August 25, VLDB 2009

Believe It or Not – Adding belief annotations to databases

Wolfgang Gatterbauer, Magda Balazinska, Nodira Khoussainova, and Dan Suciu

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

reason: disagreement !

- 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

Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion

Motivating application

- NatureMapping project (http://depts.washington.edu/natmap/)
  - volunter contribute animal observations
  - one person curates the database

problem: does not scale!

Observations

id	uid	species	date	location	comment
2	Alice	Crow	06-14-08	Lake Placid	found feathers

Sightings (S)

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

Comments (C)

cid	comment	sid
c1	found feathers	s2

1. Distinct database instances

Alice

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

Bob

S

sid	uid	species	date	location
s2	Alice	Raven	06-14-08	Lake Placid

D1: Belief worlds: individually consistent, mutually possibly inconsistent

1. Distinct database instances

Alice

S

<u>sid</u>	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

Bob

S

<u>sid</u>	uid	species	date	location
s2	Alice	Raven	06-14-08	Lake Placid

BeliefSQL

I: Alice believes that she saw a crow.

insert into **BELIEF** 'Alice' Sightings
values ('s2','Alice','Crow','06-14-08','Lake Placid')

I: Bob believes that she actually saw a raven.

insert into **BELIEF** 'Bob' Sightings
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' Sightings as S1,
BELIEF U.uid Sightings as S2,
where S1.sid = S2.sid
and S1.species <> S2.species

A: {('Bob', 'Crow', 'Raven')}

2. Open world assumption

Alice

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

Bob

S

sid	uid	species	date	location
s2	Alice	Raven	06-14-08	Lake Placid

Carol

S

sid	uid	species	date	location	
s2	Alice	Crow	06-14-08	Lake Placid	−
s2	Alice	Raven	06-14-08	Lake Placid	−

Adapted key constraints !

D2: Model incomplete knowledge with exlicit negative beliefs

2. Open world assumption

Alice

S

sid	uid	specie
s2	Alice	Crow

Bob

S

sid	uid	specie		
s2	Alice	Raven	06-14-08	Lake Placid

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')

Carol

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid
s2	Alice	Raven	06-14-08	Lake Placid

2. Open world assumption

Alice

S

sid	uid	species	dat
s2	Alice	Crow	06-

Bob

S

sid	uid	species	dat
s2	Alice	Raven	06-

Carol

S

sid	uid	species	dat		
s2	Alice	Crow	06-14-08	Lake Placid	−
s2	Alice	Raven	06-14-08	Lake Placid	−

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

```
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
```

A: {('Bob', 'Crow'), ('Carol', 'Crow')}

3. Higher-order beliefs


Alice

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid


Bob

S

sid	uid	species	date	location
s2	Alice	Raven	06-14-08	Lake Placid

C

cid	comment	sid
c1	plain black feathers	s2



Bob Alice

C

cid	comment	sid
c1	purple-black feathers	s2

D3: Beliefs about other user's beliefs: allow discussion between users

3. Higher-order beliefs

Alice

S

sid	uid	specie
s2	Alice	Crow

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

insert into **BELIEF** 'Bob' **BELIEF** 'Alice' Comments
values ('c1', 'plain black feathers', 's2')

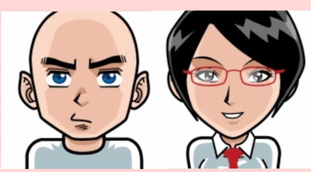
Bob

S

sid	uid	species		
s2	Alice	Raven	06-14-08	Lake Placid

C

cid	comment	sid
c1	plain black feathers	s2



Bob Alice

C

cid	comment	sid
c1	purple-black feathers	s2

3. Higher-order beliefs

Alice

S

sid	uid	specie
s2	Alice	Crow

Bob

S

sid	uid	specie
s2	Alice	Raven

C

cid	comment
c1	plain black fea

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

```
select   C1.cid, C1.comment
from     BELIEF 'Bob' BELIEF 'Alice' Comments as C1,
         BELIEF 'Bob' not Comments as C2
where    C1.cid = C2.cid
and      C1.comment = C2.comment
and      C1.sid = C2.sid
```

