CS 595 - Hot topics in database systems: **Data Provenance**

I. Database Provenance

I.1 Provenance Models and Systems

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Outline

1. Where-Provenance and DBNotes
   - Introduction
   - Where-Provenance Model
   - Insensitive Where-Provenance
   - Insensitive Where-Provenance for Queries With Union
   - DBNotes
   - Recap

Where-Provenance

Motivation

- Annotation Propagation
  - Given database, annotations on attribute values
  - How to annotate query results?
  - Alterative Goal: study Where values (data) are copied from

Rationale

- From which attribute values in the input is a target attribute value $t.A$ in the result of q copied from.
- Annotated DBs: add annotations based on annotations in Where-provenance

Provenance Representation

- Set of input attribute values (locations)

Annotated Databases

Perquisites

- Relational Model
- Cell (R, t, a): Relation R at tuple t and attribute a

Annotated Database

- Each cell (R, t, a) is associated with a set of annotations $\mathcal{A}(R, t, a)$ (Strings)
- For query results: $\mathcal{A}(Q(I), t, a)$

Example

Excursion - Query Containment

Query Equivalence

- Recall: $q \equiv q' \Leftrightarrow \forall I : Q(I) = Q'(I)$
- Queries have same results over same input

Query Containment

- $q \subseteq q'$: Query q contained in q'
- $q \subseteq q' \Leftrightarrow \forall I : Q(I) \subseteq Q(I')$
- $\Rightarrow$The result of q is contained in the result of q'
- Relationship to equivalence: $q \subseteq q' \wedge q' \subseteq q \Leftrightarrow q \equiv q'$

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Annotation Containment

Annotation Containment

- $q \subseteq_{\mathcal{A}} q'$: Query q annotation contained in q' iff
  1. $q \subseteq q'$: q contained in q'
  2. $\forall I, t, A : \mathcal{A}(Q(I), t, A) \subseteq \mathcal{A}(Q'(I), t, A)$
- $\Rightarrow q$ only has tuples from q' with the same or some of the annotations

Annotation Equivalence

- $q =_{\mathcal{A}} q' : q \subseteq_{\mathcal{A}} q' \wedge q' \subseteq_{\mathcal{A}} q$
- Direct definition $\forall I, t, a$:
  1. $Q(I) = Q'(I)$
  2. $\mathcal{A}(Q(I), t, a) = \mathcal{A}(Q'(I), t, a)$

Annotation Example

EnzymeProduce

Enzyme	Gene
EC 1.1.1.1$^{\{a_1\}}$	4q11-q13$^{\{a_4\}}$
EC 1.97.1.6$^{\{a_3\}}$	4q11-q13$^{\{a_4\}}$

```
CREATE VIEW EnzymeProduce AS
SELECT Enzyme, Id AS Gene
FROM Gene G, Enzyme E
WHERE G.Id = E.ProducedBy
PROPAGATE G.Id TO Gene, E.Enzyme TO Enzyme
```

Gene

Id	Name
4q11-q13$^{\{a_4\}}$	ALB
18q21.3	BCL2

Enzyme

Enzyme	Weight	ProducedBy
EC 1.1.1.1$^{\{a_1\}}$	45	4q11-q13$^{\{a_2\}}$
EC 1.97.1.6$^{\{a_3\}}$	12	4q11-q13$^{\{a_2\}}$

Relationship Annotation Propagation and Where-Provenance

- Where-provenance one possible way to define annotation propagation

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- ⇒Output attribute value carries annotations from all input values in its provenance

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- Where-provenance one possible way to define annotation propagation
- ⇒Output attribute value carries annotations from all input values in its provenance
- ⇒Copying values ⇒ copying annotations

Relationship Annotation Propagation and Where-Provenance

- Where-provenance one possible way to define annotation propagation
- $\Rightarrow$Output attribute value carries annotations from all input values in its provenance
- $\Rightarrow$Copying values $\Rightarrow$ copying annotations
- What about functions or aggregation?
  - E.g., $sum(a)$
  - E.g., $f(a_1, a_2)$
- Not always what user wants
  - Allow user to specify how to propagate?

