# Provenance for Database Transformations

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**Joint work with**

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|---|---|---|---|
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# Data Provenance

***provenance, n.***

*The fact of coming from some particular source or quarter; origin, derivation* [Oxford English Dictionary]

•**Data provenance** [BunemanKhannaTan 01]**:** aims to explain how a particular result (in an experiment, simulation, query, workflow, etc.) was derived.

•Most science today is **data-intensive**. Scientists, eg., biologists, astronomers, worry about data provenance all the time.

# Provenance? Lineage? Pedigree?

- Cf. Peter Buneman:
  - Pedigree is for **dogs**
  - Lineage is for **kings**
  - Provenance is for **art**
- For data, let's be artistic (artsy?)

# Database transformations?

- Queries
- Views
- ETL tools
- Schema mappings (as used in data exchange)

# The story of database provenance

- As opposed to **workflow provenance,** another story. Both waiting to merge (recent progress)!
- Motivated by data integration **[**WangMadnic**k** 90, LeeBressanMadnick 98]
- Motivated by data warehousing, "lineage" [CuiWidomWiener 00, Cui Thesis 01, etc.]
- Motivated by scientific data management, "why- and where-provenance" [BunemanKhannaTan 01, etc.]
- Excellent accounts of the story in Buneman+ PODS 08 keynote and in Tan+ tutorials, edited collections, and recent journal article

# My own journey to the study of provenance

- Working on the integration of genomics databases, since 1992
- At Penn with Peter Buneman and Wang-Chiew Tan, around 1999: "provenance is a form of annotation".

  (They also studied other forms of annotation, such as time.)

  But I was preoccupied with other things…
- At Penn with Zack Ives, around 2005, I joined his project Orchestra: motivated by data sharing
- Working in phyloinformatics, since 2006, very interesting provenance problems

# Teaser
## Annotations capture …

- Provenance
- Uncertainty (conditional tables [ImielinskiLipski 84])
- Trust scores
- Security
- Multiplicity (bag semantics)

# This talk is based on the following papers

"Provenance semirings"
[GreenKarvounarakis&T PODS 07]

"Update exchange with mappings and provenance"
[GreenKarvounarakisIves&T VLDB 07]

"Annotated XML: queries and provenance"
[FosterGreen&T PODS 08]

"Containment of conjunctive queries on annotated relations" [Green ICDT 09]

See also the dissertations of T.J. Green and G. Karvounarakis, University of Pennsylvania 2009.

# Rounds

- **What's with the semirings? Annotation propagation**
- **Housekeeping in the zoo of provenance models**
- **Beyond tuple annotation**
- **The fundamental property and its applications**
- **Queries that annotate**
- **Datalog**

- **What's with the semirings? Annotation propagation** [GK&T PODS 07,  GKI&T VLDB 07]