A: {('c1','plain-black feathers')}

Bob Alice

C

cid	comment	sid
c1	purple-black feathers	s2

3. Higher-order beliefs

Alice

S

sid	uid	specie…
s2	Alice	Crow

Bob

S

sid	uid	specie…
s2	Alice	Raven

C

cid	comment
c1	plain black fea…

Bob Alice

C

cid	comment	sid
c1	purple-black feathers	s2

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

Alice

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

Bob

S

sid	uid	species	date	location
s2	Alice	Raven	06-14-08	Lake Placid

C

cid	comment	sid
c1	plain black feathers	s2

Bob Alice

S

sid	uid	species	date	location
s2	Alice	Crow	06-14-08	Lake Placid

C

cid	comment	sid
c1	purple-black feathers	s2

D4: Default assumption: models a trusting attitude & avoids repeated inserts

4. Message board assumption

S

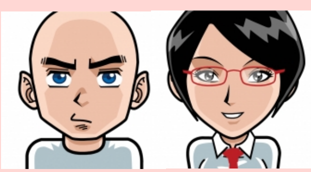
sid	uid	specie…
s2	Alice	Crow

S

sid	uid	specie…
s2	Alice	Raven

C

cid	comment
c1	plain black fea…



S

sid	uid	species		
s2	Alice	Crow	06-14-08	Lake Placid

C

cid	comment	sid
c1	purple-black feathers	s2

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')}

What we have seen so far

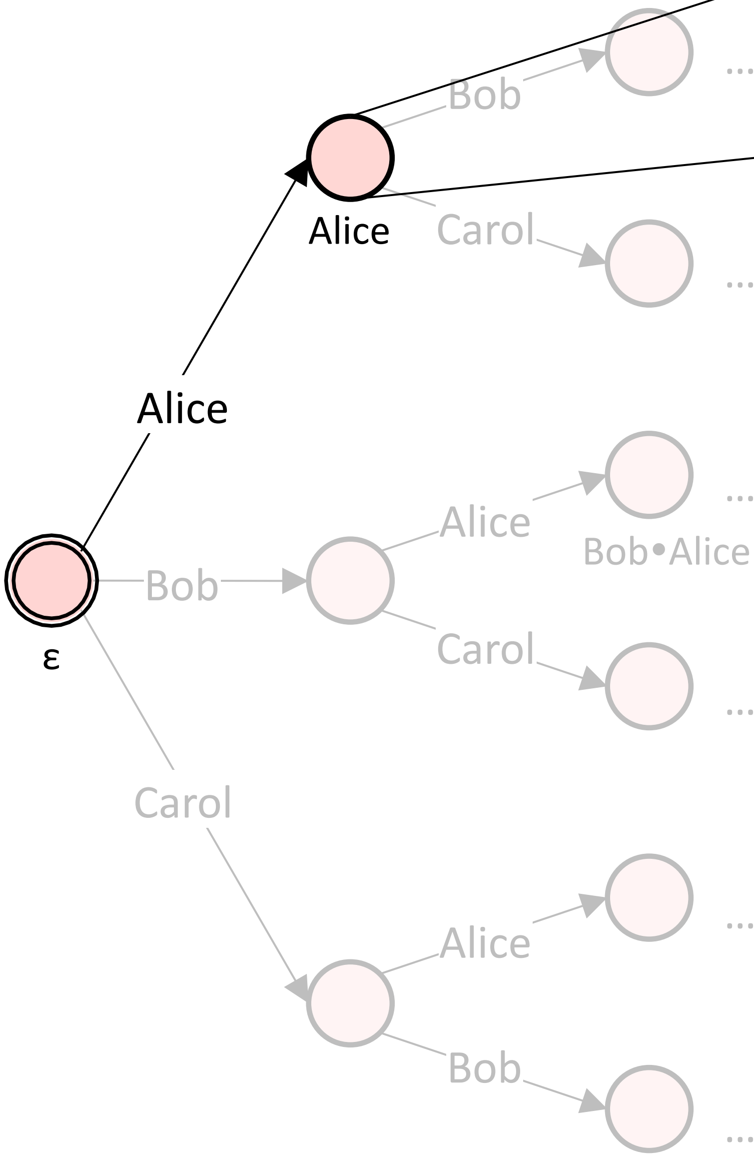
- 4 Design decisions for Belief Database model
  - Distinct belief worlds
  - Open world assumption (OWA)
  - Higher-order beliefs
  - Message board assumption

- **BeliefSQL**
  - SQL + ‘BELIEF’ (+ ‘not’)

Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion

Logic foundations: Belief statements



S

<u>sid</u>	uid	species	…
s2	Alice	Crow	…

insert into **BELIEF** 'Alice' S
values ('s2', 'Alice', 'Crow',…)

i: $\square_{\text{Alice}}\ S^{+}$('s2','Alice','Crow',…)

modal operator
& belief path (w)

relational tuple (t)
sign (s)

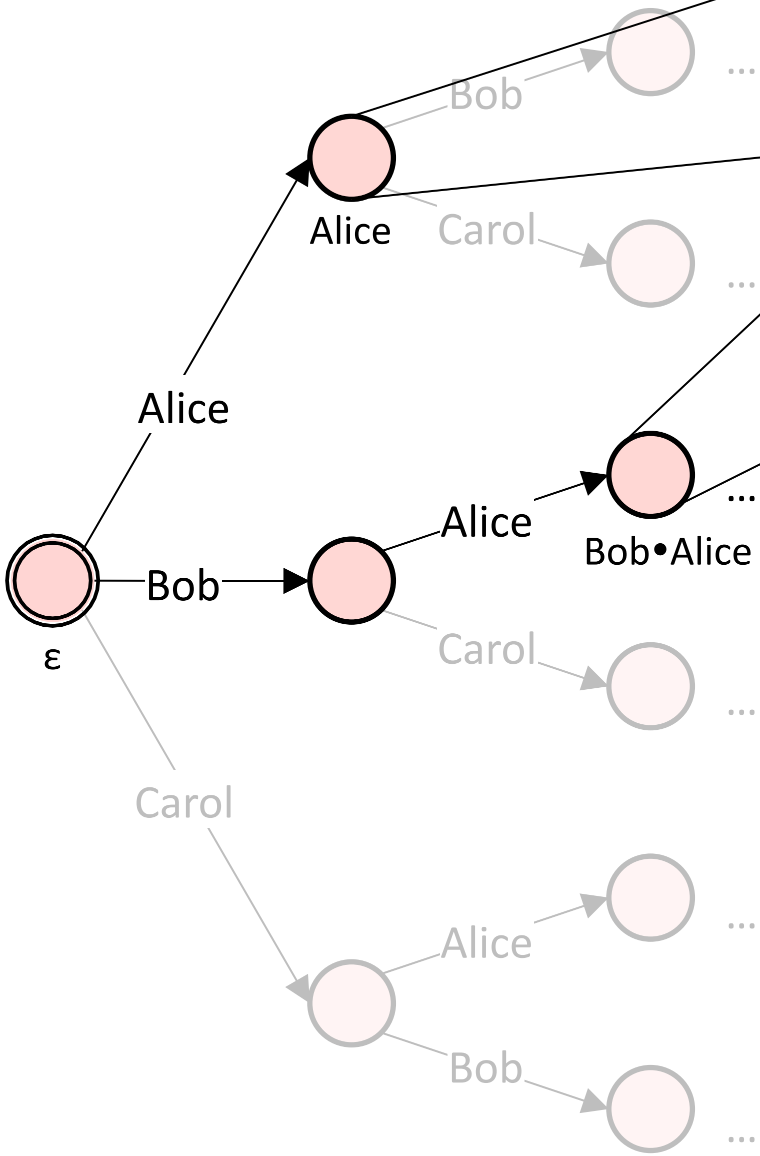
belief statement

$\varphi = \square_w\, t^s$

"annotation of ground tuple"

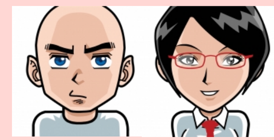
Belief database D = $\{\varphi_1, \ldots, \varphi_n\}$

Logic foundations: Entailment



S

<u>sid</u>	uid	species	...
s2	Alice	Crow	...



S

<u>sid</u>	uid	species	...
s2	Alice	Crow	...

```
select *
from   BELIEF 'Bob' BELIEF 'Alice' S
```

One belief annotation:

$D = \{\varphi_1\}$

$\varphi_1 = \Box_{Alice}\, S^{+}(\ldots\text{'Crow'},\ldots)$

More than one entailed belief:

