(D, Q) \land \text{Eval}(D, Q') \\
\text{Eval}(D, \neg Q) &= \neg \text{Eval}(D, Q) \\
\text{Eval}(D, \exists x \ Q(x, \bar{a})) &= \lor \{ \text{Eval}(D, Q(a', \bar{a})) \mid a' \in \text{dom}(D) \} \\
\text{Eval}(D, \forall x \ Q(x, \bar{a})) &= \land \{ \text{Eval}(D, Q(a', \bar{a})) \mid a' \in \text{dom}(D) \}
\end{align*}
$$
Standard semantics for logical connectives cont’d

Of course $\lor, \land, \neg$ are given by truth tables for the logic: the usual Boolean logic for relational calculus, or the 3-valued logic for SQL.

So we just need to define rules for atoms, $R(\bar{x})$ and basic comparisons.

We assume comparisons are just equalities $a = b$. 
FO evaluation procedure

$$\text{Eval}_{\text{FO}}(D, R(\bar{a})) = \begin{cases} t & \text{if } \bar{a} \in R \\ f & \text{if } \bar{a} \not\in R \end{cases}$$

$$\text{Eval}_{\text{FO}}(D, a = b) = \begin{cases} t & \text{if } a = b \\ f & \text{if } a \neq b \end{cases}$$
Correctness via $\text{Eval}_{\text{FO}}$

Recall:

$$\text{Eval}_{\text{FO}}(Q, D) = \{ \bar{a} \mid \text{Eval}_{\text{FO}}(D, Q(\bar{a})) = t \}$$

We want at least simple correctness guarantees

constant tuples in $\text{Eval}_{\text{FO}}(Q, D) \subseteq \text{certain}(Q, D)$
Correctness via $\text{Eval}_{FO}$

Recall:

$$\text{Eval}_{FO}(Q, D) = \{ \bar{a} \mid \text{Eval}_{FO}(D, Q(\bar{a})) = t \}$$

We want at least simple correctness guarantees

constant tuples in $\text{Eval}_{FO}(Q, D) \subseteq \text{certain}(Q, D)$

Ideally:

constant tuples in $\text{Eval}_{FO}(Q, D) = \text{certain}(Q, D)$
Correctness for CQs

**UCQ**: unions of conjunctive queries, or positive relational algebra $\pi, \sigma, \land, \lor$.

For **UCQs**, constant tuples in $\text{Eval}_{\text{FO}}(Q, D) = \text{certain}(Q, D)$ for both open and closed world semantics.

First, $[D]_{\text{cwa}}$ and $[D]_{\text{owa}}$ have a “copy” of $D$ (replace all nulls by new constants) so if $\text{certain}_{\text{OWA}}(D, Q) = t$ or $\text{certain}_{\text{CWA}}(D, Q) = t$ then $D \models Q$. 
Correctness for CQs cont’d

Now we need the converse: if $D \models Q$, then
\[ \text{certain}_{\text{OWA}}(D, Q) = \text{certain}_{\text{CWA}}(D, Q) = t. \]

Idea: let’s look at a Boolean CQ $Q$ with a tableau $T_Q$. Then

\[ D \models Q \Rightarrow T_Q \leftrightarrow D \]
\[ \Rightarrow \forall D' : D \leftrightarrow D' \text{ implies } T_Q \leftrightarrow D' \]
\[ \Rightarrow \forall D' : D \leftrightarrow D' \text{ implies } D' \models Q \]
\[ \Rightarrow \forall D' \in \llbracket D \rrbracket_{\text{OWA}} \text{ (or in } \llbracket D \rrbracket_{\text{CWA}}) : D' \models Q \]
\[ \Rightarrow \text{certain}_{\text{OWA}}(D, Q) = \text{certain}_{\text{CWA}}(D, Q) = t \]

Same idea works for UCQs with free variables.
Correctness for CQs cont’d

Can the class of UCQs be extended? Answer:

- no under open world semantics, and
- yes under closed world semantics.

If $Q$ is a relational calculus query, and

$$D \models Q \iff \text{certain}_{\text{OWA}}(D, Q) = t$$

for all $D$, then $Q$ is equivalent to a UCQ.
Correctness for CQs under closed world

Recall: UCQ is the fragment of relational calculus without $\forall$ and $\neg$. That is, $\land$, $\lor$, $\exists$.

$\text{RelCalc}_{\text{certain}}$ — UCQs extended with the formation rule:

if $\varphi(\bar{x}, \bar{y})$ is a query in $\text{RelCalc}_{\text{certain}}$, then so is:

$$\forall \bar{y} \ (\text{atom}(\bar{y}) \rightarrow \varphi(\bar{x}, \bar{y}))$$

Here atom is $R(\bar{y})$ or $y_1 = y_2$. 
Correctness for CQs under closed world cont’d

Also recall: UCQs are positive relational algebra, $\pi, \sigma, \times, \cup$.

