Foundations and Applications of Data Provenance

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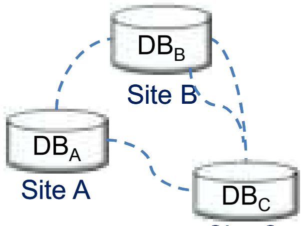
BigProv'13 Workshop

Data sharing in the era of Big Data (3V's)



- Data sharing among large number of diverse data sources (high **variety**)
  - Sites can have different schemas or even data models, and viewpoints on "truth"
- Sites contribute and import (map) large **volumes** of data
- Need to handle frequent updates to local and imported data and mappings efficiently (high **velocity**)
- Big Data Analytics: quality of results only as high as that of input data, need to determine what to trust

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"Where Did this Data Come from and how?"

- A common set of questions:
  - Which sources did the data originate from?
  - What operations were used to create and propagate the data?
  - How can we assess trust, data quality etc based on this information?
- *Data provenance* captures the relationships between items in data instances created through declarative queries or views
  - Different from workflow provenance (e.g., [OPM], [PROV-O]) which captures procedural code and usually treats operations as black boxes due to their complexity

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Main topics of this talk

- What data provenance models are there? What data models and query language operators can they capture? How do they compare to each other?
- How can data provenance support assessment of various dimensions of data quality and help in dealing with the 3V's? What systems and applications take advantage of this?
- What are the benefits of data provenance in Big Data settings, what are the challenges introduced by the 3V's, and how can we deal with them?

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Outline

- Data provenance models for positive relational algebra queries
- Applications of data provenance
- Extensions to the theoretical framework
- Benefits and challenges of data provenance on Big Data

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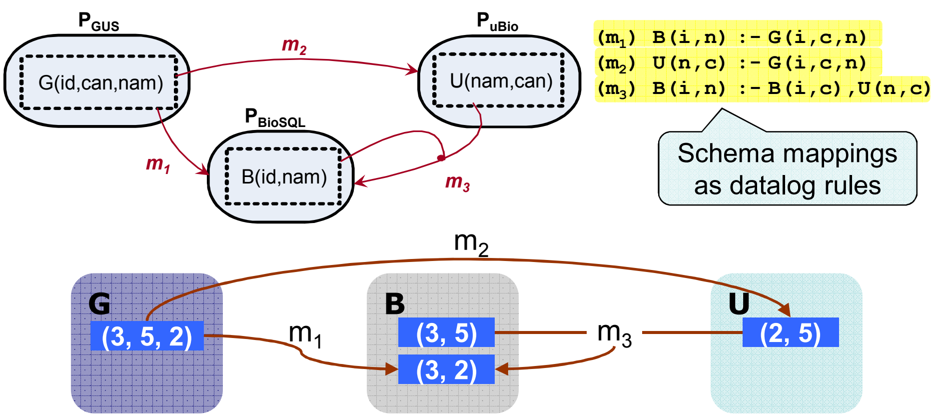
An Example Data Sharing Scenario: Collaborative Data Sharing in ORCHESTRA [VLDB07]



How do we record provenance for the operations prescribed by these mappings (join, union)?

