Believe It or Not – Adding belief annotations to databases

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University of Washington
http://db.cs.washington.edu/beliefDB/
High-level overview

- DBMS: manage consistent data
- Applications need inconsistent DM
  - Scientific databases
  - Internet community databases
- Community DBMS: manage inconsistent views

- This work: **Belief databases**
  - manage data and curation
  - grounded in modal and default logic
  - implemented on top of relational model

reason: disagreement!
Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion
Motivating application

  - volunteer contribute animal observations
  - one person curates the database

```
<table>
<thead>
<tr>
<th>id</th>
<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Alice</td>
<td>Crow</td>
<td>06-14-08</td>
<td>Lake Placid</td>
<td>found feathers</td>
</tr>
</tbody>
</table>
```

**problem: does not scale!**

```
<table>
<thead>
<tr>
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<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
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</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Crow</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>
```

```
<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>found feathers</td>
<td>s2</td>
</tr>
</tbody>
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```
1. Distinct database instances

<table>
<thead>
<tr>
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<th>uid</th>
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<th>date</th>
<th>location</th>
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</thead>
<tbody>
<tr>
<td>s2</td>
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<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>

D1: Belief worlds: individually consistent, mutually possibly inconsistent
1. Distinct database instances

<table>
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<th>date</th>
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<tbody>
<tr>
<td>s2</td>
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<td>Lake Placid</td>
</tr>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>

BeliefSQL

I: Alice believes that she saw a crow.
insert into BELIEF ‘Alice’ SighLngs
values (‘s2’,‘Alice’,’Crow’,’06-14-08’,’Lake Placid’)

I: Bob believes that she actually saw a raven.
insert into BELIEF ‘Bob’ SighLngs
values (‘s2’,‘Alice’,’Raven’,’06-14-08’,’Lake Placid’)

Q: Who believes something different than Alice and what?
select U2.name, S1.species, S2.species
from Users as U,
    BELIEF ‘Alice’ SighLngs as S1,
    BELIEF U uid SighLngs as S2,
where S1.sid = S2.sid
and S1.species <> S2.species
A: {{‘Bob’, ‘Crow’, ‘Raven’}}
2. Open world assumption

<table>
<thead>
<tr>
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<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
</tr>
</thead>
<tbody>
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<td>s2</td>
<td>Alice</td>
<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>

Adapted key constraints!

D2: Model incomplete knowledge with explicit negative beliefs
2. Open world assumption

I: Carol does not believe that Alice saw a crow nor a raven.

- Insert into BELIEF 'Carol' not Sightings values (‘s2’, ‘Alice’, ‘Crow’, ‘06-14-08’, ‘Lake Placid’)
- Insert into BELIEF 'Carol' not Sightings values (‘s2’, ‘Alice’, ‘Raven’, ‘06-14-08’, ‘Lake Placid’)

<table>
<thead>
<tr>
<th>sid</th>
<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Crow</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>
2. Open world assumption

Q: Who disagrees with a sighting from '06-14-08' that Alice believes?

A: \{(’Bob’, ’Crow’), (’Carol’, ’Crow’)}