$D \models \Box_{Bob \bullet Alice}\, S^{+}(\ldots\text{'Crow'},\ldots)$

Logic foundations: Message board assumption

Message board assumption

If $D \models \Box_{w}\, t^{s}$

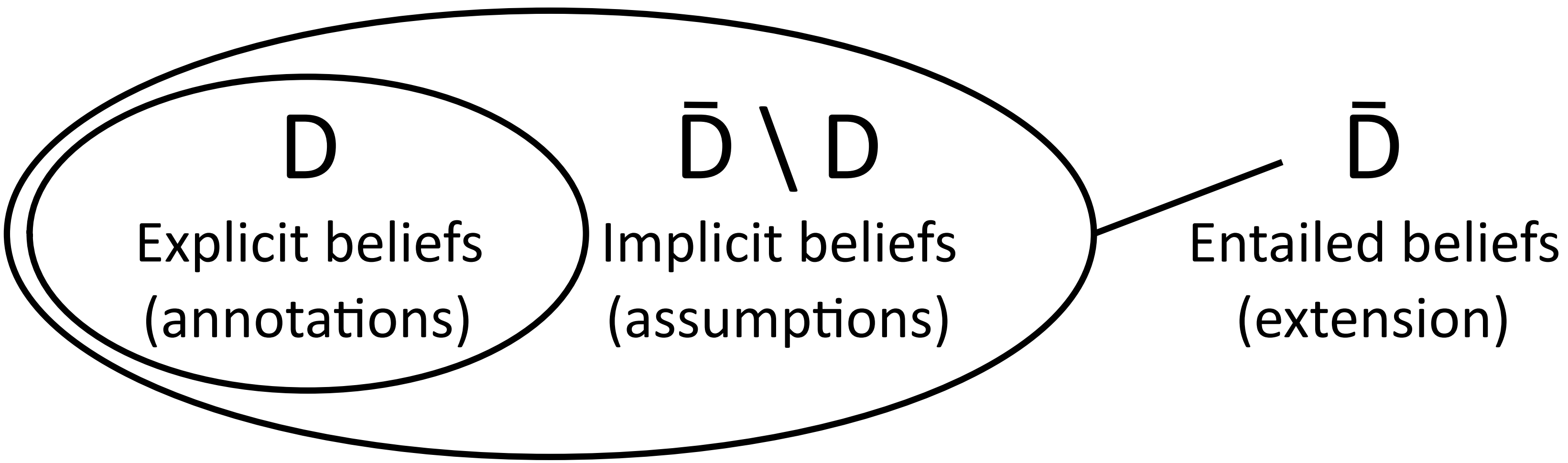
and $\Box_{u \bullet w}\, t^{s}$ consistent with D

then $D \models \Box_{u \bullet w}\, t^{s}$

Default logic

$$\frac{\varphi : \Box_{u}\, \varphi}{\Box_{u}\, \varphi}$$

non-monotonic reasoning !



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

$$\frac{\varphi : \Box_u \varphi}{\Box_u \varphi}$$

OUTPUT

$D \models \varphi$?

$D \models \Box_{w1\ldots wd} R^+(x_1,\ldots x_l)$?

$q(\bar{x}) :- \Box_{\bar{w}} R_i^+(\bar{x}_i)$

Belief Conjunctive Queries (BCQ)

$q(\bar{x}) :- \Box_{\bar{w}_1} R_1^{s_1}(\bar{x}_1), \ldots, \Box_{\bar{w}_g} R_g^{s_g}(\bar{x}_g)$

Agenda

- Motivating example
- Logic foundations
- Relational implementation
- Discussion