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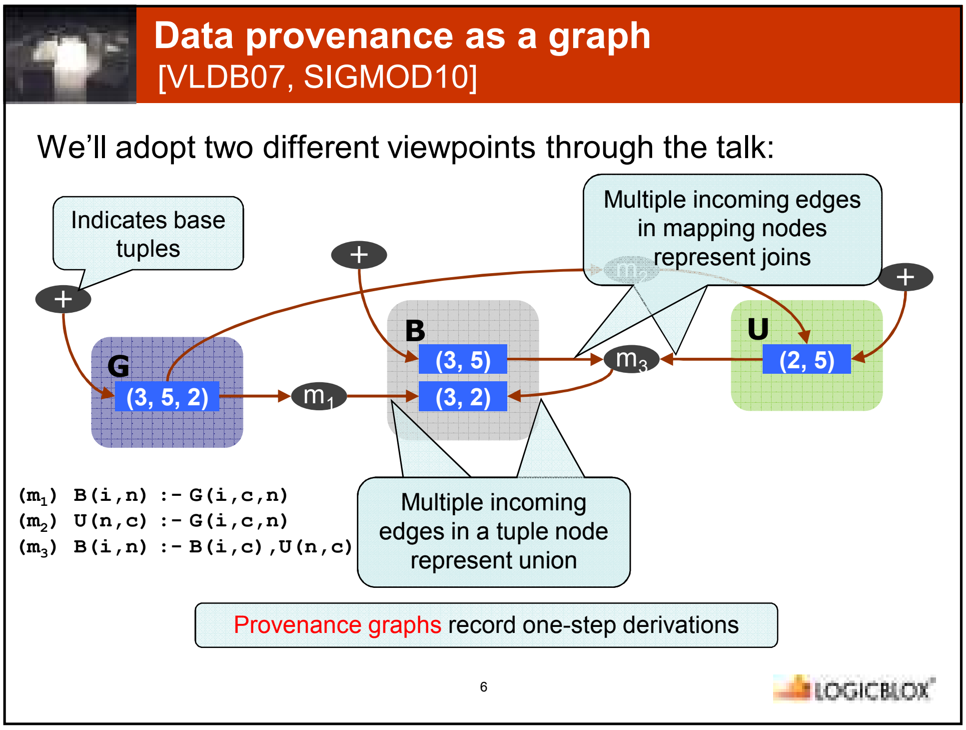
Data provenance as a graph
[VLDB07, SIGMOD10]
We'll adopt two different viewpoints through the talk:
Indicates base tuples
Multiple incoming edges in mapping nodes represent joins
G
(3, 5, 2)
m1
B
(3, 5)
(3, 2)
m3
U
(2, 5)
(m1) B(i,n) :- G(i,c,n)
(m2) U(n,c) :- G(i,c,n)
(m3) B(i,n) :- B(i,c),U(n,c)
Multiple incoming edges in a tuple node represent union
Provenance graphs record one-step derivations
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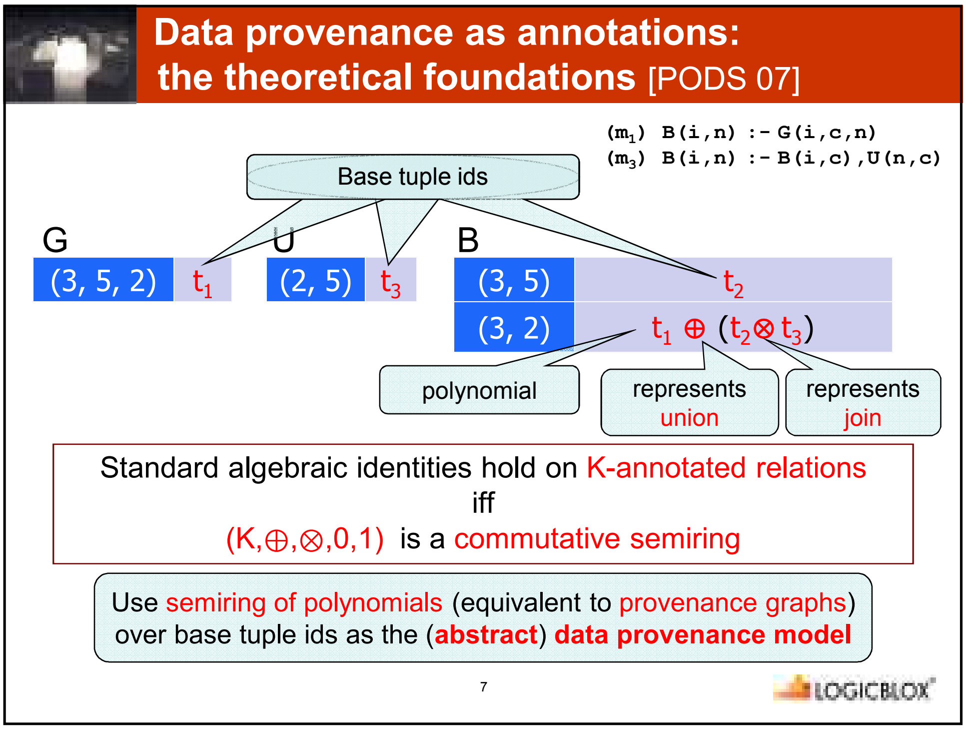
Data provenance as annotations: the theoretical foundations [PODS 07]
(m1) B(i,n) :- G(i,c,n)
(m3) B(i,n) :- B(i,c),U(n,c)
Base tuple ids
G
(3, 5, 2) t1
U
(2, 5) t3
B
(3, 5) t2
(3, 2) t1 ⊕ (t2⊗t3)
polynomial
represents union
represents join
Standard algebraic identities hold on K-annotated relations
iff
(K,⊕,⊗,0,1) is a commutative semiring
Use semiring of polynomials (equivalent to provenance graphs) over base tuple ids as the (abstract) data provenance model
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Semirings unify commonly-used database semantics involving annotations

