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CS520
Data Integration, Warehousing, and Provenance

8. Provenance

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Outline

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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**

8. What is Data Provenance?

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- **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**

8.What is Data Provenance?

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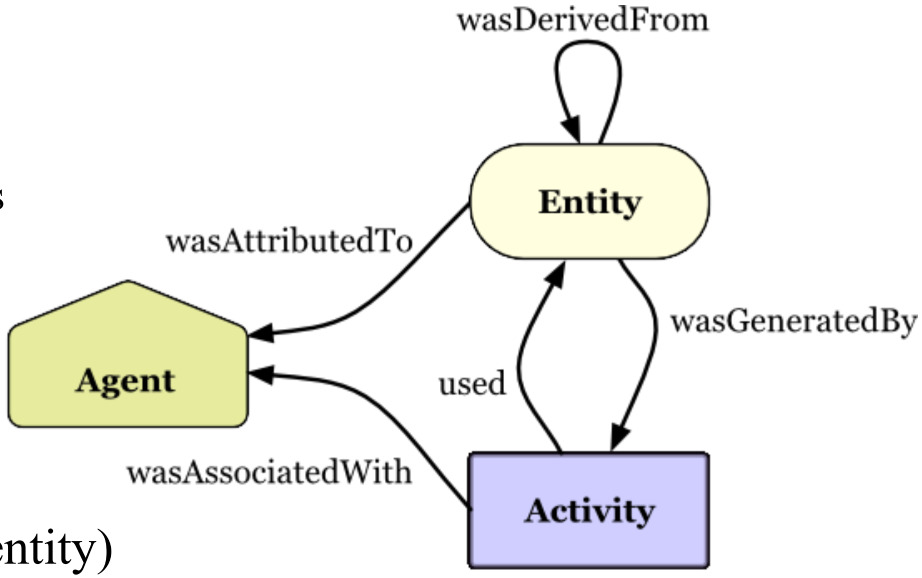
- **Provenance** records **dependencies**
  - **Data dependencies**
    - Data item x was used to generate data item y
  - **Dependencies between transformations and data**
    - Transformations generated a data item
    - Transformations used a data item

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

8. PROV example

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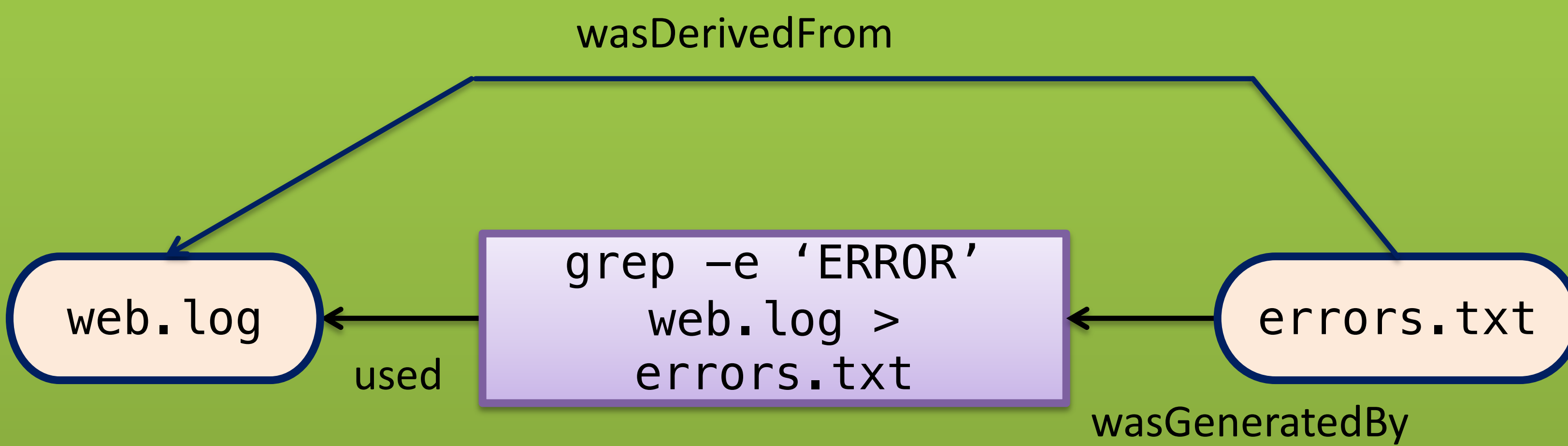
Example: find errors in a weblog with grep



8. Provenance for Databases

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

8. Databases Prov. – Data items

Example: data item granularity

database

row

Name	Address
Peter	1
Alice	3
Bob	3

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

table

cell

8. Provenance for Queries

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- **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**

Example: data item granularity

Name	City
Peter	Chicago
Alice	New York
Bob	New York

t

```
SELECT name, city
FROM Person p, Address a
WHERE p.address = a.id
```

Prov(Q,D,t)

Name	Address
Peter	1
Alice	3
Bob	3

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

8. Formalizing data dependencies

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- **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

8. Sufficiency - Example

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$\{p_1, a_1\}, \{p_1, a_1, a_2\}, \{p_1, a_1, a_3\},$

$\ldots$

$\{p_1, p_2, p_3, a_1, a_2, a_3\}$

Name	City
Peter	Chicago
Alice	New York
Bob	New York

t

```
SELECT name, city
FROM Person p, Address a
WHERE p.address = a.id
```

	Name	Address
p1	Peter	1
p2	Alice	3
p3	Bob	3

	Id	City	Office-contact
a1	1	Chicago	(312) 123 4343
a2	2	Chicago	(312) 555 7777
a3	3	New York	(465) 123 1234