Outline

Where-Provenance

Properties

- **Granularity**: Attribute values
- **Representation**: Set of attribute locations: (R, t, a)
- **Definition**: Syntactic, recursive definition
  - Hard to come up with declarative definition!
- Sensitive to query rewrite
- $\Rightarrow$Insensitive declarative version

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Definition (Where-Provenance)

1. $Where(R, t, a) = \mathcal{A}(R, t, a)$

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3. $Where(\pi_A(q), t, b) = \bigcup_{u.A=t} Where(q, u, a)$
   - Assuming that a is projected on b: $(a \rightarrow b) \in A$

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   - Assuming that a is projected on b: $(a \rightarrow b) \in A$
4. $Where(q_1 \bowtie_C q_2, t, a) =$
   $Where(q_1, t.Q_1, a) \cup Where(q_2, t.Q_2, a)$

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4. $Where(q_1 \bowtie_C q_2, t, a) =$
   $Where(q_1, t.Q_1, a) \cup Where(q_2, t.Q_2, a)$
5. $Where(q_1 \cup q_2, t, a) = Where(q_1, t, a) \cup Where(q_2, t, a)$

Comments

- $Where(q, t, a) = \emptyset$ if q has no result attribute a
- Projection only on attribute + renaming
- Tuple t here refers to the values not the identity!
  - E.g., $(Peter, Chicago)$ and not t_2

Where-Provenance Example

Example

result

	name	street	city
t_1	Bob	10 W 31st	Chicago
t_2	Alice	75 Cermak	Chicago
t_3	Gertrud	15 Ellis	Berlin

```sql
SELECT P.name, A.street, A.city
FROM person P, address A
WHERE P.addr = A.street
```

person

	name	addr
p_1	Bob	10 W 31st
p_2	Alice	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago
a_2	75 Cermak	Chicago
a_3	15 Ellis	Berlin

Where-Provenance Example

Example

result

	name	street	city
t_1	Bob	10 W 31st	Chicago
t_2	Alice	75 Cermak	Chicago
t_3	Gertrud	15 Ellis	Berlin

$$q = \pi_{name,A.street,A.city}(q_1)$$

$$q_1 = person \bowtie_{addr=street} address$$

person

	name	addr
p_1	Bob	10 W 31st
p_2	Alice	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago
a_2	75 Cermak	Chicago
a_3	15 Ellis	Berlin

Where-Provenance Example

Example

$$Where(q, t_2, name) = Where(q_1, i_2, name)$$
$$Where(q_1, i_2, name) = Where(person, p_2, name) \cup Where(address, a_2, name)$$
$$Where(person, p_2, name) = \{a_2, a_3\}$$
$$Where(address, a_2, name) = \{\}$$

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

a_1 ="since 2005" a_2 ="artist" a_3 ="single" a_4 ="south side"
a_5 ="construction"

Where-Provenance Example

Example

result

	name	street	city
t_1	Bob	10 W 31st	Chicago$^{\{a_4\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak$^{\{a_5\}}$	Chicago
t_3	Gertrud	15 Ellis	Berlin

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
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$a_1 =$"since 2005" $a_2 =$"artist" $a_3 =$"single" $a_4 =$"south side"
$a_5 =$"construction"

Sensitivity to Query Rewrite

- Consider equivalent variation of example query

Example

```
SELECT P.name, A.street, A.city
FROM person P, address A
WHERE P.addr = A.street
```

result

	name	street	city
t_1	Bob	10 W 31st	Chicago$^{\{a_4\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak$^{\{a_5\}}$	Chicago
t_3	Gertrud	15 Ellis	Berlin