Standard database models	
set semantics	
bag semantics	
Trust, security	
boolean trust, derivability	[VLDB07]
ranked trust	[SIGMOD10]
confidentiality	[Foster+08]
Uncertainty, incompleteness	
incomplete DBs	[Imielinski+84]
probabilistic DBs	[Fuhr+97]
ranks, scores	[Talukdar+08]

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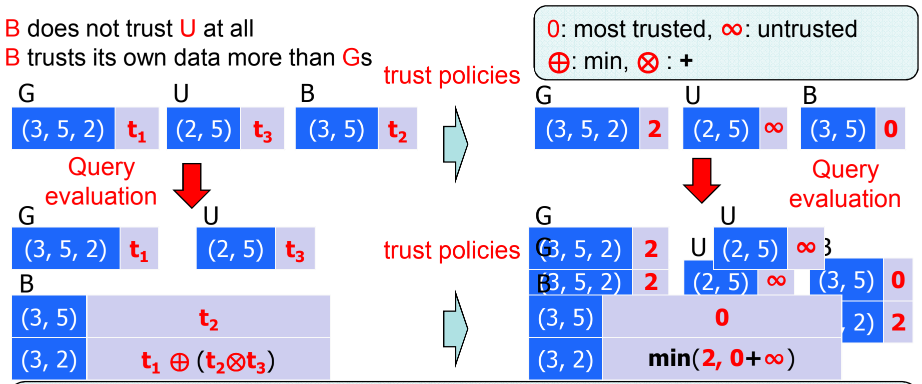
Example: computing ranked (dis)trust annotations through provenance

Provenance polynomials abstract calculations in **all** commutative semirings



- Record data provenance (i.e., abstract annotations) during query evaluation
- Evaluate different trust policies or various other annotations through provenance later, often on small subset of query results, without recomputation
  - Especially important for Big Data, due to high volume and velocity

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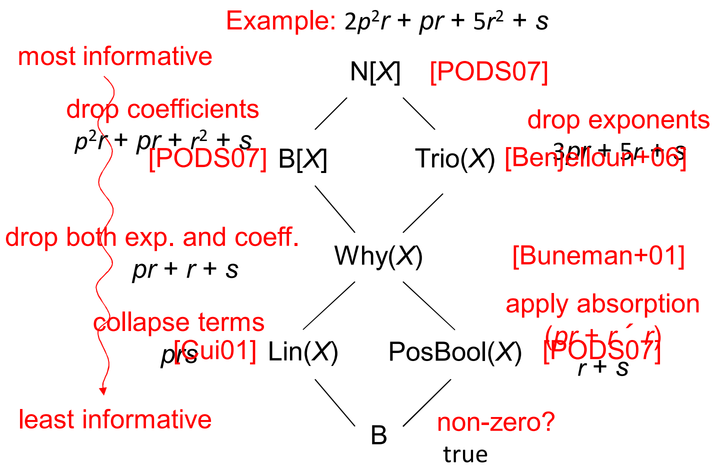
Hierarchy of relational abstract provenance models [Green11]



A path downward from K_1 to K_2 indicates that we can compute K_2 from K_1

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Outline

- Data provenance models for positive relational algebra queries
- Applications of data provenance
  - Provenance querying and annotation computations
  - Uses in research prototypes and commercial systems
- Extensions to the theoretical framework
- Benefits and challenges of data provenance on Big Data

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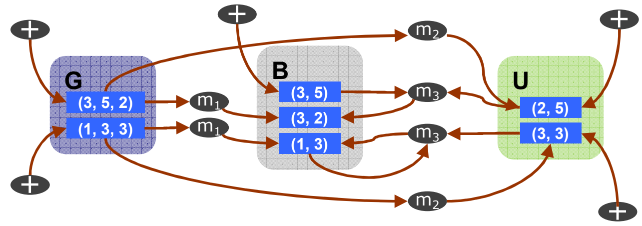
Storing provenance in relations
(Orchestra [VLDB07, SIGMOD10] – LogicBlox [Datalog12])

- Similar to storing graphs in edge relations, but here mapping nodes have multiple "input" and "output" tuples: hyperedges
- Use tuple values (keys) as ids for base tuples