$\text{RelCalc}_{\text{certain}}$ is its extension with the division operator $\div$

- but only $Q \div R$ queries
- meaning: find tuples $\bar{a}$ that occur in $Q(D)$ together with every tuple $\bar{b}$ in $R$

For $\text{RelCalc}_{\text{certain}}$ queries,

constant tuples in $\text{Eval}_{\text{FO}}(Q, D) = \text{certain}_{\text{CWA}}(Q, D)$
SQL evaluation procedure

All that changes is the rule for comparisons.

SQL’s rule: if one attribute of a comparison is null, the result is unknown.

\[
\text{Eval}_{\text{SQL}}(D, a = b) = \begin{cases} 
  t & \text{if } a = b \text{ and } \text{NotNull}(a, b) \\
  f & \text{if } a \neq b \text{ and } \text{NotNull}(a, b) \\
  u & \text{if null}(a) \text{ or null}(b)
\end{cases}
\]

We write \text{null}(a) if \(a\) is a null and \text{NotNull}(a) if it is not.
When does it work?

For UCQs,

constant tuples in $\text{Eval}_{\text{SQL}}(Q, D) \subseteq \text{certain}(Q, D)$

Questions:

- can we extend this, say to all of relational calculus? That is, get an evaluation without false positives, and
- do we really need 3 truth values in SQL?
Is there a Boolean solution?

Perhaps the committee design missed something and we don’t need 3-valued logic? Actually, we do....

Every query evaluation that uses the Boolean semantics for $\land$, $\lor$, $\neg$ generates false positives on databases with nulls.

Every evaluation means: complete freedom for

- $\text{Eval}(R(\bar{x}))$
- $\text{Eval}(x = y)$
- $\text{Eval}(\forall x \varphi)$
- $\text{Eval}(\exists x \varphi)$;

the only restriction is that $\land$, $\lor$, $\neg$ come from the usual Boolean logic.
No Boolean solution: by contradiction

Take a Boolean evaluation \( \text{Eval} \) with \( \text{Eval}(Q, D) \subseteq \text{certain}(\varphi, D) \).

Take \( D = \{ R(1), S(\bot) \} \).

If \( \text{Eval}(R(1), D) = f \), then \( \text{Eval}(\neg R(1), D) = t \), but \( 1 \notin \text{certain}(\neg R(x), D) \implies \text{Eval}(R(1), D, a) = t \).

If \( \text{Eval}(\neg S(1), D) = f \), then \( \text{Eval}(S(1), D) = t \). But \( 1 \notin \text{certain}(S(x), D) \implies \text{Eval}(\neg S(1), D) = t \).

Now take \( Q(x) = R(x) \land \neg S(x) \); we have \( \text{Eval}(Q(1), D) = t \), but \( 1 \notin \text{certain}(Q, D) \):

- just take a complete database where \( \bot \) becomes 1; in it \( Q(1) \) is false.
What’s wrong with SQL’s 3VL?

It gives us both false positives and false negatives. Can we eliminate false positives?

SQL is too eager to say no.

If we say no to a result that ought to be unknown, when negation applies, no becomes yes! And that’s how false positives creep in.

Consider $R =$ \[
\begin{array}{cc}
A & B \\
1 & \text{null}
\end{array}
\]

What about $(\text{null}, \text{null}) \in R$?

SQL says no but correct answer is unknown: what if null is really 1?
Towards a good evaluation: unifying tuples

Two tuples $\bar{t}_1$ and $\bar{t}_2$ unify if there is a mapping $h$ of nulls to constants such that $h(\bar{t}_1) = h(\bar{t}_2)$.

\[
\begin{pmatrix}
1 & \_ & 1 & 3 \\
\_ & 2 & \_ & 3
\end{pmatrix}
\quad \Rightarrow \quad
\begin{pmatrix}
1 & 2 & 1 & 3
\end{pmatrix}
\]

but \[
\begin{pmatrix}
1 & \_ & 2 & 3 \\
\_ & 2 & \_ & 3
\end{pmatrix}
\]
do not unify.

This can be checked in linear time.
Proper 3-valued procedure

\[
\text{Eval}_{3v}(D, R(\bar{a})) = \begin{cases} 
    t & \text{if } \bar{a} \in R \\
    f & \text{if } \bar{a} \text{ does not unify with any tuple in } R \\
    u & \text{otherwise}
\end{cases}
\]

\[
\text{Eval}_{3v}(D, a = b) = \begin{cases} 
    t & \text{if } a = b \\
    f & \text{if } a \neq b \text{ and } \text{NotNull}(a, b) \\
    u & \text{otherwise}
\end{cases}
\]
Simple correctness guarantees: no false positives

If $\bar{a}$ is a tuple without nulls, and $\text{Eval}_{3v}(D, Q(\bar{a})) = 1$ then $\bar{a} \in \text{certain}(Q, D)$.