- **Housekeeping in the zoo of provenance models**

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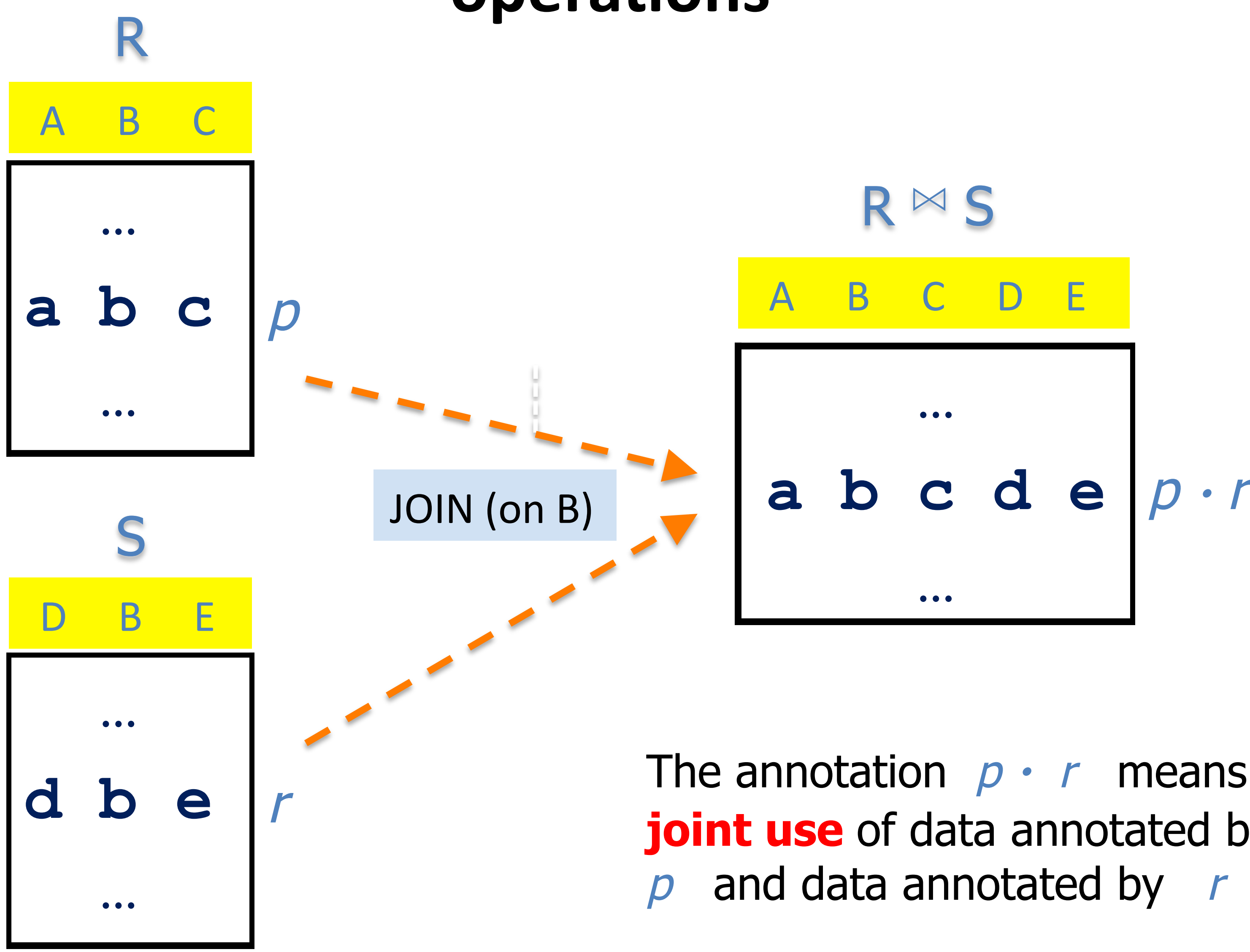
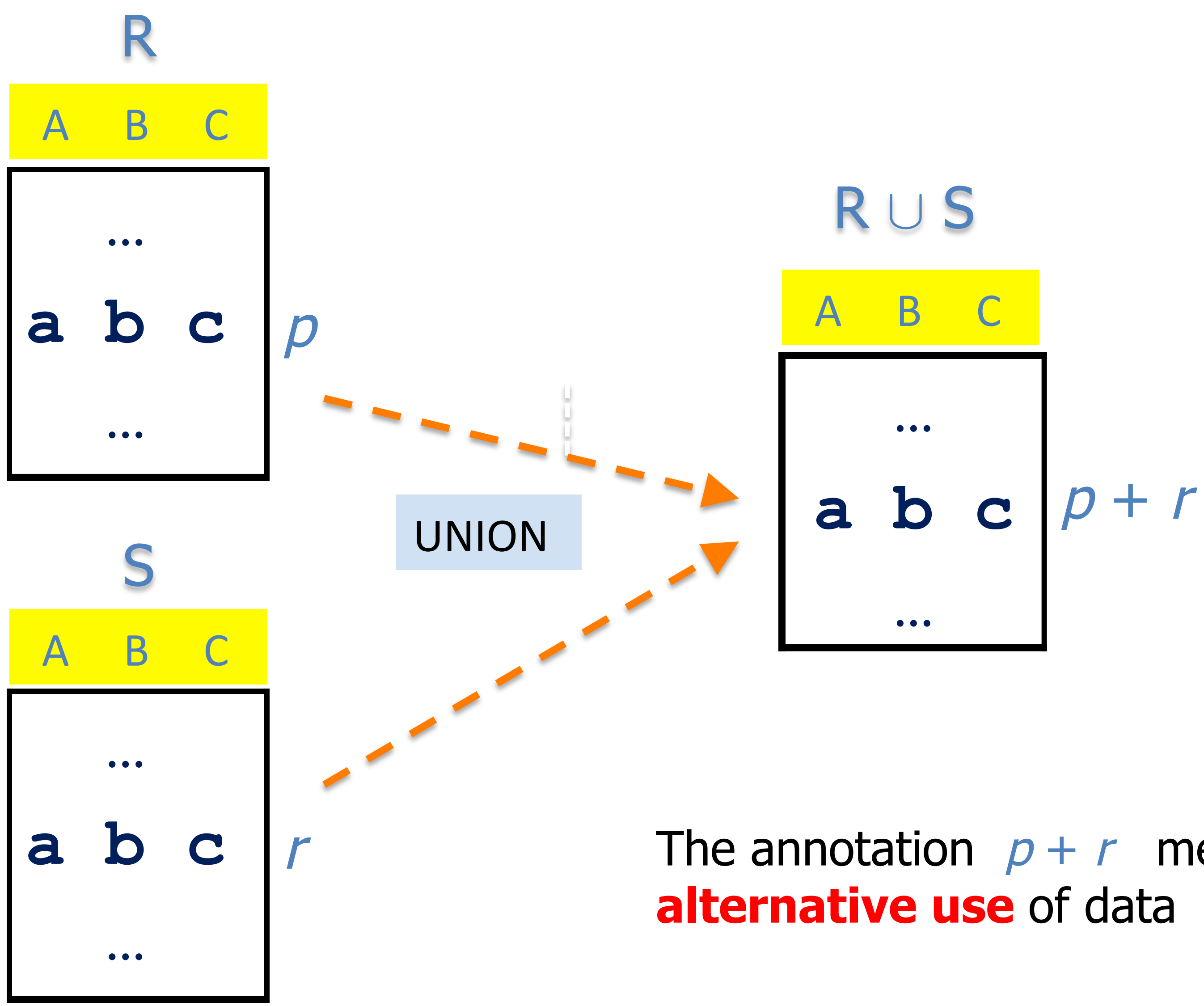
# Propagating annotations through database operations