Sensitivity to Query Rewrite

- Consider equivalent variation of example query

Example

```sql
SELECT P.name, P.addr AS street, A.city
FROM person P, address A
WHERE P.addr = A.street
```

result

	name	street	city
t_1	Bob	10 W 31st$^{\{a_1\}}$	Chicago$^{\{a_4\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak$^{\{a_5\}}$	Chicago
t_3	Gertrud	15 Ellis	Berlin

Outline

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Insensitive Where-Provenance

Idea

- For query q
- Consider all queries equivalent to q
- Annotate output with the union of the annotations produced for each of these queries
- $\Rightarrow$Gather all annotations that could have been copied

Insensitive Where-Provenance

Definition (Insensitive Where-Provenance)

$$IWhere(q, t, a) = \bigcup_{q' \equiv q} Where(q', t, a)$$

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Insensitive Where-Provenance

Definition (Insensitive Where-Provenance)

$IWhere(q, t, a) = \bigcup_{q' \equiv q} Where(q', t, a)$

- Consider definition of union: Union annotations
- $\Rightarrow IWhere(q, t, a) = Where(\bigcup_{q' \equiv q} q', t, a)$

Insensitive Where-Provenance

Definition (Insensitive Where-Provenance)

$IWhere(q, t, a) = \bigcup_{q' \equiv q} Where(q', t, a)$

- Consider definition of union: Union annotations
- $\Rightarrow IWhere(q, t, a) = Where(\bigcup_{q' \equiv q} q', t, a)$

Problem

- There are infinitely many equivalent queries
- How to practically compute this?

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Equivalent Queries

- Even though the number of equivalent queries is infinite

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Equivalent Queries

- Even though the number of equivalent queries is infinite
- The number of queries with different annotation propagation behaviour is finite
  - The number of cells in input/output is finite
  - For each output cells - either input cells annotations are added or not
  - $\Rightarrow 2^{IC*OC}$ potential annotation behaviours
    - IC number of input cells
    - OC number of output cells

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Equivalent Queries

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  - For each output cells - either input cells annotations are added or not
  - $\Rightarrow 2^{IC*OC}$ potential annotation behaviours
    - *IC* number of input cells
    - *OC* number of output cells
  - $\Rightarrow$large, but finite
  - $\Rightarrow$unlikely that equivalent queries produce all these combinations!

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Query Basis

- $\mathcal{E}(q) = \{q' \mid q' \equiv q\}$
- Query Basis $\mathcal{B}(q)$ for q:
  - $\bigcup_{q' \in \mathcal{B}(q)} q' =_{\mathcal{A}} \bigcup_{q' \in \mathcal{E}(q)} q'$
  - A Query basis has same annotation behaviour as all equivalent queries!

Query Basis

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  - $\bigcup_{q' \in \mathcal{B}(q)} q' =_{\mathcal{A}} \bigcup_{q' \in \mathcal{E}(q)} q'$
  - A Query basis has same annotation behaviour as all equivalent queries!
  - How to find a query basis?

Query Basis For SPJ Queries

Types of equivalent SPJ queries

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Query Basis For SPJ Queries

Types of equivalent SPJ queries

1. Through attributes that are equated
    - Can project on either of them with different propagation behaviour
    - See gene example
    - E.g., $\pi_a(\sigma_{a=b}(R)) \equiv \pi_b(\sigma_{b=a}(R))$

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Query Basis For SPJ Queries

Types of equivalent SPJ queries

1. Through attributes that are equated
   - Can project on either of them with different propagation behaviour
   - See gene example
   - E.g., $\pi_a(\sigma_{a=b}(R)) \equiv \pi_b(\sigma_{b=a}(R))$
2. Through redundant joins
   - $\pi_A(R) \equiv \pi_A(R \bowtie_{A=A'} \pi_{A \rightarrow A'}(R))$
   - Each tuple finds at least one join partner (itself)
   - Additional join partners can carry additional annotations