Simple correctness guarantees:

constant tuples in $\text{Eval}_{3v}(Q, D) \subseteq \text{certain}_{\text{CWA}}(Q, D)$

Thus:

- Fast evaluation (checking $\text{Eval}_{3v}(D, Q(\bar{a})) = 1$ in $\text{AC}^0$)
- Correctness guarantees: no false positives
Strong correctness guarantees: involving nulls

How can we give correctness guarantees for tuples with nulls? By a natural extension of the standard definition (proposed in 1984 but quickly forgotten).

A tuple without nulls $\bar{a}$ is a certain answer if

$$\bar{a} \in Q(h(D))$$

for every valuation $h$ of nulls.
Strong correctness guarantees: involving nulls

How can we give correctness guarantees for tuples with nulls? By a natural extension of the standard definition (proposed in 1984 but quickly forgotten).

A tuple without nulls $\bar{a}$ is a certain answer if

$$\bar{a} \in Q(h(D))$$

for every valuation $h$ of nulls.

An arbitrary tuple $\bar{a}$ is a certain answers with nulls if

$$h(\bar{a}) \in Q(h(D))$$

for every valuation $h$ of nulls.

Notation: $\text{certain}_\bot(Q, D)$
Certain answers with nulls: properties

\[ \text{certain}(Q, D) \subseteq \text{certain}_\bot(Q, D) \subseteq \text{Eval}_{\text{FO}}(Q, D) \]

Moreover:

- \( \text{certain}(Q, D) \) is the set of null free tuples in \( \text{certain}_\bot(Q, D) \)
- \( \text{certain}_\bot(Q, D) = \text{Eval}_{\text{FO}}(Q, D) \) for \( \text{RelCalc}_{\text{certain}} \) queries
Correctness with nulls: strong guarantees

- $D$ – a database,
- $Q(\vec{x})$ – a first-order query
- $\vec{a}$ – a tuple of elements from $D$.

Then:

- $\text{Eval}_{3v}(D, Q(\vec{a})) = t \implies \vec{a} \in \text{certain}_\bot(Q, D)$
- $\text{Eval}_{3v}(D, Q(\vec{a})) = f \implies \vec{a} \in \text{certain}_\bot(\neg Q, D)$

3-valuedness extended to answers: certainly true, certainly false, don't know.
Same in relational algebra

There is an effective translation of queries

\[ Q \leftrightarrow (Q^t, Q^f) \]

such that:

- \(Q^t\) approximates certain answers to \(Q\)
- \(Q^f\) approximates certain answers to the negation of \(Q\)
- both queries have \(AC^0\) data complexity

\[
\begin{align*}
certain(Q, D) & \quad Q^t(D) \\
certain(\neg Q, D) & \quad Q^f(D)
\end{align*}
\]
Relational algebra translations: $Q^t$

For a relation $R$: $R^t = R$

For $op \in \{ \cap, \cup, \times \}$: $(Q_1 \ op \ Q_2)^t = Q_1^t \ op \ Q_2^t$

For projection: $\pi_\alpha(Q)^t = \pi_\alpha(Q^t)$

For difference: $(Q_1 - Q_2)^t = Q_1^t \cap Q_2^f$

For selection: $\sigma_\theta(Q)^t = \sigma_{\theta^*}(Q^t)$

where $(A = B)^* = (A = B)$

$(A \neq B)^* = (A \neq B) \land \text{not-null}(A) \land \text{not-null}(B)$

$(\theta_1 \ op \ \theta_2)^* = \theta_1^* \ op \ \theta_2^*$ \hspace{1cm} \text{for } op \in \{ \land, \lor \}$
Relational algebra translations: $Q^f$

$$R^f = \{ \bar{r} \in \text{dom}^\text{ar}(R) \mid \bar{r} \text{ does not match any tuple in } R \}$$

$$(Q_1 \cup Q_2)^f = Q_1^f \cap Q_2^f$$

$$(Q_1 \cap Q_2)^f = Q_1^f \cup Q_2^f$$

$$(Q_1 - Q_2)^f = Q_1^f \cup Q_2^t$$

$$(\sigma_\theta(Q))^f = Q^f \cup \sigma(\neg \theta)^* (\text{dom}^\text{ar}(Q))$$

$$(Q_1 \times Q_2)^f = Q_1^f \times \text{dom}^\text{ar}(Q_2) \cup \text{dom}^\text{ar}(Q_1) \times Q_2^f$$

$$(\pi_\alpha(Q))^f = \pi_\alpha(Q^f) - \pi_\alpha(\text{dom}^\text{ar}(Q) - Q^f)$$
Does it work in practice?

**Not a chance:** With as few as 1000 tuples and 3 attributes bad queries start computing relations with billions of tuples!