```sql
select U.name, S1.species
from Users as U,
    BELIEF ‘Alice’ Sightings as S1,
    BELIEF U.uid not Sightings as S2
where S1.sid = S2.sid
    and S1.uid = S2.uid
    and S1.species = S2.species
    and S1.date = ’06-14-08’
    and S2.date = ’06-14-08’
    and S1.location = S2.location
```
3. Higher-order beliefs

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sid</th>
<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
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<td>Raven</td>
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<td>Lake Placid</td>
</tr>
<tr>
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<td>Alice</td>
<td>Crow</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>

D3: Beliefs about other user’s beliefs: allow discussion between users
3. Higher-order beliefs

According to Bob, Alice believes that the feathers of the sighted animal were plain black.

I: insert into BELIEF ‘Bob’ BELIEF ‘Alice’ Comments values (‘c1’, ‘plain black feathers’, ‘s2’)

<table>
<thead>
<tr>
<th>sid</th>
<th>uid</th>
<th>species</th>
<th>date</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>plain black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>
3. Higher-order beliefs

Q: Which comments does Alice believe according to Bob, which he does not believe himself?

A: {{‘c1’,'plain-black feathers’}}
3. Higher-order beliefs

<table>
<thead>
<tr>
<th>sid</th>
<th>uid</th>
<th>species</th>
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</thead>
<tbody>
<tr>
<td>s2</td>
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<td>Raven</td>
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</table>

Alice

Bob

<table>
<thead>
<tr>
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<th>uid</th>
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</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
</tr>
</tbody>
</table>

Bob

Alice

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
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</tbody>
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<table>
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<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

Q: Which comments does Alice believe according to somebody, which (s)he does not believe themself?

```
select U.name, C1.sid, C1.comment
from Users as U,
    BELIEF U.uid
BELIEF 'Alice'
Comments as C1,
BELIEF U.uid
not Comments as C2
where C1.cid = C2.cid
and C1.comment = C2.comment
and C1.sid = C2.sid
```

A: `{'Bob', 'c1', 'plain-black feathers'}`
4. Message board assumption

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
</tbody>
</table>

**C**

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>plain black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

<table>
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<th>date</th>
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<tbody>
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<td>s2</td>
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<td>Crow</td>
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</tr>
</tbody>
</table>

**C**

<table>
<thead>
<tr>
<th>cid</th>
<th>comment</th>
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</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

D4: Default assumption: models a trusting attitude & avoids repeated inserts
4. Message board assumption

Q: Which animal sightings does Alice believe according to Bob, which he does not believe himself?