Canonical Kripke structure

Belief statements*

i_1: $s1_1^+$

i_2: $\Box_{Bob}\ s1_1^-$

i_3: $\Box_{Bob}\ s1_2^-$

i_4: $\Box_{Alice}\ s2_1^+$

i_5: $\Box_{Alice}\ c1_1^+$

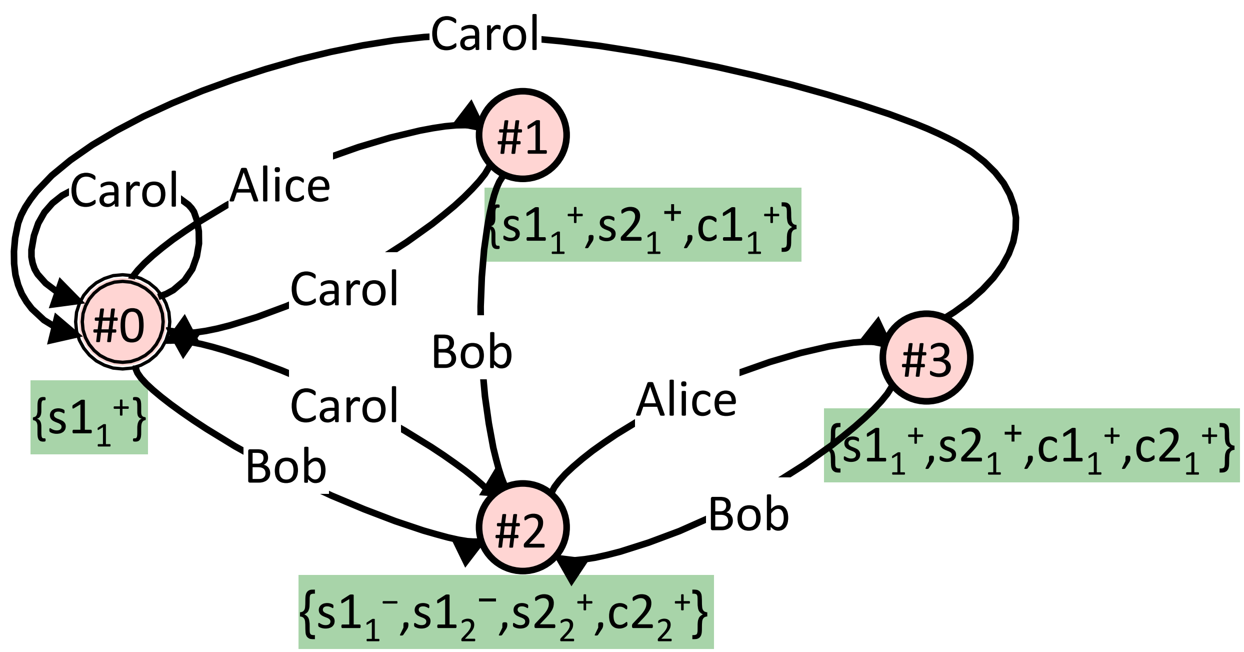
i_6: $\Box_{Bob}\ s2_2^+$

i_7: $\Box_{Bob \bullet Alice}\ c2_1^+$

i_8: $\Box_{Bob}\ c2_2^+$

Message board assumption

$$\frac{\varphi : \Box_i \varphi}{\Box_i \varphi}$$



* Running example from the paper

Relational representation

Sightings_INTERNAL

tid	sid	uid	species	date	location
s1.1	s1	Carol	Bald eagle	06-14-08	Lake Forest
s1.2	s1	Carol	Fish eagle	06-14-08	Lake Forest
s2.1	s2	Alice	Crow	06-14-08	Lake Placid
s2.2	s2	Alice	Raven	06-14-08	Lake Placid

Comments_INTERNAL

tid	cid	comment	sid
c1.1	c1	found feathers	s2
c2.1	c2	plain black feathers	s2
c2.2	c2	purple-black feathers	s2

Sightings_V

wid	tid	sid	s	e
#0	s1.1	s1	+	y
#1	s1.1	s1	+	n
#1	s2.1	s2	+	y
#2	s1.1	s1	–	y
#2	s1.2	s1	–	y
#2	s2.2	s2	+	y
#3	s1.1	s1	+	n
#3	s2.1	s2	+	n

E

wid1	uid	wid2
#0	Alice	#1
#0	Bob	#2
#0	Carol	#0
#1	Bob	#2
#1	Carol	#0
#2	Alice	#3
#2	Carol	#0
#3	Bob	#2
#3	Carol	#0