Inefficient translations

\[
R^f = \{ \bar{r} \in \text{adom}^{\text{ar}}(R) \mid \bar{r} \text{ does not match any tuple in } R \}
\]

\[
(\sigma_{\theta}(Q))^f = Q^f \cup \sigma_{(\neg \theta)^*}(\text{adom}^{\text{ar}}(Q))
\]

\[
(Q_1 \times Q_2)^f = Q_1^f \times \text{adom}^{\text{ar}}(Q_2) \cup \text{adom}^{\text{ar}}(Q_1) \times Q_2^f
\]

\[
(\pi_{\alpha}(Q))^f = \pi_{\alpha}(Q^f) - \pi_{\alpha}(\text{adom}^{\text{ar}}(Q) - Q^f)
\]

With the best tricks we can only handle a few hundred tuples:

AC⁰ and efficiency are NOT the same!
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(\sigma_\theta(Q))^f = Q^f \cup \sigma(\neg \theta)^* \left( \text{adom}^{\text{ar}}(Q) \right)
\]

\[
(Q_1 \times Q_2)^f = Q_1^f \times \text{adom}^{\text{ar}}(Q_2) \cup \text{adom}^{\text{ar}}(Q_1) \times Q_2^f
\]

\[
(\pi_\alpha(Q))^f = \pi_\alpha(Q^f) - \pi_\alpha \left( \text{adom}^{\text{ar}}(Q) - Q^f \right)
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Inefficient translations

\[ R^f = \{ \bar{r} \in \text{adom}^\text{ar}(R) \mid \bar{r} \text{ does not match any tuple in } R \} \]

\[ (\sigma_\theta(Q))^f = Q^f \]

\[ (Q_1 \times Q_2)^f = Q_1^f \times \text{adom}^\text{ar}(Q_2) \cup \text{adom}^\text{ar}(Q_1) \times Q_2^f \]

\[ (\pi_\alpha(Q))^f = \pi_\alpha(Q^f) - \pi_\alpha(\text{adom}^\text{ar}(Q) - Q^f) \]

With the best tricks we can only handle a few hundred tuples:

\[ \text{AC}^0 \text{ and efficiency are NOT the same!} \]
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**Inefficient translations**

\[
R^f = \{ \bar{r} \in \text{adom}^{\text{ar}}(R) \mid \bar{r} \text{ does not match any tuple in } R \}
\]

\[
(\sigma_\theta(Q))^f = Q^f
\]

\[
(Q_1 \times Q_2)^f = Q_1^f \times Q_2^f
\]

\[
(\pi_\alpha(Q))^f = \pi_\alpha(Q^f) - \pi_\alpha(\text{adom}^{\text{ar}}(Q) - Q^f)
\]

With the best tricks we can only handle a few hundred tuples:

AC\(^0\) and efficiency are **NOT** the same!
Does it work in practice?

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Inefficient translations

\[ R^f = \{ \bar{r} \in \text{adom}^{\text{ar}(R)} \mid \bar{r} \text{ does not match any tuple in } R \} \]

\[ (\sigma_\theta(Q))^f = Q^f \]

\[ (Q_1 \times Q_2)^f = Q_1^f \times Q_2^f \]

\[ (\pi_\alpha(Q))^f = \pi_\alpha(Q^f) - \pi_\alpha(\text{adom}^{\text{ar}(Q)} - Q^f) \]

With the best tricks we can only handle a few hundred tuples:

\[ AC^0 \text{ and efficiency are NOT the same!} \]
Let’s rethink the basics

We only needed $Q^f$ to handle difference: $(Q_1 - Q_2)^t = Q_1^t \cap Q_2^f$

**Intuition**: A tuple is for sure in $Q_1 - Q_2$ if
- it is certainly in $Q_1$ and
- it is certainly not in $Q_2$

This is not the only possibility
A tuple is for sure in $Q_1 - Q_2$:
- it is certainly in $Q_1$ and
- it does not match any tuple that could be in $Q_2$
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**This is not the only possibility**
A tuple is for sure in $Q_1 - Q_2$:
- it is certainly in $Q_1$ and
- it does not match any tuple that could be in $Q_2$
What is “match”?

**Unification**: Two tuples unify if there is an instantiation of nulls with constants that makes them equal

\[ R \triangleright_u S = \{ \bar{r} \in R \mid \not\exists \bar{s} \in S : \bar{s} \text{ unifies with } \bar{r} \} \]
What is “match”?  