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Example Redundant Joins

Example

```
SELECT P.name, A.street, A.city
FROM person P, address A
WHERE P.addr = A.street
```

```
SELECT P.name, A.street, R.city
FROM person P, address A, address R
WHERE P.addr = A.street AND A.city = R.city
```

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Algorithm - Generate Query Basis

1. Initialize $\mathcal{B}(q) = \emptyset$
2. For each $a = a'$ in q with a in result schema
   - Add variant of q where projection on a is replaced with projection on a'
3. For each query in $\mathcal{B}(q)$ and attribute a from relation R in projection
   - Add variant of q where an addition join $\bowtie_{a=a'} \pi_{a \rightarrow a'}(R)$ is added and replace final projection of a with a'

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Example - Query Basis

Example

Step 2

$$q = \pi_{name,street,city}(person \bowtie_{addr=street} address)$$
$$q' = \pi_{name,addr,city}(person \bowtie_{addr=street} address)$$

Example - Query Basis

Example

Step 3

$$q'' = \pi_{name',street,city}(person \bowtie_{addr=street} address \bowtie_{name=name'} \pi_{name \rightarrow name'}(person))$$

$$q''' = \pi_{name,street,city'}(person \bowtie_{addr=street} address \bowtie_{city=city'} \pi_{city \rightarrow city'}(address))$$

$$q'''' = \pi_{name,addr',city}(person \bowtie_{addr=street} address \bowtie_{addr=addr'} \pi_{addr \rightarrow addr'}(person))$$

$$q''''' = \pi_{name,street',city}(person \bowtie_{addr=street} address \bowtie_{street=street'} \pi_{street \rightarrow street'}(address))$$

Example - Query Basis

Example

result

	name	street	city
t_1	Bob	10 W 31st$^{\{a_1\}}$	Chicago$^{\{a_4\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak$^{\{a_5\}}$	Chicago$^{\{a_4\}}$
t_3	Gertrud	15 Ellis	Berlin

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

Discussion

Effect of Insensitive Where-Provenance

- Annotations from equated attributes are propagated too
  - Reasonable, can be seen as type of copying

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Discussion

Effect of Insensitive Where-Provenance

- Annotations from equated attributes are propagated too
  - Reasonable, can be seen as type of copying
- Annotations in attribute *a* from other tuples in the same relation are propagated if the tuple has the same value in attribute *a*
  - E.g., `city` attribute in running example
  - debatable whether correct semantics for every use case!

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Outline

1. Where-Provenance and DBNotes
   - Introduction
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   - Insensitive Where-Provenance
   - Insensitive Where-Provenance for Queries With Union
   - DBNotes
   - Recap

From SPJ to Union queries

Observations

- Adding Union adds new types of equivalent queries
- ⇒every query that is contained in a query can be union-ed to the query without changing the result
- ⇒this is independent of whether original query uses union!

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Query Containment with Union

- Relation $R(a, b)$ and $S(c)$
- $q = \pi_a(R)$

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Query Containment with Union

- Relation $R(a, b)$ and $S(c)$
- $q = \pi_a(R)$
- $q' = (\pi_a(R) \cup \pi_c(R \bowtie_{a=c} S))$

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Query Containment with Union

- Relation $R(a, b)$ and $S(c)$
- $q = \pi_a(R)$
- $q' = (\pi_a(R) \cup \pi_c(R \bowtie_{a=c} S))$
- $q \equiv q'$

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Generating Query Basis - Union

Step 4

- For each attribute a in result of q and relation R with attribute b in database
  - Add query $q \cup q'$ to $\mathcal{B}(q)$ with
  - q' is q with additional join with R on $a = b$

Example Query Basis

Example

Step 2

$$q = \pi_{name,street,city}(person \bowtie_{addr=street} address)$$
$$q' = \pi_{name,addr,city}(person \bowtie_{addr=street} address)$$