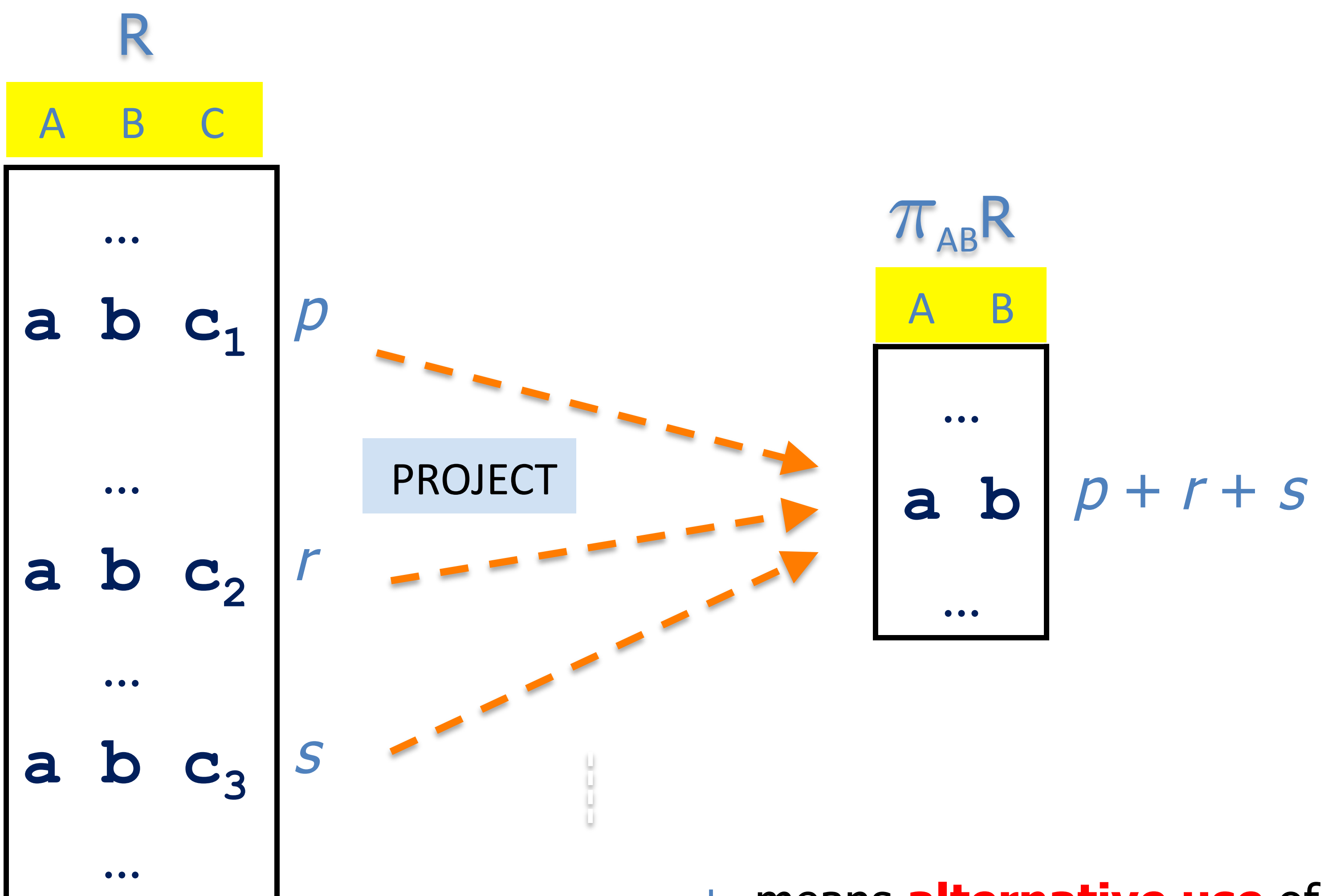

The annotation $p \cdot r$ means **joint use** of data annotated by $p$ and data annotated by $r$

# Another way to propagate annotations




The annotation $p + r$ means **alternative use** of data

# Another use of +




$+$ means **alternative use** of data

# An example in positive relational algebra (SPJU)

$$\mathbf{Q} = \sigma_{C=e}\pi_{AC}(\ \pi_{AC}R \bowtie \pi_{BC}R \ \cup\ \pi_{AB}R \bowtie \pi_{BC}R\ )$$

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

| A | C | |
|---|---|---|
| a | c | $(p \cdot p + p \cdot p) \cdot 0$ |
| a | e | $p \cdot r \cdot 1$ |
| d | c | $r \cdot p \cdot 0$ |
| d | e | $(r \cdot r + r \cdot s + r \cdot r) \cdot 1$ |
| f | e | $(s \cdot s + s \cdot r + s \cdot s) \cdot 1$ |

For selection we multiply
with two special annotations, 0 and 1

# Summary so far

A space of annotations, *K*

*K*-**relations**: every tuple annotated with some element from *K*.

Binary operations on *K*: $\cdot$ corresponds to joint use (join), and $+$ corresponds to alternative use (union and projection).

We assume *K* contains special annotations 0 and 1.

"Absent" tuples are annotated with 0!

1 is a "neutral" annotation (no restrictions).

**Algebra of annotations**? What are the **laws** of $(K, +, \cdot, 0, 1)$ ?

# Annotated relational algebra

- DBMS query optimizers assume certain equivalences:
  - union is associative, commutative
  - join is associative, commutative, distributes over union
  - projections and selections commute with each other and with union and join (when applicable)
  - Etc., but no $R \bowtie R = R \cup R = R$ (i.e., no idempotence, to allow for bag semantics)
- Equivalent queries should produce same annotations!