Unification: Two tuples unify if there is an instantiation of nulls with constants that makes them equal

Left unification antijoin

\[ R \overset{\bar{x}}{\sqsubseteq_u} S = \{ \bar{r} \in R \mid \nexists \bar{s} \in S: \bar{s} \text{ unifies with } \bar{r} \} \]
Second translation

Translate $Q$ into $(Q^+, Q^?)$ where:

- $Q^+$ approximates certain answers
- $Q^?$ represents possible answers

Topics in FD 2017 incomplete and inconsistent data 48/78
Second translation

Translate $Q$ into $(Q^+, Q^?)$ where:

- $Q^+$ approximates certain answers
- $Q^?$ represents possible answers

\[
(Q_1 - Q_2)^+ = Q_1^+ \sqcup_u Q_2^\
R^? = R
(Q_1 \cup Q_2)^? = Q_1^? \cup Q_2^?
(Q_1 \cap Q_2)^? = Q_1^? \sqcup_u Q_2^?
(Q_1 - Q_2)^? = Q_1^? - Q_2^+
(\sigma_{\theta}(Q))^? = \sigma_{\neg\theta^*}(Q^?)
(Q_1 \times Q_2)^? = Q_1^? \times Q_2^?
(\pi_{\alpha}(Q))^? = \pi_{\alpha}(Q^?)
\]
Certain and possible answers

For every valuation $h$ of nulls:

\[ h(Q^+(D)) \subseteq Q(h(D)) \]

\[ Q(h(D)) \subseteq h(Q?^+(D)) \]

▶ in particular, $Q^+(D) \subseteq \text{certain}_\bot(Q, D)$
New translation: example

For queries with difference, $Q^+$ is much more efficient than $Q^t$.

$$Q = R - (\pi_\alpha(T) - \sigma_\theta(S))$$

of arity $k$.

Translations:

$$Q^t = R \cap \left( (\pi_\alpha(\text{adom}^k \ominus_u T) - \pi_\alpha(\text{adom}^k \bowtie_u T)) \cup \sigma_\theta^*(S) \right)$$

(uncomputable in practice) but

$$Q^+ = R \ominus_u (\pi_\alpha(T) - \sigma_\theta^*(S))$$

(easy to compute)
Does it work in practice?

We ran our queries and translations on TPC-H instances with nulls and measured the relative runtime performance of $Q^+$ w.r.t. $Q$

- SQL was designed for efficiency
  $\implies$ we cannot expect to outperform native SQL
- but we can hope for the overhead to be acceptable

We observed the following behaviors:

- **The good**: small overhead
  (less than $< 4\%$)

- **The fantastic**: significant speed-up
  (more than $10^3$ times faster)

- **The tolerable**: moderate slow-down
  (half the speed on 1GB instances, a quarter on 10GB ones)
Does it work in practice?

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  (half the speed on 1GB instances, a quarter on 10GB ones)
The good

Q₃  Find orders supplied entirely by a specific supplier

SELECT  o_orderkey
FROM    orders
WHERE   NOT EXISTS (  
          SELECT  * 
          FROM    lineitem 
          WHERE   l_orderkey = o_orderkey 
          AND      l_suppkey <> $supp_key
)

AND      l_suppkey <> $supp_key

In relational algebra:  \( \pi_{o\_orderkey} ( \text{orders} \hspace{1em} \Join \hspace{1em} \theta \hspace{1em} \text{lineitem} ) \)
becomes  \( \pi_{o\_orderkey} ( \text{orders} \hspace{1em} \Join \neg \hspace{1em} \theta \hspace{1em} \text{lineitem} ) \)
Q₃  Find orders supplied entirely by a specific supplier

SELECT  o_orderkey
FROM    orders
WHERE   NOT EXISTS ( 
    SELECT  *
    FROM     lineitem
    WHERE    ( l_orderkey = o_orderkey
        OR l_orderkey IS NULL
        OR o_orderkey IS NULL )
    AND      ( l_suppkey <> $supp_key
        OR l_suppkey IS NULL )
)

In relational algebra: \( \pi_{o\_orderkey}(orders \bowtie_{\theta} lineitem) \)
becomes
\( \pi_{o\_orderkey}(orders \bowtie_{\neg\theta}*(lineitem)) \)
Q₃  *Find orders supplied entirely by a specific supplier*

```sql
SELECT  o_orderkey
FROM    orders
WHERE   NOT EXISTS ( 
    SELECT  *
    FROM    lineitem
    WHERE   l_orderkey = o_orderkey
    AND     l_suppkey <> $supp_key
    OR      l_suppkey IS NULL
)
```

In relational algebra: \( \pi_{o\text{-}orderkey}(\text{orders} \Join_{\theta} \text{lineitem}) \) becomes \( \pi_{o\text{-}orderkey}(\text{orders} \Join_{\neg\theta}^* \text{lineitem}) \)
The good: Results

< 4% overhead (the same behavior scales up to 10GB instances)
The fantastic

\textbf{Q}_2 \quad \textit{Identify countries where there are customers who may be likely to make a purchase}

\begin{verbatim}
SELECT c_custkey, c_nationkey
FROM customer
WHERE c_nationkey IN ($countries)
AND c_acctbal > (SELECT avg(c_acctbal) FROM customer
WHERE c_acctbal > 0.00
AND c_nationkey IN ($countries))
AND NOT EXISTS (SELECT * FROM orders
WHERE o_custkey = c_custkey)
\end{verbatim}
The fantastic