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

8. Why provenance

- **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

8. Minimality

- **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**

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

8. Minimal Why provenance

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

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

8. Sufficiency - Example

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$$MWhy(Q, D, T) = \{p_1, a_1\}$$

Name	City
Peter	Chicago
Alice	New York
Bob	New York

t

```
SELECT name, city
FROM Person p, Address a
WHERE p.address = a.id
```

	Name	Address
p1	Peter	1
p2	Alice	3
p3	Bob	3

	Id	City	Office-contact
a1	1	Chicago	(312) 123 4343
a2	2	Chicago	(312) 555 7777
a3	3	New York	(465) 123 1234

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

8. MWhy – top-down recursion

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

$$W(R,t,I) = \{\{t\}\}$$

$$W(\sigma_\theta(Q),t,I) = W(Q,t,I)$$

$$W(\pi_A(Q),t,I) = \bigcup_{u \in Q(I) : u.A = t} W(Q,u,I)$$

$$W(Q_1 \bowtie_\theta Q_2,t,I) = \{(w_1 \cup w_2) \mid w_1 \in W(Q_1,t_1,I) \\ \wedge w_2 \in W(Q_2,t_2,I) \wedge t = (t_1,t_2)\}$$

$$W(Q_1 \cup Q_2,t,I) = W(Q_1,t,I) \cup W(Q_2,t,I)$$

8. Why provenance – discussion 2

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- **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

8. Semiring annotations - Agenda

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- **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

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

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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- **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

8. Example – bag semantics

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

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

- **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

- **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

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

$$k_1 \oplus_{\mathcal{K}} k_2 = k_2 \oplus_{\mathcal{K}} k_1 \qquad \text{(commutativity)}$$

$$k_1 \oplus_{\mathcal{K}} (k_2 \oplus_{\mathcal{K}} k_3) = (k_1 \oplus_{\mathcal{K}} k_2) \oplus_{\mathcal{K}} k_3 \qquad \text{(associativity)}$$

$$k_1 \otimes_{\mathcal{K}} k_2 = k_2 \otimes_{\mathcal{K}} k_1 \qquad \text{(commutativity)}$$

$$k_1 \otimes_{\mathcal{K}} (k_2 \otimes_{\mathcal{K}} k_3) = (k_1 \otimes_{\mathcal{K}} k_2) \otimes_{\mathcal{K}} k_3 \qquad \text{(associativity)}$$

$$k \oplus_{\mathcal{K}} 0_{\mathcal{K}} = k \qquad \text{(neutral element)}$$

$$k \otimes_{\mathcal{K}} 1_{\mathcal{K}} = k \qquad \text{(neutral element)}$$

$$k \otimes_{\mathcal{K}} 0_{\mathcal{K}} = 0_{\mathcal{K}} \qquad \text{(annihilation by zero)}$$

$$k_1 \otimes_{\mathcal{K}} (k_2 \oplus_{\mathcal{K}} k_3) = (k_1 \otimes_{\mathcal{K}} k_2) \oplus (k_1 \otimes_{\mathcal{K}} k_3) \qquad \text{(distributivity)}$$

8. Semirings - Examples

$$\mathbb{N} = (\mathbb{N}, +, \cdot, 0, 1)$$

$$\mathbb{B} = (\mathbb{B}, \vee, \wedge, false, true)$$

$$\mathcal{K}_{MWhy}[X] = (\mathcal{P}(\mathcal{P}(X)), \cup, \Cup, \emptyset, \{\emptyset\})$$

$$\mathcal{K}_{\Omega}[X] = (\mathcal{P}(\Omega), \cup, \cap, \emptyset, \Omega)$$

$$\mathbb{N}[X] = (\mathbb{N}[X], +, \cdot, 0, 1)$$

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

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

Union: $(R_1 \cup R_2)(t) = R_1(t) \oplus_{\mathcal{K}} R_2(t)$

Join: $(R_1 \bowtie R_2)(t) = R_1(t[R_1]) \otimes_{\mathcal{K}} R_2(t[R_2])$

Projection: $(\pi_A(R))(t) = \bigoplus_{t=t'[A]} R(t')$

Selection: $(\sigma_\theta(R))(t) = R(t) \otimes_{\mathcal{K}} \theta(t)$

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

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

8. Query Semantics - MWhy

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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	$\{\{x_6\}\}$

8. Query Semantics - PP

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City	N[x]
Chicago	$x_1 * x_4$
New York	$x_2 * x_6 + x_3 * x_6$

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

Name	Address	N[X]
Peter	1	x_1
Alice	3	x_2
Bob	3	x_3

Id	City	Office-contact	N[X]
1	Chicago	(312) 123 4343	x_4
2	Chicago	(312) 555 7777	x_5
3	New York	(465) 123 1234	x_6

8. Provenance Polynomials - Computability

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- 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

8. Query Semantics - PP

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If (Peter,1) appears twice and (1,Chicao,312123434) appears once, then Chicago appears twice in the result

City	N[x]
Chicago	$x_1 * x_4 = 2 * 1 = 2$
New York	$x_2 * x_6 + x_3 * x_6 = 1 * 2 + 3 * 2 = 8$

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

Name	Address	N[X]
Peter	1	$X_1 = 2$
Alice	3	$X_2 = 1$
Bob	3	$X_3 = 3$

Id	City	Office-contact	N[X]
1	Chicago	(312) 123 4343	$X_4 = 1$
2	Chicago	(312) 555 7777	$X_5 = 3$
3	New York	(465) 123 1234	$X_6 = 2$

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

8. Fundamental theorem

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- **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

8. Summary

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- **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