```
select S1.sid, S1.species
from BELIEF 'Bob' BELIEF 'Alice' Sightings as S1,
    BELIEF 'Bob' not Sightings as S2
where S1.sid = S2.sid
    and S1.uid = S2.uid
    and S1.species = S2.species
    and S1.date = S2.date
    and S1.location = S2.location
```

A: {('s2', 'Crow')}

<table>
<thead>
<tr>
<th>sid</th>
<th>uid</th>
<th>species</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
<td>Alice</td>
<td>Crow</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sid</th>
<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>s2</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>
What we have seen so far

• 4 Design decisions for Belief Database model
  – Distinct belief worlds
  – Open world assumption (OWA)
  – Higher-order beliefs
  – Message board assumption

• BeliefSQL
  – SQL + ‘BELIEF’ (+ ‘not’)

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Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion
Logic foundations: Belief statements

Belief database $D = \{ \varphi_1, ..., \varphi_n \}$

insert into BELIEF ‘Alice’ $S$ values (‘s2’, ‘Alice’, ‘Crow’,...)

$i: \Box_{Alice} S^+(‘s2’,‘Alice’,‘Crow’,...)$

belief statement $\varphi = \Box_w t^s$

“annotation of ground tuple”
Logic foundations: Entailment

One belief annotation:

\[ D = \{ \varphi_1 \} \]

\[ \varphi_1 = \square_{\text{Alice}} S^+ (\ldots \text{‘Crow’,} \ldots) \]

More than one entailed belief:

\[ D \models \square_{\text{Bob}, \text{Alice}} S^+ (\ldots \text{‘Crow’,} \ldots) \]
Logic foundations: Message board assumption

Message board assumption

If $D \models \Box_w t^s$
and $\Box_{u \cdot w} t^s$ consistent with $D$
then $D \models \Box_{u \cdot w} t^s$

Default logic

$\varphi : \Box_u \varphi$

$\Box_u \varphi$

non-monotonic reasoning!

$D$
Explicit beliefs (annotations)

$\overline{D} \setminus D$
Implicit beliefs (assumptions)

$\overline{D}$
Entailed beliefs (extension)

belief database “contains” more than the explicit belief annotations!
“Semi-formal” problem statement

INPUT
Belief statements
\[ i_1: \varphi_1 \]
\[ i_2: \varphi_2 \]
... 
\[ i_n: \varphi_n \]

Adapted key constraints
Message board assumption
\[ \varphi: \Box_u \varphi \]
\[ \Box_u \varphi \]

OUTPUT
\[ D \models \varphi \]?
\[ D \models \Box_{w_1...w_d} R^+(x_1,...x_l) \]?
\[ q(\bar{x}):= \Box_{\bar{w}} R_i^+(\bar{x}_i) \]

Belief Conjunctive Queries (BCQ)
\[ q(\bar{x}) := \Box_{\bar{w}_1} R_{1}^{s_1}(\bar{x}_1), ..., \Box_{\bar{w}_g} R_{g}^{s_g}(\bar{x}_g) \]
Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion
Canonical Kripke structure

Belief statements*

- $i_1$: $\Box_{\text{Alice}} s_{11}^+$
- $i_2$: $\Box_{\text{Bob}} s_{11}^-$
- $i_3$: $\Box_{\text{Bob}} s_{12}^-$
- $i_4$: $\Box_{\text{Alice}} s_{21}^+$
- $i_5$: $\Box_{\text{Alice}} c_{11}^+$
- $i_6$: $\Box_{\text{Bob}} s_{22}^+$
- $i_7$: $\Box_{\text{Bob}} \cdot \Box_{\text{Alice}} c_{21}^+$
- $i_8$: $\Box_{\text{Bob}} c_{22}^+$

Message board assumption

- $\varphi: \Box_i \varphi$
- $\Box_i \varphi$

* Running example from the paper
### Relational representation

#### Sightings_INTERNAL

<table>
<thead>
<tr>
<th>tid</th>
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<td>s1.1</td>
<td>s1</td>
<td>Carol</td>
<td>Bald eagle</td>
<td>06-14-08</td>
<td>Lake Forest</td>
</tr>
<tr>
<td>s1.2</td>
<td>s1</td>
<td>Carol</td>
<td>Fish eagle</td>
<td>06-14-08</td>
<td>Lake Forest</td>
</tr>
<tr>
<td>s2.1</td>
<td>s2</td>
<td>Alice</td>
<td>Crow</td>
<td>06-14-08</td>
<td>Lake Placid</td>
</tr>
<tr>
<td>s2.2</td>
<td>s2</td>
<td>Alice</td>
<td>Raven</td>
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<td>Lake Placid</td>
</tr>
</tbody>
</table>

#### Comments_INTERNAL

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<th>comment</th>
<th>sid</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1.1</td>
<td>c1</td>
<td>found feathers</td>
<td>s2</td>
</tr>
<tr>
<td>c2.1</td>
<td>c2</td>
<td>plain black feathers</td>
<td>s2</td>
</tr>
<tr>
<td>c2.2</td>
<td>c2</td>
<td>purple-black feathers</td>
<td>s2</td>
</tr>
</tbody>
</table>

#### Sightings_V

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<td>s1</td>
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<td>#1</td>
<td>s1.1</td>
<td>s1</td>
<td>+</td>
<td>n</td>
</tr>
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<td>−</td>
<td>y</td>
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<tr>
<td>#3</td>
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#### E

<table>
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</tr>
<tr>
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#### Comments_V

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<th>e</th>
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<td>c1</td>
<td>+</td>
<td>y</td>
</tr>
<tr>
<td>#2</td>
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<td>c2</td>
<td>+</td>
<td>y</td>
</tr>
<tr>
<td>#3</td>
<td>c1.1</td>
<td>c1</td>
<td>+</td>
<td>n</td>
</tr>
<tr>
<td>#3</td>
<td>c2.1</td>
<td>c2</td>
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<td>y</td>
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#### D

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<tr>
<td>#2</td>
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<tr>
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#### S

<table>
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<tr>
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<tbody>
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<td>#2</td>
<td>#0</td>
</tr>
<tr>
<td>#3</td>
<td>#1</td>
</tr>
</tbody>
</table>
Example Translation of a Belief CQ (BCQ)

Q: Who disagrees with a sighting from ’06-14-08’ that Alice believes?

BeliefSQL

