CS520 Data Integration, Warehousing, and Provenance

8. Provenance

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0

Outline

0) Course Info
1) Introduction
2) Data Preparation and Cleaning
3) Schema matching and mapping
4) Virtual Data Integration
5) Data Exchange
6) Data Warehousing
7) Big Data Analytics
8) Data Provenance

1

8.What is Data Provenance?

- **Metadata** describing the **origin** and **creation process** of **data**
  - **Data items**
    - Data item **granularity**
      - **A File**
      - **A Database**
      - **An Attribute value**
      - **A Row**
  - **Transformations**
    - Transformation **granularity**
      - **A program**
      - **A query**
      - **An operator in a query**
      - **A line in a program**

2

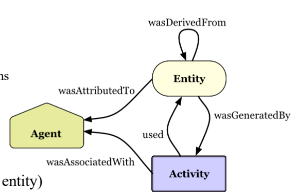
8.What is Data Provenance?

- **Provenance** records **dependencies**
  - **Data dependencies**
    - Data item x was used to generate data item y
  - **Dependencies between transformations and data**
    - Transformations generated a data item
    - Transformations used a data item

3

8. Provenance as graphs

- **Provenance graphs** (W3C PROV standard)
  - https://www.w3.org/TR/2013/NOTE-prov-primer-20130430/
  - **Nodes**
    - **Entities**
      - what we call data items
    - **Activities**
      - what we call transformations
    - **Agents**
      - Trigger / control activities
      - E.g., users and machines

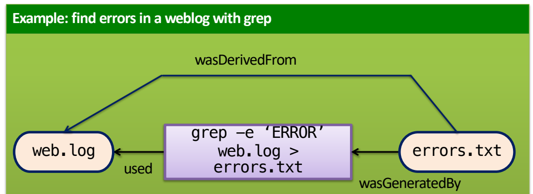


  - **Edges**
    - **wasDerivedFrom** (entity – entity)
      - Data dependencies
    - **wasGeneratedBy** (activity – entity)
      - Transformation generated an output data item
    - **used** (entity – activity)
      - Transformation read and input data item

4

8. PROV example

Example: find errors in a weblog with grep



5

8. Provenance for Databases

- **Transformations**
  - **SQL queries**
  - **Updates and transactions**
  - **Procedural code**
- **Data items**
  - **Databases**
  - **Tables**
  - **Rows**
  - **Cells** (attribute value of a row)

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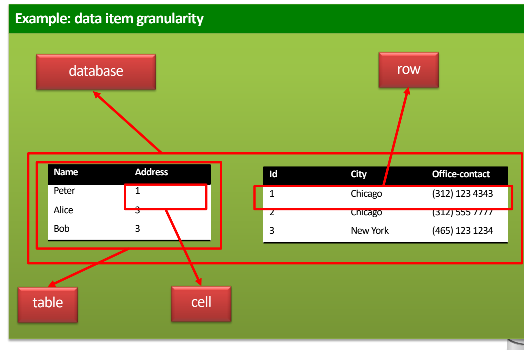
6

8. Databases Prov. – Data items



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7

8. Provenance for Queries

- **Data dependencies**
  - For each **output tuple** (**cell**) of the query determine which **input tuples** (**cells**) of the query it depends on
- **Formally (kind of)**
  - Given database **D** and query **Q** and tuple **t** in **Q(D)**
    - **Prov(Q,D,t)** = the subset of **D** that was used to derive **t** through **Q**

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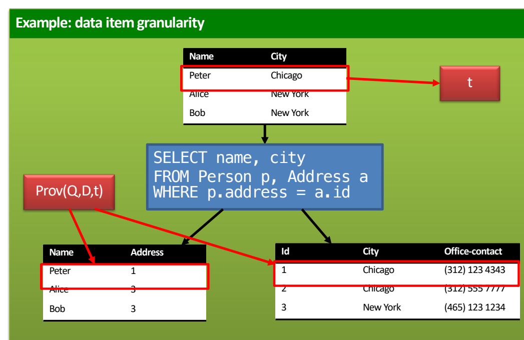
8