(m_1) B(i,n) :- G(i,c,n) (m_2) U(n,c) :- G(i,c,n) (m_3) B(i,n) :- B(i,c), U(n,c)

P_1(B.i, B.n, G.i, G.c, G.n)
(3, 2, 3, 5, 2)
(1, 3, 1, 3, 3)

P_2(i,c,n)
(3, 5, 2)
(1, 3, 3)

P_3(i,c,n)
(3, 5, 2)
(1, 3, 3)

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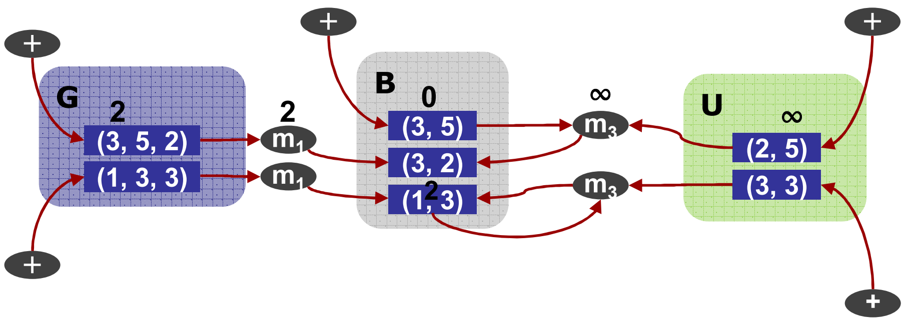
Example of provenance query for ranked (dis)trust computation [SIGMOD10]

Find derivations of B(3,2) from base data



B does not trust U at all

B trusts its own data more than G's

What is the trust rank of B(3,2)?

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ProQL syntax for ranked (dis)trust assessment [SIGMOD10]

```
EVALUATE RANK OF {
     FOR [B $x] <-+ []
     WHERE $x.id = 3 AND $x.nam = 2
     INCLUDE PATH [$x] <-+ []
     RETURN $x
}
ASSIGNING EACH leaf_node $y {
     CASE $y in G : SET 2
     CASE $y in U : SET inf
     DEFAULT : SET 0
}
ASSIGNING EACH mapping $p($z) {
     CASE $p = m2 : SET 2*$z
     DEFAULT : SET $z
}
```

DERIVABILITY
TRUST
LINEAGE
CONFIDENTIALITY
PROBABILITY

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Provenance enables incremental algorithms for handling updates to data and views

- Updates to source data (incremental view maintenance)
  - Past approaches (DRed [Gupta+93]) over-delete and recompute
  - Use data provenance to determine incrementally if derived tuples should be deleted without recomputation [V

Very important due to high volume and velocity

- Updates to derived data (view update)
  - Past approaches ([Dayal+82]) statically check and reject views that may cause side effects on some inputs
  - Use data provenance to determine at runtime if propagating specific deletions to source tuples will actually cause side effects [WebDB07]
- Updates to views (view adaptation)
  - Can be cast as applications of rewriting queries using materialized views, and data provenance can enable more efficient rewritings [Green+11, Green+12]

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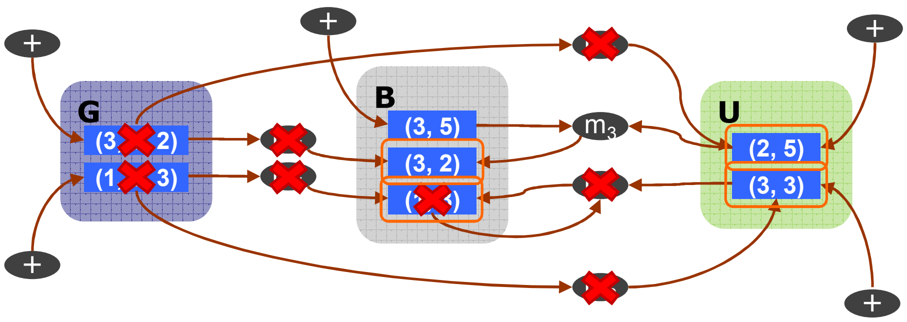
Provenance for incremental deletion propagation along unidirectional mappings [VLDB07]



- **Step 1**: Use provenance to find derived tuples which should also be deleted
- **Step 2**: Use provenance to also test other affected tuples for derivability, and delete any not derivable
- **Step 3**: Repeat until fixpoint

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Program analysis and debugging in LogicBlox [Datalog+12]