Comments_V

wd	tid	cid	s	e
#1	c1.1	c1	+	y
#2	c2.2	c2	+	y
#3	c1.1	c1	+	n
#3	c2.1	c2	+	y

D

wid	d
#0	0
#1	1
#2	1
#3	2

S

wid1	wid2
#1	#0
#2	#0
#3	#1

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' 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
```

$$q(x,y) :- \Box_{Alice}\ S^{+}(u,v,y,\text{'06-14-08'},z),$$
$$\Box_{x}\ S^{-}(u,v,y,\text{'06-14-08'},z)$$

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, Sightings_V as V, Sightings_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, Sightings_V as V, Sightings_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<>'6-14-08' 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 $\rho := \dfrac{|R^*|}{n}$

$\boxed{\rho = O(m^{d_{max}})}$

m ... #users
d_{max} ... maximum depth of belief annotation

In theory: e.g. 100 users, max. depth 2

$\rho \to 10{,}000$

Experiments: $\rho \to 21 - 1{,}009$

Size not limitation of semantics, but of relational implementation!

Time

Depends on type of query (3 types in paper)

Experiments on 10,000 annotations (ρ =22.4):

Q1: ~0.1 s
Q2: ~0.4 s
Q3: ~4.5 s

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

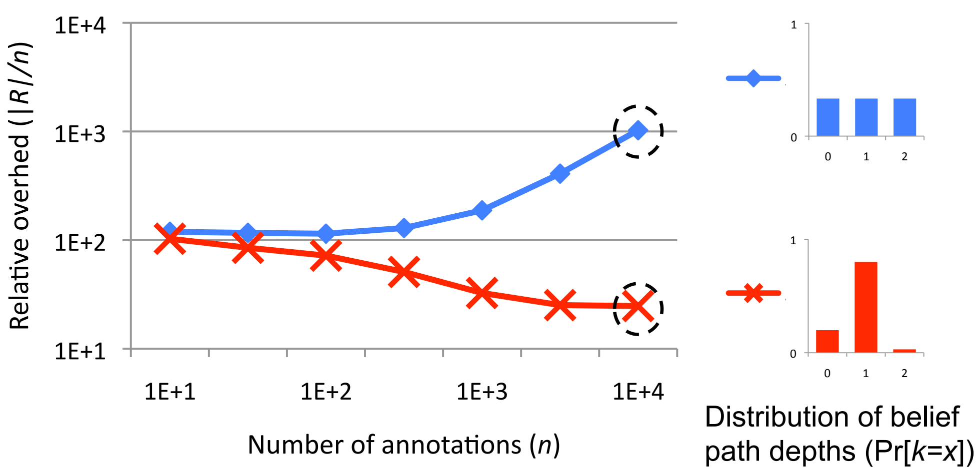
Relative overhead of relational representation

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

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:

$\Pr[d = \{0, 1, 2\}]$	uniform	Zipf
$[0.\dot{3},0.\dot{3},0.\dot{3}]$	1,009	130
$[0.8, 0.19, 0.01]$	162	68
$[0.199, 0.8, 0.001]$	26	21

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?" $d \in \{0, \ldots, 4\}$:

$$q_{1,d}(x, y) :- \Box_w S^+(x, \_, y, \_, \_), \text{ with } |w| \in \{ 0, \ldots, 4\}$$

2. *Query for conflicts*: "Which animal sightings does Bob believe that Alice believes, which he does not believe himself?"

$$q_2(x, y) :- \Box_{2\cdot 1} S^+(x, z, y, u, v), \Box_2 S^-(x, z, y, u, v)$$

3. *Query for users*: Who disagrees with any of Alice's beliefs of sightings at Lake Placid?"

$$q_3(x) :- \Box_x S^-(y, z, u, v, \text{'a'}), \Box_1 S^+(y, z, u, v, \text{'a'})$$

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

	$q_{1,0}$	$q_{1,1}$	$q_{1,2}$	$q_{1,3}$	$q_{1,4}$	q_2	q_3
E(Time) [msec]	105	145	146	152	144	436	4473
σ(Time) [msec]	120	168	153	162	162	186	661
Result size	1626	2816	2253	2061	1931	196	99

Belief Conjunctive Queries (BCQ)

Conjunctive Queries (CQ) in Datalog form:

$$q(\bar{x}) :- R_1(\bar{x}_1), \ldots, R_g(\bar{x}_g)$$

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

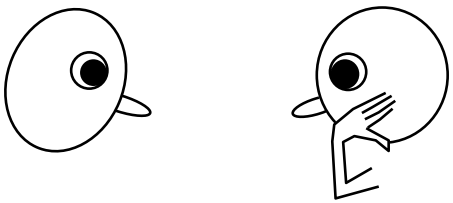
$$q(\bar{x}) :- \Box_{\bar{w}_1} R_1^{s_1}(\bar{x}_1), \ldots, \Box_{\bar{w}_g} R_g^{s_g}(\bar{x}_g)$$

q_1 : "*Who disagrees with any sighting from '06-14-08' that Alice believes?*"

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

$q_1(D) =$\{('Bob','bald eagle'),('Bob','crow')\}

Revisiting the semantics / the user



(3) ?

-> Structured discourse

(2) BeliefSQL

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

(1) SQL

Standard relational model

BELIEF ’Alice’ (…,’eagle’,…)

-> ’Alice’ASSERTS (…,’eagle’,…)

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

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