```
select U.name, S1.species
from Users as U,
    BELIEF ‘Alice’ Sighings as S1,
    BELIEF U.uid not Sighings as S2
where S1.sid = S2.sid
and S1.uid = S2.uid
and S1.species = S2.species
and S1.date = ‘06-14-08’
and S2.date = ‘06-14-08’
and S1.location = S2.location
```

Translation into SQL

```
select E1.uid as uid1, V.tid, V.sid, R.uid, R.species, R.date, R.location, V.s
into T2
from E as E1, Sighings_V as V, Sighings_STAR as R
where E1.wid1=0
and V.wid=E1.wid2
and V.tid=R.tid
and E1.uid=’1’;

select E1.uid as uid1, V.tid, V.sid, R.uid, R.species, R.date, R.location, V.s
into T1
from E as E1, Sighings_V as V, Sighings_STAR as R
where E1.wid1=0
and V.wid=E1.wid2
and V.tid=R.tid;

select T1.uid1, T2.species
from T1 as T1, T2 as T2
where T1.sid=T2.sid
and ((T1.s=0 and T1.uid=T2.uid and T1.species=T2.species
and T1.date='6-14-08' and T1.location=T2.location) or
(T1.s=1 and (T1.uid<T2.uid or T1.species<T2.species
or T1.date<T2.date or T1.location<T2.location)))
and T2.s=1
and T2.date='6-14-08';