- Static (BloxAnalysis)
  - Represent Datalog programs using relational predicates
  - Use Datalog to query and analyze Datalog programs
- Examples of BloxAnalysis queries:
  - "get all predicates whose names matches foo and all rules in which those predicates appear in the head"
  - "find all predicates that are ``reachable'' from a certain predicate through rules in the program"
- Basis for performing more complex reasoning about Datalog programs in Datalog: dead code detection, clone detection …

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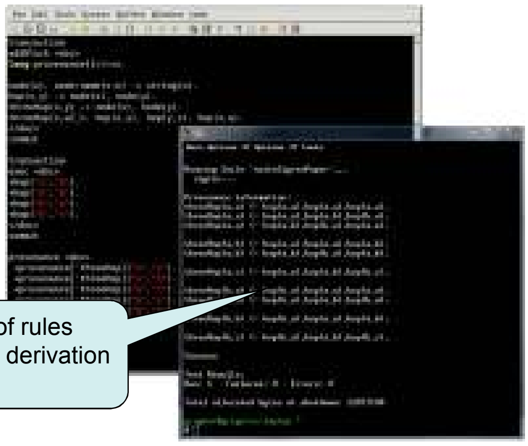
Analysis and debugging of declarative programs in LogicBlox

- Dynamic/runtime:
  - Record data provenance during program evaluation,
  - Use Datalog programs to explore and query resulting provenance graph.



Instantiations of rules involved in the derivation of each fact

- [Rugaber+13] describe how this functionality could be exposed in an Interactive Development Environment (IDE) for Datalog for program debugging

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Provenance for debugging in other systems

- GPad [Koehler+12] Declarative debugging for Datalog
  - Implemented on top of LogicBlox, taking advantage of BloxAnalysis and provenance recording capabilities
  - Uses Datalog and Statelog to represent and query provenance (firing) graphs, e.g., to compute stage of program evaluation at which each fact was derived
- SPIDER [Chiticariu+06] uses a form of data provenance (routes) for debugging schema mappings
  - Compute a single derivation for an output tuple, or enumerate all derivations (when there are finitely many)

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Outline

- Data provenance models for positive relational algebra queries
- Applications of data provenance
- Extensions to the theoretical framework
  - Provenance models for other query languages/operators
  - Other related theoretical results
- Benefits and challenges of data provenance on Big Data

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Relational difference

- M-semirings [Geerts+10] extend semirings with a monus operator to capture relational difference
- Unfortunately there is no suitable abstract structure that can be used as provenance model for m-semirings e.g., to compute various annotations
- [Amsterdamer+11c] identified further difficulties due to the fact that relational difference satisfies two sets of incompatible equivalences in the set and bag semantics

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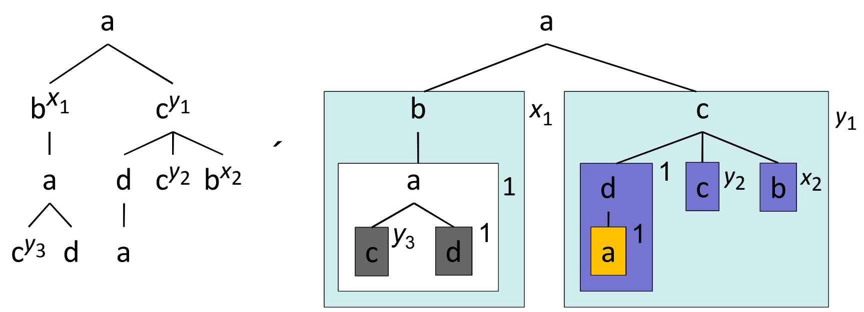
Provenance for unordered XML [Foster+08]



K-UXQuery: Based on Xquery, contains FOR loops and *//*

Main result: Provenance of K-UXQueries over unordered XML can still be captured by provenance polynomials, and annotations can be computed through it.