8. Databases Prov. – Data items



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8. Formalizing data dependencies

- **How to formalize data dependencies?**
  - **Access**: query did read the data
    - No! Everything depends on everything!
  - **Sufficiency**: the provenance is enough to produce the result tuple **t**
    - **t** is in **Q(Prov(Q,D,t))**
    - Guarantees that everything that was needed to produce **t** is in the provenance

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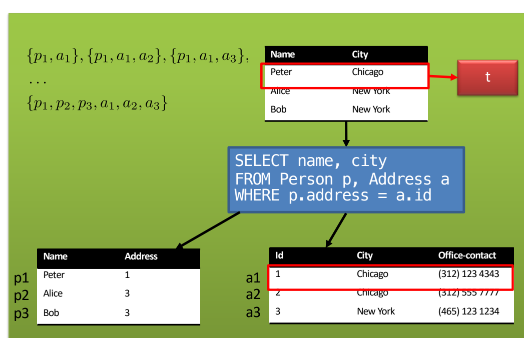
10

8. Sufficiency - Example



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11

8. Sufficiency cont.

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- **Is sufficiency enough?**
  - No, sufficiency does not prevent irrelevant inputs to be included in the provenance!
  - Sufficiency does not uniquely define provenance
- **Monotone Queries**
  - A query **Q** is monotone if

$$\forall D, D' : D \subseteq D' \Rightarrow Q(D) \subseteq Q(D')$$

- **For all monotone queries Q:**
  - If D is sufficient then so is any superset of D
  - in particular the input database D is sufficient

12

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12

8. Why provenance

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- **Rationale:** define provenance as the set of all sufficient subsets of the input
  - this uniquely defines provenance
  - this does not solve the redundancy issue!
- **Why provenance**:

$$Why(Q, D, t) = \{D' \mid D' \subseteq D \wedge t \in Q(D')\}$$

- Each sufficient subset of D in the why provenance is called a witness

13

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13

8. Minimality

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- **Rationale:**
  - Remove tuples that do not contribute to the result
  - If a subset of a witness is already sufficient then everything not in the subset is unnecessary and should be removed
- **Definition**

witness D' is minimal if $\forall D'' \subset D' : Q(D'') \neq Q(D)$

14

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14

8. Minimal Why provenance

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- **Minimal Why provenance**:
- Only include minimal witnesses

$$MWhy(Q, D, t) = \{D' \mid D' \in Why(Q, D, t) \wedge \nexists D'' \subset D' : D'' \in Why(Q, D, t)\}$$

15

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15

8. Sufficiency - Example

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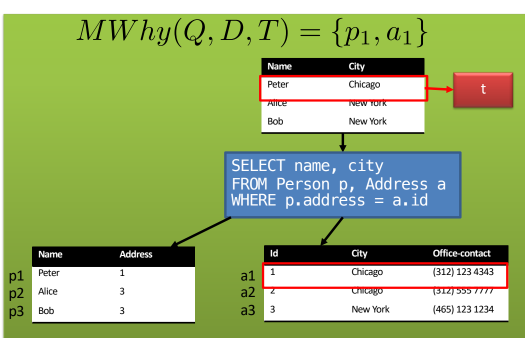

16

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16

8. Why provenance - discussion

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- **Independent of query syntax**
  - Queries are treated as blackbox functions
  - Equivalent queries have the same provenance!
- How to compute this efficiently?
  - The discussion so far only gives a brute force exponential time algorithm
    - For each subset D' of D test whether it is a witness
    - Then for every witness test whether it is minimal by testing for a subset relationship with all other witnesses
  - Top-down rules that calculate MWhy in a syntax driven manner

17

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17

8. MWhy – top-down recursion

- Define top-down syntax-driven rules
  - calculate a set of witnesses
  - Minimizing the result of these rules returns MWhy

$$W(R,t,I) = \{\{t\}\}$$
$$W(\sigma_\theta(Q),t,I) = W(Q,t,I)$$
$$W(\pi_A(Q),t,I) = \bigcup_{u \in Q(I):u.A=t} W(Q,u,I)$$
$$W(Q_1 \bowtie_\theta Q_2,t,I) = \{(w_1 \cup w_2) \mid w_1 \in W(Q_1,t_1,I) \wedge w_2 \in W(Q_2,t_2,I) \wedge t = (t_1,t_2)\}$$
$$W(Q_1 \cup Q_2,t,I) = W(Q_1,t,I) \cup W(Q_2,t,I)$$