Example Query Basis

Example

Step 3

$$q_3 = \pi_{name',street,city}(person \bowtie_{addr=street} address \bowtie_{name=name'} \pi_{name \rightarrow name'}(person))$$

$$q_3' = \pi_{name,street,city'}(person \bowtie_{addr=street} address \bowtie_{city=city'} \pi_{city \rightarrow city'}(address))$$

$$q_3'' = \pi_{name,addr',city}(person \bowtie_{addr=street} address \bowtie_{addr=addr'} \pi_{addr \rightarrow addr'}(person))$$

$$q_3''' = \pi_{name,street',city}(person \bowtie_{addr=street} address \bowtie_{street=street'} \pi_{street \rightarrow street'}(address))$$

Example Query Basis

Example

Step 4

Joins on `person.name`

$$q_4 = q \cup \pi_{addr',street,city}(person \bowtie_{addr=street} address \bowtie_{name=addr'} \pi_{addr \rightarrow addr'}(person))$$

$$q'_4 = q \cup \pi_{street',street,city}(person \bowtie_{addr=street} address \bowtie_{name=street'} \pi_{street \rightarrow street'}(address))$$

$$q''_4 = q \cup \pi_{city',street,city}(person \bowtie_{addr=street} address \bowtie_{name=city'} \pi_{city \rightarrow city'}(address))$$

Example Query Basis

Example

Step 4

Joins on `address.street`

$$q_4''' = q \cup \pi_{name,name',city}(person \bowtie_{addr=street} address \bowtie_{street=name'} \pi_{name \rightarrow name'}(person))$$

...

Joins on `address.city`

...

Example Query Basis

Example

result

	name	street	city
t_1	Bob	10 W 31st$^{\{a_1\}}$	Chicago$^{\{a_4\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak$^{\{a_5\}}$	Chicago$^{\{a_4\}}$
t_3	Gertrud	15 Ellis	Berlin

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

Discussion

- An output cell (q, t, a) will carry all annotations from cells in the database that have the same attribute value

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- **Rationale**: annotations are bound to values not cells

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Discussion

- An output cell (q, t, a) will carry all annotations from cells in the database that have the same attribute value
- **Rationale**: annotations are bound to values not cells
- Still strange in a lot of cases.
  - E.g., numeric attributes age in `person` and `street number` in `company`
  - Query `SELECT * FROM person`
  - ⇒Annotations on company street numbers should carry over to the age of a person?

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Outline

DBNotes

Approach

- Add annotations to DBMS
- User queries DB with pSQL:
  - USPJ SQL queries
  - plus language constructs to define how annotations are propagated
- Implement as middleware layer over standard DBMS
- Store annotations + data in standard DBMS
- Middleware translates pSQL into SQL queries DB
- DB results are transformed into annotated relations

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pSQL

pSQL query block

```
SELECT DISTINCT selectlist
FROM            fromlist
WHERE           wherelist
PROPAGATE       (DEFAULT
                 | DEFAULT-ALL
                 | R1.a1 TO b1, ..., Rn.an TO bn)
```

- pSQL query is union of query blocks
- *selectlist*: Select attributes and rename ($R_1.a_1 \rightarrow b_1$)
- *fromlist*: List of relations with potential aliases
- *wherelist*: conjunction of attribute-attribute or attribute-constant equalities

pSQL - the PROPAGATE clause

- Defines how annotations are copied from input to output
- Three different options:
  - Custom
  - `DEFAULT`
  - `DEFAULT-ALL`

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Custom

- User defines annotation propagation at the query level
- $R_1.a_1 \texttt{TO} b_1$ = add annotations from input attribute $R_1.a_1$ to result attribute b_1.