Q₂  Identify countries where there are customers who may be likely to make a purchase

SELECT c_custkey, c_nationkey
FROM  customer
WHERE c_nationkey IN ($countries)
    AND c_acctbal > ( 
        SELECT avg(c_acctbal) FROM customer 
        WHERE c_acctbal > 0.00 
        AND c_nationkey IN ($countries) 
    )
    AND NOT EXISTS ( 
        SELECT * FROM orders 
        WHERE o_custkey = c_custkey 
        OR o_custkey IS NULL 
    )
Q2  Identify countries where there are customers who may be likely to make a purchase

SELECT  c_custkey, c_nationkey
FROM    customer
WHERE   c_nationkey IN ($countries)
   AND   c_acctbal > (SELECT avg(c_acctbal) FROM customer
                      WHERE  c_acctbal > 0.00
                      AND    c_nationkey IN ($countries))
   AND   NOT EXISTS (SELECT * FROM orders
                      WHERE  o_custkey = c_custkey)
   AND   NOT EXISTS (SELECT * FROM orders
                      WHERE  o_custkey IS NULL)
The fantastic: Results

Over $10^3$ times faster (same or better up to 10GB)

The original query spends most of the time looking for wrong answers
The fantastic: Results

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The fantastic: Results

Over $10^3$ times faster (same or better up to 10GB)

The original query spends most of the time looking for wrong answers
The tolerable

Q₄ Orders not supplied with any part of a specific color by any supplier from a specific country

SELECT o_orderkey
FROM orders
WHERE NOT EXISTS ( 
    SELECT * 
    FROM lineitem, part, supplier, nation 
    WHERE l_orderkey = o_orderkey 
    AND l_suppkey = s_suppkey 
    AND p_name LIKE '%%||$color||%' 
    AND s_nationkey = n_nationkey 
    AND n_name = $nation )
### The tolerable