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18

8. Why provenance – discussion 2

- **This works well for set semantics, but not bag semantics**
  - Minimization can lead to incorrect results with bag semantics
  - Treating the provenance as sets of tuples does not align well with bags
- **This only encodes data dependencies**
  - We know from which tuples we have derived a result, but not how the tuples were combined to produce the result

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19

8. Semiring annotations - Agenda

- **We will now discuss a model that …**
  - Provides provenance for both sets and bags
  - Allows us to track how tuples where combined
  - Can express many other provenance models including MWhy
  - Can also express bag and set semantics and other extensions of the relational model such as the incomplete databases we discussed earlier

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8. Annotations on Data

- **Annotations**
  - Allow data to be associated with additional metadata
    - Comments from users
    - Trust annotations
    - Provenance
    - …
  - Here we are interested in annotations on the tuples of a table

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21

8. K-relations

- **Annotation domain**
  - We fix a set K of possible annotations
  - Examples
    - Powerset(Powerset(D)) = all possible sets of witnesses
      - We can annotate each tuple with its Why or MWhy provenance
    - Natural numbers
      - We can simulate bag semantics by annotating each tuple with its multiplicity
    - A set of possible world identifiers D1 to Dn
      - Incomplete databases

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22

8. K-relations

- **K-relations**
  - We fix a set **K** of possible annotations
  - **K** has to have a distinguished element $\mathbf{0_K}$
  - Assume some data domain **U**
  - An n-ary K-relation is a function

$$\mathcal{U}^n \rightarrow K$$

    - We associate an annotation with every possible n-ary tuple
    - $\mathbf{0_k}$ is used to annotate tuples that are not in the relation
    - Only finitely many tuples are allowed to be mapped to a non-zero annotation

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8. Example – bag semantics

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Bag Semantics

Name	Address
Peter	1
Peter	1
Peter	1
Alice	3
Alice	3
Bob	3

N-relation

Name	Address	Annotation
Peter	1	3
Alice	3	2
Bob	3	1

8. Example – set semantics

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Bag Semantics

Name	Address
Peter	1
Peter	1
Peter	1
Alice	3
Alice	3
Bob	3

B-relation

Name	Address	Annotation
Peter	1	true
Alice	3	true
Bob	3	true

$$\mathbb{B} = \{false, true\}$$

8. Example – incomplete DBs

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Incomplet Database

D_1

Name	Address
Peter	1
Peter	2
Bob	3

D_2

Name	Address
Peter	1
Alice	2
Bob	3

Ω -relation

Name	Address	Annotation
Peter	1	{D1,D2}
Peter	2	{D1}
Alice	2	{D2}
Bob	3	{D1,D2}

$$\Omega = \mathcal{P}(\{D_1, D_2\})$$
$$= \{\emptyset, \{D_1\}, \{D_2\}, \{D_1, D_2\}\}$$

8. Example – MWhy

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MWhy

Name	Address
Peter	1
Peter	2
Bob	3

MWhy(p1) = {{x1}}
MWhy(p2) = {{x2,a1},{x3}}
Mwhy(p3) = {{x4,a1},{x4,a2}}

PosBool[X]-relation

Name	Address	Annotation
Peter	1	{{x1}}
Peter	2	{{x2,a1},{x3}}
Bob	3	{{x4,a1},{x4,a2}}

$$X = D$$
$$PosBool[X] = \mathcal{P}(\mathcal{P}(X))$$

8. K-relations – Query semantics

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- **Annotated Databases are powerful**
  - We can many different types of information
  - However, what is the right query semantics?
    - e.g., bag and set semantics queries do not have the same semantics, let along queries over incomplete databases or calculating provenance
- **Query Semantics**
  - Split the query semantics into two parts
    - One part is generic and independent of the choice of K
    - One part is specific to the choice of K
  - => every K has to be paired with operations that define how annotations propagate through queries
    - The generic semantics uses these operations to calculate query result annotations