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pSQL - the PROPAGATE clause

- Defines how annotations are copied from input to output
- Three different options:
  - Custom
  - `DEFAULT`
  - `DEFAULT-ALL`

DEFAULT

- Propagate annotations from all cells in the Where-provenance

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pSQL - the PROPAGATE clause

- Defines how annotations are copied from input to output
- Three different options:
  - Custom
  - `DEFAULT`
  - `DEFAULT-ALL`

DEFAULT-ALL

- Propagate annotations from all cells in the insensitive Where-provenance

pSQL example query

Example

```
SELECT P.name, A.street, A.city
FROM person P, address A
WHERE P.addr = A.street
PROPAGATE P.name TO name,
          P.addr TO street,
          P.addr TO city
```

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

pSQL example query

Example

result

	name	street	city
t_1	Bob	10 W 31st$^{\{a_1\}}$	Chicago$^{\{a_1\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak	Chicago
t_3	Gertrud	15 Ellis	Berlin

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
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address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

Storage Scheme

- Schema
  - For each attribute A in relation R
  - Add attribute A_a that stores annotations on A
- Instance
  - Each tuple can store one annotation on each attribute
  - Duplicate tuples to fit in more annotations

Example

- $R(a, b)$ will be $R(a, a_a, b, b_a)$

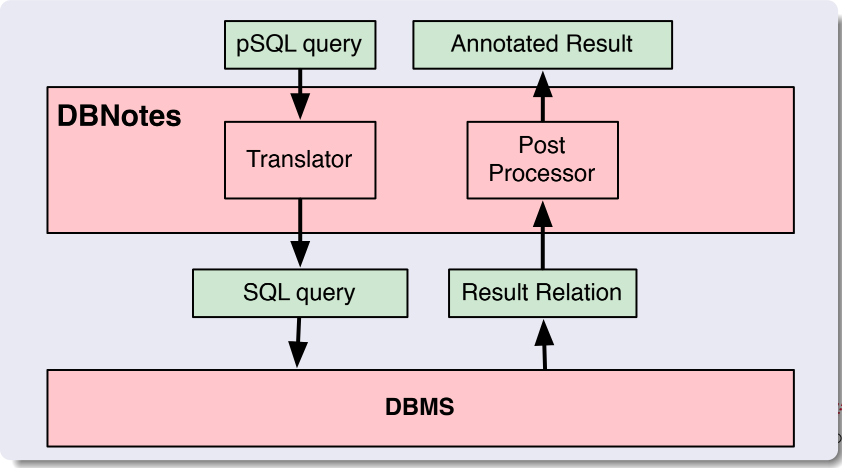
R

	a	b
r_1	$1^{a_1,a_2}$	2^{a_3}
r_2	2^{a_4}	3

R'

	a	a_a	b	b_a
r_1	1	a_1	2	a_3
r_1	1	a_2	2	-
r_1	2	a_4	3	-

DBNotes - Approach



Translator

1. Transform propagate clauses into *Custom* form
2. Build bins for each output attribute b
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Translator

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   - Take one attribute a from each bin
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4. Generate wrapper query
   - *orderlist* all attribute of pSQL query

```
SELECT DISTINCT *
FROM (Q1 UNION ... UNION Qn)
ORDER BY orderlist
```

Post-Processor

- Gather all annotations for each result tuple
- Works like aggregation
  1. Initialize each attribute annotation sets to empty set
  2. For each tuple add annotations to sets
  3. If tuple has different attribute value
     - Output annotated result tuple
     - Start over at (1)

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Example Processing

```
SELECT P.name, A.street, A.city
FROM person P, address A
WHERE P.addr = A.street
PROPAGATE P.name TO name,
          P.addr TO street,
          P.addr TO city
```

person

	name	addr
p_1	Bob	10 W 31st$^{\{a_1\}}$
p_2	Alice$^{\{a_2,a_3\}}$	75 Cermak
p_2	Gertrud	15 Ellis

address

	street	city
a_1	10 W 31st	Chicago$^{\{a_4\}}$
a_2	75 Cermak$^{\{a_5\}}$	Chicago
a_3	15 Ellis	Berlin