**Q4** Orders not supplied with any part of a specific color by any supplier from a specific country

```sql
SELECT o_orderkey
FROM orders
WHERE NOT EXISTS (  
SELECT *  
FROM lineitem, part, supplier, nation  
WHERE ( l_orderkey = o_orderkey  
    OR l_orderkey IS NULL )  
    AND ( l_suppkey = s_suppkey  
    OR l_suppkey IS NULL )  
    AND ( p_name LIKE '%'||$color||'%'  
    OR p_name IS NULL )  
    AND ( s_nationkey = n_nationkey  
    OR s_nationkey IS NULL )  
    AND n_name = $nation  )  
)"
The tolerable: Problems with the optimizer

Query **times out**. Reason: optimizer resorts to a nested loop plan.

On the **smallest** benchmark instance, we have relations with

- 6,000,000 tuples,
- 200,000 tuples,
- 10,000 tuples,
- 100 tuples.

Nested loop: look at 1,200,000,000,000 tuples.

No chance.
Join processing by example

\[ R(A, B), \ S(B, C) \]

\[ R \bowtie S = \{(x, y, z) \mid (x, y) \in R, \ (y, z) \in S\} \]

- Nested loop: look at all tuples \((x, y) \in R, \ (y', z) \in S\) and check if \(y = y'\).
  - Hopelessly \(O(n^2)\) — terrible on large data.

- Sort-merge join: Sort on \(B\) in \(O(n \log n)\) and merge sorted lists.
  - Without too many repetitions of values of \(B\), sort dominates, merge is fast, i.e., often \(O(n \log n)\).

- Hash-join: apply a (good) hash function on the \(B\) attribute, only join tuples with the same hash value.
  - As sort-merge, often \(O(n \log n)\) under some assumptions. Most commonly used in query processing.
The tolerable: Problems with the optimizer

Joins with disjunctions in correlated subqueries

\[
R \join_{R.A=S.A} \left( S \join_{S.B=T.B} T \lor \text{null}(S.B) \right)
\]

nested-loop join

As bad as computing a Cartesian product

We can do better

\[
R \join_{R.A=S.A} \left( S \join_{S.B=T.B} T \right) \cap R \join_{\text{null}(S.B)} \left( S \join T \right)
\]

hash join

decorrelated EXISTS
The tolerable: Problems with the optimizer

Joins with disjunctions in correlated subqueries

$$R \bowtie_{R.A = S.A} \left( S \bowtie_{S.B = T.B \lor \text{null}(S.B)} T \right)$$

nested-loop join

As bad as computing a Cartesian product

We can do better

$$R \bowtie_{R.A = S.A} \left( S \bowtie_{S.B = T.B} T \right) \cap R \bowtie_{\text{null}(S.B)} \left( S \bowtie T \right)$$

hash join
decorrelated EXISTS
Towards an improved translation

Conditions \( \text{NOT EXISTS} \ (\ldots \text{ OR } \ldots \text{ OR } 
\ldots) \)

\[
\neg \exists (\ldots \lor \ldots \lor \ldots) \Rightarrow \neg \exists \bigvee \varphi_i \Rightarrow \bigwedge_{i} \neg \exists \varphi_i
\]

Eliminate ORs and get conjunctions of nested \text{NOT EXISTS} subqueries.

Note: exponential blowup!
WITH part_view AS (SELECT p_partkey FROM part WHERE p_name IS NULL
UNION SELECT p_partkey FROM part WHERE p_name LIKE '%%'||$color||'%%' ),
supp_view AS (SELECT s_suppkey FROM supplier WHERE s_nationkey IS NULL
UNION SELECT s_suppkey FROM supplier, nation WHERE s_nationkey=n_nationkey
AND n_name='$nation'
)
SELECT o_orderkey FROM orders
WHERE NOT EXISTS (SELECT *
FROM lineitem, part_view, supp_view
WHERE l_orderkey=o_orderkey AND l_partkey=p_partkey AND l_suppkey=s_suppkey)
AND NOT EXISTS (SELECT *
FROM lineitem, supp_view
WHERE l_orderkey=o_orderkey AND l_partkey IS NULL AND l_suppkey=s_suppkey
AND EXISTS (SELECT * FROM part_view))
AND NOT EXISTS (SELECT *
FROM lineitem, part_view
WHERE l_orderkey=o_orderkey AND l_partkey IS NULL AND l_suppkey IS NULL
AND EXISTS (SELECT * FROM part_view) AND EXISTS (SELECT * FROM supp_view))
AND NOT EXISTS (SELECT * FROM lineitem
WHERE l_orderkey=o_orderkey AND l_partkey IS NULL AND l_suppkey IS NULL
AND EXISTS (SELECT * FROM part_view) AND EXISTS (SELECT * FROM supp_view))
What we’ve done

- Exponential blowup of the query.
- Complexity went from $|D|^{O(|Q|)}$ to $|D|^{2O(|Q|)}$.
  - Double-exponential query complexity!
  - Theory teaches us that this is impossible to evaluate.
- Split one nested subquery into several ones.
  - Practice teaches us that this is much harder to evaluate.
- What happens in real life?
  - The query becomes several orders of magnitude faster!
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The tolerable: Results

Half the speed (on 1GB; a quarter on 10GB instances)

![Bar chart showing average relative performance for Query Q^+ for different null rates.](chart.png)
The bad and the ugly

- Optimizers (we used PostgreSQL, others seem to be similar).
- Many translations amount to
  \[ A = B \iff A = B \text{ OR } B \text{ IS NULL.} \]
- They can't handle it, throw away the original plan and resort to nested loops!
- Why?
- We saw part of the reason above but there is more to it.
Join size estimate

▶ We observed that the query planner often underestimates the size of joins.

▶ Actually, this is known: Leis, Gubichev, Boncz, Kemper, Neumann: *How Good Are Query Optimizers, Really?* VLDB 2015

▶ All major ones (Microsoft, Oracle, IBM) and Postgres underestimate join sizes, sometimes by several orders of magnitude.

▶ If they wrongly think the join is small, $O(n^2)$ nested loop is no big deal to them compared to $O(n \log n)$
Disjunctions

- It is not just the **IS NULL** condition that is problematic, it is also the **OR**.

- Take some TPC-H queries, and change conditions like `R.A=S.B` into `(R.A=S.B OR S.B=0)`

- Basic benchmark queries: good plans, low costs

- Modified benchmark queries: nested-loops, high costs, queries don't terminate.

- In fact optimizers **don’t optimize** with **ORs**!
SQL nulls vs marked nulls