8. Semirings

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- **A semiring** $\mathcal{K} = (K, \oplus_\mathcal{K}, \otimes_\mathcal{K}, 0_\mathcal{K}, 1_\mathcal{K})$
  - K is the set of elements of semiring
    - We use them as annotations
  - There are two binary operations
    $\oplus_\mathcal{K}, \otimes_\mathcal{K} : K \times K \rightarrow K$
    - We will use them to combine annotations of input tuples
      - Addition will be used to model operations that are disjunctive in nature (union, projection)
      - Multiplication will be used to model operations that are conjunctive (join)
  - Two distinguished elements $0_\mathcal{K}, 1_\mathcal{K}$

8. Semiring Laws

- **A semiring** $\mathcal{K} = (K, \oplus_\mathcal{K}, \otimes_\mathcal{K}, 0_\mathcal{K}, 1_\mathcal{K})$

$$
\begin{aligned}
k_1 \oplus_\mathcal{K} k_2 &= k_2 \oplus_\mathcal{K} k_1 && \text{(commutativity)}\\
k_1 \oplus_\mathcal{K} (k_2 \oplus_\mathcal{K} k_3) &= (k_1 \oplus_\mathcal{K} k_2) \oplus_\mathcal{K} k_3 && \text{(associativity)}\\
k_1 \otimes_\mathcal{K} k_2 &= k_2 \otimes_\mathcal{K} k_1 && \text{(commutativity)}\\
k_1 \otimes_\mathcal{K} (k_2 \otimes_\mathcal{K} k_3) &= (k_1 \otimes_\mathcal{K} k_2) \otimes_\mathcal{K} k_3 && \text{(associativity)}\\
k \oplus_\mathcal{K} 0_\mathcal{K} &= k && \text{(neutral element)}\\
k \otimes_\mathcal{K} 1_\mathcal{K} &= k && \text{(neutral element)}\\
k \otimes_\mathcal{K} 0_\mathcal{K} &= 0_\mathcal{K} && \text{(annihilation by zero)}\\
k_1 \otimes_\mathcal{K} (k_2 \oplus_\mathcal{K} k_3) &= (k_1 \otimes_\mathcal{K} k_2) \oplus (k_1 \otimes_\mathcal{K} k_3) && \text{(distributivity)}
\end{aligned}
$$

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30

8. Semirings - Examples

$$
\begin{aligned}
\mathbb{N} &= (\mathbb{N}, +, \cdot, 0, 1)\\
\mathbb{B} &= (\mathbb{B}, \vee, \wedge, false, true)\\
\mathcal{K}_{MWhy}[X] &= (\mathcal{P}(\mathcal{P}(X)), \cup, \Cup, \emptyset, \{\emptyset\})\\
\mathcal{K}_{\Omega}[X] &= (\mathcal{P}(\Omega), \cup, \cap, \emptyset, \Omega)\\
\mathbb{N}[X] &= (\mathbb{N}[X], +, \cdot, 0, 1)
\end{aligned}
$$

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31

8. Provenance Polynomials

- **Semiring** $\mathbb{N}[X] = (\mathbb{N}[X], +, \cdot, 0, 1)$
  - N[X] is the set of all polynomials over variables X
    - Intuitively X are tuple identifiers
  - **Provenance polynomials** are used to track provenance for **bag semantics**!
  - Provenance polynomials record how a result has been derived by combining input tuples
    - Multiplication means conjunctive use (as in join)
    - Addition means disjunctive use