drop table T2;
drop table T1;
```
Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion
Experiments

Size

Relative overhead $\rho := \frac{|R^*|}{n}$  \[ \rho = O(m^{d_{\text{max}}}) \]

In theory: e.g. 100 users, max. depth 2
$\rho \rightarrow 10,000$

Experiments: $\rho \rightarrow 21 – 1,009$

Size not limitation of semantics, but of relational implementation!

Time

Depends on type of query (3 types in paper)

Q1: $\sim 0.1$ s
Q2: $\sim 0.4$ s
Q3: $\sim 4.5$ s

Experiments on 10,000 annotations ($\rho = 22.4$):

Considerable speed-up to come!
Inspirations and related work (excerpt)

- Annotations
  - Buneman et al. [ICDT 2001 / ICDT 2007]
  - Bhagwat et al. [VLDBJ 2005], Geerts et al. [ICDE 2006]
  - Srivastava & Velegrakis [SIGMOD 2007]

- Modal logic
  - Fagin et al. [1995]
  - Calvanese et al. [IS 2008]
  - Nguyen [LJ-IGPL 2008]

- Uncertain / incomplete information
  - Sarma et al. [ICDE 2006]
  - Green & Tannen [IEEE Data Eng. 2006]
  - Dalvi & Suciu [PODS 2007]

- Inconsistency / key violations
  - Arenas et al. [PODS 1999]
  - Fuxman et al. [SIGMOD 2005]

- Peer-to-peer computing / collaborative data sharing
  - Bernstein et al. [WebDB 2002]
  - Ives et al. [SIGMOD record 2008]
Conclusions

• Proposed BELIEF databases
  – Goal: manage, curate inconsistent data

• Implementation
  – Logical foundations
  – Relational translation

• Current work
  – making it compact and fast
BACKUP
Relative overhead of relational representation

Bound for relative overhead \( \frac{|\mathcal{R}^*|}{n} = \mathcal{O}(m^{d_{\text{max}}}) \)

Measured relative overhead \( \frac{|\mathcal{R}^*|}{n} \) for \( n = 10,000 \) annotations, \( m = 100 \) users, uniform or Zipf user participation, and 3 distributions of annotation depth:

<table>
<thead>
<tr>
<th>( \Pr[d = {0, 1, 2}] )</th>
<th>uniform</th>
<th>Zipf</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0.3, 0.3, 0.3])</td>
<td>1,009</td>
<td>130</td>
</tr>
<tr>
<td>([0.8, 0.19, 0.01])</td>
<td>162</td>
<td>68</td>
</tr>
<tr>
<td>([0.199, 0.8, 0.001])</td>
<td>26</td>
<td>21</td>
</tr>
</tbody>
</table>

Measured relative overhead \( \frac{|\mathcal{R}^*|}{n} \) for \( m = 100 \) users, uniform user participation, and 2 distributions of annotation depth:
Query types and execution times

1. *Query for content*: “What does Alice believe?” $d \in \{0, \ldots, 4\}$:
   
   $$q_{1,d}(x, y) : \neg \Box_w S^+(x, \_ , y, \_ , \_), \text{ with } |w| \in \{0, \ldots, 4\}$$

2. *Query for conflicts*: “Which animal sightings does Bob believe that Alice believes, which he does not believe himself?”
   
   $$q_2(x, y) : \neg \Box_{2 \cdot 1} S^+(x, z, y, u, v), \Box_{2} S^-(x, z, y, u, v)$$

3. *Query for users*: Who disagrees with any of Alice’s beliefs of sightings at Lake Placid?”
   
   $$q_3(x) : \neg \Box_x S^-(y, z, u, v, ’a’), \Box_{1} S^+(y, z, u, v, ’a’)$$

Execution times and size of result sets for example queries executed over a belief database with 10,000 annotations and relative overhead 22.4.

<table>
<thead>
<tr>
<th></th>
<th>$q_{1,0}$</th>
<th>$q_{1,1}$</th>
<th>$q_{1,2}$</th>
<th>$q_{1,3}$</th>
<th>$q_{1,4}$</th>
<th>$q_2$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$(Time) [msec]</td>
<td>105</td>
<td>145</td>
<td>146</td>
<td>152</td>
<td>144</td>
<td>436</td>
<td>4473</td>
</tr>
<tr>
<td>$\sigma$(Time) [msec]</td>
<td>120</td>
<td>168</td>
<td>153</td>
<td>162</td>
<td>162</td>
<td>186</td>
<td>661</td>
</tr>
<tr>
<td>Result size</td>
<td>1626</td>
<td>2816</td>
<td>2253</td>
<td>2061</td>
<td>1931</td>
<td>196</td>
<td>99</td>
</tr>
</tbody>
</table>
Belief Conjunctive Queries (BCQ)

Conjunctive Queries (CQ) in Datalog form:

\[ q(\bar{x}) : \neg R_1(\bar{x}) , \ldots, R_g(\bar{x}) \]

Belief Conjunctive Queries (BCQ) in ”Modal Datalog” form:

\[ q(\bar{x}) : \neg \Boxw_1 R_{s1}^1(\bar{x}), \ldots, \Boxw_g R_{sg}^g(\bar{x}) \]

\[ q_1 : \text{”Who disagrees with any sighting from ’06-14-08’ that Alice believes?”} \]

\[ q_1(x, y) : \neg \Box_{\text{Alice}} S^+(u, v, y, ’06-14-08’, z), \Box_x S^-(u, v, y, ’06-14-08’, z) \]

\[ q_1(D) = \{ (’Bob’, ’bald eagle’), (’Bob’, ’crow’) \} \]
Revisiting the semantics / the user

Standard relational model

Conflicts in belief worlds:
OWA, keys, ML, DA

BeliefSQL

Structured discourse

(3) ?

Belief ’Alice’ (…,’eagle’,…)

Belief ’Alice’ (…,’eagle’,…)

Belief ’Bob’ Belief ’Alice’ (…,’black feathers’,…)

Belief ’Bob’ SUGGESTS that the ASSUMPTION (…,’black feathers’,…) has led ’Alice’ to her original observation