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Provenance for RDF

- RDF inference rules [Flouris+09, Udrea+10,Buneman+11,Zimmerman+12]
  - based on similar algebraic structures (idempotent semirings)
- SPARQL queries: main challenge from non-monotone OPTIONAL operator (akin to relational left-outer join)
  - Provenance polynomials can still capture provenance of positive SPARQL queries [IntComp11]
  - OPTIONAL can be encoded through relational difference [Damasio+12] (caveat: problems capturing provenance of relational difference)
  - Semirings with an embedded boolean algebra [ICDT13] can be used to construct a suitable data provenance model for SPARQL queries that can be used e.g., to compute various annotations

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Other related theoretical results

- Recursion [PODS07]: Results for positive relational algebra can be extended to Datalog for omega-continuous semirings
  - Provenance games [Zinn+13]: Novel unifying framework for dealing with recursion, negation and "why-not" provenance
- Aggregate operators [Amsterdamer+11a]
- Query containment [Green11,Kostylev+12]
- Minimization [Amsterdamer+11b]
- Factorization [Olteanu+12]

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- Data provenance models for positive relational algebra queries
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- Benefits and challenges of data provenance on Big Data

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Benefits of data provenance for Big Data (1/2)

- Data provenance is crucial for trusted Big Data Analytics due to 3Vs
  - Can be used to assess quality of data imported from large number of diverse sources, possibly using different data models and query languages (relational, XML, RDF) (high **variety**)
    - combinations of data and workflow provenance [Acar+10, Amsterdamer+12] may help in also dealing with unstructured data
  - Enables quality assessment at any time, even if sources have changed or are unavailable (due to high **velocity**)
  - Facilitates more efficient provenance querying and annotation computations for small subsets of data, by avoiding recomputation (infeasible, due to high **volume** and **velocity**)

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Benefits of data provenance for Big Data (2/2)

  - Can be used for assessment of various dimensions of data quality, based of different users' beliefs, again preventing the need for recomputation
- Data provenance enables efficient incremental algorithms for handling updates to data and views in data sharing systems
  - Such updates are frequent, due to high **velocity**
  - Avoid redundant computations, enable more flexible propagation and more efficient rewritings
- Supports analysis and debugging of declarative programs
  - Especially useful because large numbers of views/mappings are generated automatically by tools

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Challenges and research directions

- Preliminary experiments in [VLDB07,SIGMOD10] have shown feasibility for medium-size data sharing settings, investigate performance and scalability in Big Data settings

Some potential ideas/directions

- Optimizations for provenance querying and annotation computations on Big provenance graphs
  - Indexing (some preliminary work in [SIGMOD10])
  - Leverage distributed techniques (e.g., MapReduce)
  - Partial provenance evaluation (e.g., may only care if provenance evaluates to "non-zero" or is over some threshold, not exact value)

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Challenges and research directions

- Techniques to optimize provenance storage overhead, and study trade-off with query performance
  - Storage scheme of [SIGMOD10] is a step in this direction
  - Theoretical results on provenance minimization and factorization
  - Explore compression methods or distributed/cloud-based storage
- Tradeoffs between more expressive provenance models and cost of storage/querying
  - Use provenance models that are as informative as necessary
  - Consider partial provenance information e.g., only involving subset of data or query operators, or ignoring some sources

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  - Floris Geerts (University of Antwerp)
  - Vassilis Christophides (University of Crete & ICS-FORTH)
  - Irini Fundulaki (ICS-FORTH)

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Based on work described in:

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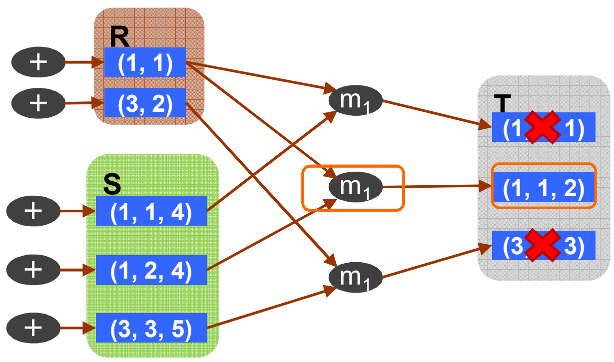
Using provenance to avoid side effects in bidirectional update exchange [WebDB08]

- Akin to view update

m_1: `*R(x,y),S(x,z) :- T(x,y,z)`



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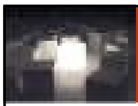

Recomputing materialized instances after changes to mappings and data [Green+12]

- Based on Z-relations [Green+11], where updates are represented as annotations
  - Update application can be expressed as regular query: R' = R ∪ R^δ

Source relation:

R

a	b	2
c	b	1
b	c	1
b	a	1

R^δ

b	**a**	**-1**
c	**d**	**+2**

deletion

insertion

- View maintenance and view adaptation can then be cast as applications of rewriting queries using materialized views
  - Uses provenance to "separate" disjuncts of a union, or "recover" values projected away and enable new (and possibly more efficient) rewritings
  - DBToaster [Koch+10] uses a similar approach for incremental view maintenance and query evaluation