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32

8. K-relations – Query semantics

- **Positive relational algebra (RA⁺)**
  - Selection, projection, cross-product, renaming, union

$$
\begin{aligned}
\textbf{Union:}\quad & (R_1 \cup R_2)(t) = R_1(t) \oplus_\mathcal{K} R_2(t)\\
\textbf{Join:}\quad & (R_1 \bowtie R_2)(t) = R_1(t[R_1]) \otimes_\mathcal{K} R_2(t[R_2])\\
\textbf{Projection:}\quad & (\pi_A(R))(t) = \bigoplus_{t=t'[A]} R(t')\\
\textbf{Selection:}\quad & (\sigma_\theta(R))(t) = R(t) \otimes_\mathcal{K} \theta(t)
\end{aligned}
$$

$$
\theta(t) = \begin{cases} 0_\mathcal{K} & \text{if } t \models \theta \\ 1_\mathcal{K} & \text{otherwise} \end{cases}
$$

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33

8. Query Semantics - Bags

City	N
Chicago	1
New York	1*1+1*1 = 2

$$\pi_{City}(\sigma_{address=id}(person \times address))$$

Name	Address	N
Peter	1	1
Alice	3	1
Bob	3	1

Id	City	Office-contact	N
1	Chicago	(312) 123 4343	1
2	Chicago	(312) 555 7777	1
3	New York	(465) 123 1234	1

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34

8. Query Semantics - MWhy

City	MWhy
Chicago	$\{\{x_1, x_4\}\}$
New York	$\{\{x_2, x_6\}, \{x_2, x_6\}\}$

$$\pi_{City}(\sigma_{address=id}(person \times address))$$

Name	Address	MWhy
Peter	1	$\{\{x_1\}\}$
Alice	3	$\{\{x_2\}\}$
Bob	3	$\{\{x_3\}\}$

Id	City	Office-contact	MWhy
1	Chicago	(312) 123 4343	$\{\{x_4\}\}$
2	Chicago	(312) 555 7777	$\{\{x_5\}\}$
3	New York	(465) 123 1234	$\{\{x_6\}\}$

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35

8. Query Semantics - PP

36

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36

8. Provenance Polynomials - Computability

- Recall our requirements of sufficiency and minimality
- Provenance polynomials fulfill a stronger requirement: **computability**
  - Given the result of a query in N[X], we can compute the query result in any other semiring K under a given assignment of input tuples (variables of the polynomials) to annotations from K

37

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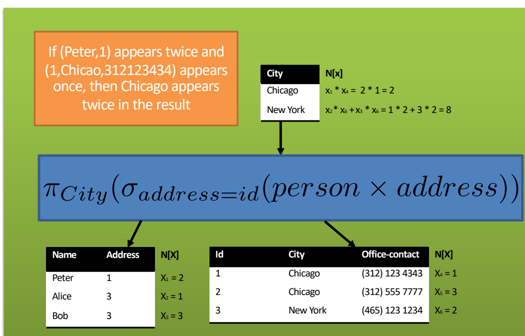
37

8. Query Semantics - PP



38

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38

8. Homomorphisms

- A function h from semiring K1 to K2 is a homomorphism if

$$h(k_1 \oplus_{\mathcal{K}_1} k_2) = h(k_1) \oplus_{\mathcal{K}_2} h(k_2)$$
$$h(k_1 \otimes_{\mathcal{K}_1} k_2) = h(k_1) \otimes_{\mathcal{K}_2} h(k_2)$$
$$h(0_{\mathcal{K}_1}) = 0_{\mathcal{K}_2}$$
$$h(1_{\mathcal{K}_1}) = 1_{\mathcal{K}_2}$$

- **Theorem**: Homomorphism commute with queries

$$Q(h(D)) = h(Q(D))$$

- **Proof Sketch**: queries are defined using semiring operations which commute with homomorphisms

39

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39

8. Fundamental theorem

- **Theorem**: Homomorphism commute with queries

$$Q(h(D)) = h(Q(D))$$

- **Proof Sketch**: queries are defined using semiring operations which commute with homomorphisms
- **Theorem**: Any assignment X -> K induces a semiring homomorphism N[X] -> K

40

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40

8. Summary

- **Provenance is information about the origin and creation process of data**
  - Data dependencies
  - Dependencies between data and the transformations that generated it
- **Provenance for Queries**
  - **Correctness criteria**:
    - sufficiency, minimality, computability
  - **Provenance models:**
    - Why, MWhy, Provenance polynomials

41

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41