- All theoretical translations assumed the model of marked nulls – these are special values distinct from the usual ones:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>⊥₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>⊥₁</td>
</tr>
<tr>
<td>⊥₂</td>
<td>⊥₃</td>
<td>3</td>
</tr>
<tr>
<td>⊥₄</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

- Subtle differences with SQL nulls: comparing a SQL null with itself is unknown, comparing a marked null with itself is true

- SELECT R.A FROM R WHERE R.B=R.B

- On 1 null it returns nothing.

- On 1 ⊥₁ it returns 1
Summary: incomplete information

- Often disregarded and leads to huge problems
- If you write SQL queries, think in 3-valued logic
- Cannot avoid errors, so need to choose which errors to tolerate
- Some types of errors can be eliminated
Inconsistent databases

- Often arise in data integration.
- Suppose have a functional dependency name $\rightarrow$ salary and two tuples (John, 10K) in source 1, and (John, 20K) in source 2.
- One may want to clean data before doing integration.
- This is not always possible.
- Another solution: keep inconsistent records, and try to address the issue later.
- Issue = query answering.
Inconsistent databases cont’d

Setting:
- a database $D$;
- a set of integrity constraints $IC$, e.g. keys, foreign keys, functional dependencies etc
- a query $Q$

$D$ violates $IC$

What is a proper way of answering $Q$?

Certain Answers:

$$\text{certain}_{IC}(Q, D) = \bigcap_{D_r \text{ is a repair of } D} Q(D_r)$$
Repairs

- How can we repair an instance to make it satisfy constraints?
- If constraints are functional dependencies: say $A \rightarrow B$ and we have

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>b1</td>
<td>c1</td>
</tr>
<tr>
<td>a1</td>
<td>b2</td>
<td>c2</td>
</tr>
</tbody>
</table>

  we have to delete one of the tuples.

- If constraints are referential constraints, e.g. $R[A] \subseteq S[B]$ and we have

<table>
<thead>
<tr>
<th>A</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>c1</td>
</tr>
<tr>
<td>a2</td>
<td>c2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>d1</td>
</tr>
<tr>
<td>a3</td>
<td>d2</td>
</tr>
</tbody>
</table>

  then we have to add a tuple to $S$. 

Repairs cont’d

- Thus to repair a database to make it satisfy IC we may need to add or delete tuples.
- Given $D$ and $D'$, how far are they from each other?
- A natural measure: the minimum number of deletions/insertions of tuples it takes to get to $D'$ from $D$.
- In other words,

$$\delta(D, D') = (D - D') \cup (D' - D)$$

- A repair is a database $D'$ so that
  - it satisfies constraints IC, and
  - there is no $D''$ satisfying constraints IC with $\delta(D, D'') \subset \delta(D, D')$
How many repairs are there?

Can easily be exponential even for keys: i.e. $\sqrt{2^N}$.

\[
\begin{array}{|c|c|}
\hline
A & B \\
\hline
1 & 0 \\
1 & 1 \\
2 & 0 \\
2 & 1 \\
\vdots & \vdots \\
\vdots & \vdots \\
n & 0 \\
n & 1 \\
\hline
\end{array}
\]

plus key $A \rightarrow B \Rightarrow$

\[
\begin{array}{|c|c|}
\hline
A & B \\
\hline
1 & \cdot \\
2 & \cdot \\
\vdots & \vdots \\
n & \cdot \\
\hline
\end{array}
\]

I.e. for $N = 2n$ tuples we have $2^n = \sqrt{2^N}$ repairs.

(A side remark: this construction gives us $\sqrt{c^n}$ repairs for any number $c$. What is the maximum of $\sqrt{c}$?)
Query answering

- Recall $\text{certain}_{IC}(Q, D) = \bigcap_{D_r \text{ is a repair of } D} Q(D_r)$.
- Computing all repairs is impractical.
- Hence one tries to obtain a rewriting $Q'$:

  $$Q'(D) = \text{certain}_{IC}(Q, D).$$

- Is this always possible?
Query rewriting: a good case

- One relation $R(A, B, C)$
- Functional dependency $A \rightarrow B$
- Query $Q$: just return $R$
- If an instance may violate $A \rightarrow B$, then we can rewrite $Q$ to
  
  $R(x, y, z) \land \forall u \forall v \left( R(x, u, v) \rightarrow u = y \right)$ or
  
  \[
  \text{SELECT * FROM } R \\
  \text{WHERE NOT EXISTS (SELECT * FROM R R1} \\
  \text{ WHERE R.A=R1.A AND R.B \neq R1.B)}
  \]

- This technique applies to a small class of queries: conjunctive queries without projections, i.e.
  
  \[
  \text{SELECT * FROM R1, R2} \\
  \text{WHERE } \land R_i.A_j = R_i.A_k
  \]
Query rewriting: a mildly bad case

- One relation $R(A, B)$; attribute $A$ is a key
- Query $Q = \exists x, y, z \ (R(x, z) \land R(y, z) \land (x \neq y))$
- When are certain answers false?
- If there is a repair in which the negation of $Q$ is true.
- What is the negation of $Q$?
  - $\neg Q = \forall x, y, z \ ((R(x, z) \land R(y, z)) \rightarrow x = y)$
- This happens precisely when $R$ contains a perfect matching
- But checking for a perfect matching cannot be expressed in SQL.
- Hence, no SQL rewriting for certain $i_C(Q)$. 
Query rewriting: the worst

- One can find an example of a rather simple relational algebra query $Q$ and a set of constraints $IC$ so that the problem of finding $\text{certain}_{IC}(Q, D)$ is coNP-complete.

- In general for most types of constraints one can limit the number of repairs but they give rather high complexity bounds:
  - typically classes “above” PTIME and contained in PSPACE – hence almost certainly requiring exponential time.
Other approaches

- Repair attribute values.
  - A common example: census data. Don’t get rid of tuples but change the values.
  - Distance: sum of absolute values of squares of differences new value – old value
  - Typically one considers aggregate queries and looks for approximations or ranges of their values

- A different notion of repair.
  - Most commonly: the cardinality of \((D - D') \cup (D' - D)\) must be minimum.
  - This is a reasonable measure but the complexity of query answering is high.