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Example Processing - Storage

person′

	name	$name_a$	addr	$addr_a$
p_1	Bob		10 W 31st	a_1
p_2	Alice	a_2	75 Cermak	
p_2	Alice	a_3	75 Cermak	
p_2	Gertrud		15 Ellis	

address′

	street	$street_a$	city	$city_a$
a_1	10 W 31st		Chicago	a_4
a_2	75 Cermak	a_5	Chicago	
a_3	15 Ellis		Berlin	

Example Processing - Intermediate Queries

- **Bin** name: {P.name}
- **Bin** street: {P.addr}
- **Bin** city: {P.addr}

```
SELECT P.name, P.name_a,
       A.street, P.addr_a AS street_a,
       A.city, P.addr_a AS city_a
FROM person' P, address' A
WHERE P.addr = A.street
```

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Example Processing - Wrapper Query

```
SELECT DISTINCT *
FROM (SELECT P.name, P.name_a,
        A.street, P.addr_a AS street_a,
        A.city, P.addr_a AS city_a
     FROM person' P, address' A
     WHERE P.addr = A.street) AS i
ORDER BY name, street, city
```

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Example Processing - Post-processing

result

	name	$name_a$	street	$street_a$	city	$city_a$
t_1	Bob		10 W 31st	a_1	Chicago	a_1
t_2	Alice	a_2	75 Cermak		Chicago	
t_2	Alice	a_3	75 Cermak		Chicago	
t_3	Gertrud		15 Ellis		Berlin	

Example Processing - Post-processing

result

	name	street	city
t_1	Bob	10 W 31st$^{\{a_1\}}$	Chicago$^{\{a_1\}}$
t_2	Alice$^{\{a_2,a_3\}}$	75 Cermak	Chicago
t_3	Gertrud	15 Ellis	Berlin

result

	name	name_a	street	street_a	city	city_a
t_1	Bob		10 W 31st	a_1	Chicago	a_1
t_2	Alice	a_2	75 Cermak		Chicago	
t_2	Alice	a_3	75 Cermak		Chicago	
t_3	Gertrud		15 Ellis		Berlin	

Discussion

Types of Annotations

- On tuples
- On rectangular regions in relations
- Queries define what to annotate

Discussion

Annotation Propagation

- DBNotes propagation is schema based!
- allow conditions
  - over data: if $a > 5$ then annotate with annotations from attribute b
  - over annotations: propagate if annotation contains word “important”
- manipulation of annotations
  - Extract pattern
  - Concatenate annotations
  - ...

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Outline

Recap

Where-Provenance

- **Rationale**: Models copy behaviour
- **Representation**: Set of cells
  - Cell is R, t, a
- **Syntactic Definition**:
  - For USPJ queries
- **Variants**:
  - Insensitive: Union for of provenance for equivalent queries

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Recap

Annotation Propagation

- One semantics is based on Where-provenance
- User defined also possible

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Recap

DBNotes

- Middleware implementations
- pSQL language
- Translated into SQL over relational storage schema
- Postprocessing

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Provenance Model Comparison

Property	Why	Lin	PI-CS	Where
Representation	Set of Set of Tuples	List of Set of Tuples	Set/Bag of List of Tuples	Sets of Attribute Value Positions
Granularity	Tuple	Tuple	Tuple	Attribute Value
Language Support	USPJ	ASPJ-Set	ASPJ-Set + Nested subqueries	U-SPJ
Semantics	Set	Set + Bag*	Bag	Set
Variants	Wit, Why, IWhy	Set/Bag	Influence + Copy	SPJ + Insensitive + Insensitive Union
Definition	Decl. - Synt. - Decl./Synt.	Decl. + Synt.	Decl. + Synt.	Synt.
Design Principles	Sufficiency - No false positives	Sufficiency + No false negatives + no false positives	Sufficiency + No false negatives + No false positives	Copying
Systems	-	WHIPS	Perm	DBNotes
Insensitivity	Yes - No - Yes	No	No	No - Yes - Yes

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