**Proposition**. Above identities hold for queries on $K$-relations iff $(K, +, \cdot, 0, 1)$ is a **commutative semiring**

# What is a commutative semiring?

An algebraic structure $(K, +, \cdot, 0, 1)$ where:

$$\left.\begin{array}{l} \circ \quad K \text{ is the domain} \\ \circ \quad + \text{ is associative, commutative, with } 0 \text{ identity} \\ \circ \quad \cdot \text{ is associative, with } 1 \text{ identity} \\ \circ \quad \cdot \text{ distributes over } + \\ \circ \quad a \cdot 0 = 0 \cdot a = 0 \end{array}\right\} \textbf{semiring}$$

- $\cdot$ is also **commutative**

Unlike ring, no requirement for inverses to $+$

# Back to the example

**R**

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

**Q**

| A | C | |
|---|---|---|
| a | c | $(p \cdot p + p \cdot p) \cdot 0$ |
| a | e | $p \cdot r \cdot 1$ |
| d | c | $r \cdot p \cdot 0$ |
| d | e | $(r \cdot r + r \cdot s + r \cdot r) \cdot 1$ |
| f | e | $(s \cdot s + s \cdot r + s \cdot s) \cdot 1$ |

# Using the laws: polynomials

**R**

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

**Q**

| A | C | |
|---|---|---|
| a | e | $pr$ |
| d | e | $2r^2 + rs$ |
| f | e | $rs + 2s^2$ |

Polynomials with coefficients in $\mathbb{N}$ and
annotation tokens as indeterminates $p, r, s$
capture a very general form of **provenance**

# Provenance reading of the polynomials

**R**

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

**Q**

| A | C | |
|---|---|---|
| a | e | $pr$ |
| d | e | $2r^2 + rs$ |
| f | e | $rs + 2s^2$ |

- three different ways to derive **d e**
- two of the ways use only $r$
- but they use it twice
- the third way uses $r$ once and $s$ once

# Low-hanging fruit: deletion propagation

We used this in **Orchestra** [VLDB07]
for update propagation

**R**

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

**Q**

| A | C | |
|---|---|---|
| a | e | $pr$ |
| d | e | $2r^2 + rs$ |
| f | e | $rs + 2s^2$ |

**Q**

| A | C | |
|---|---|---|
| a | e | 0 |
| d | e | 0 |
| f | e | $2s^2$ |

**Q**

| A | C | |
|---|---|---|
| f | e | $2s^2$ |

Delete `d b e` from R ?

Set $r = 0$ !

# But are there useful commutative semirings?

| | |
|---|---|
| **($\mathbb{B}$, $\wedge$, $\vee$, $\top$, $\bot$)** | **Set semantics** |
| **($\mathbb{N}$,** $+$, $\cdot$, 0, 1**)** | **Bag semantics** |
| ($\mathcal{P}(\Omega)$, $\cup$, $\cap$, $\emptyset$, $\Omega$) | Probabilistic events [FuhrRölleke 97] |
| (BoolExp($X$), $\wedge$, $\vee$, $\top$, $\bot$) | Conditional tables ($c$-tables) [ImielinskiLipski 84] |
| ($\mathbb{R}_+^\infty$, min, +, $\infty$, 0) | Tropical semiring (cost/distrust score/confidence need) |
| ($\mathbb{A}$, min, max, 0, P) where $\mathbb{A}$ = P < C < S < T < 0 | Access control levels [PODS8] |

top secret

public

- What's with the semirings? Annotation propagation
- **Housekeeping in the zoo of provenance models**
  [GK&T PODS 07,  FG&T PODS 08,  Green ICDT 09]
- **Beyond tuple annotation**
- **The fundamental property and its applications**
- **Queries that annotate**
- **Datalog**

# Semirings for various models of provenance (1)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | *p* |
| d | b | e | *r* |
| f | g | e | *s* |

**Q**

| A | C | |
|---|---|---|
| … | | |
| d | e | $\{r, s\}$ |
| … | | |

**Lineage** [CuiWidomWiener 00 etc.]

Sets of contributing tuples

**Semiring:** $(\mathrm{Lin}(X), \cup, \cup^*, \emptyset, \emptyset^*)$

# Semirings for various models of provenance (2)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

Q

| A | C | |
|---|---|---|
| … | | |
| d | e | $\{\{r\}, \{r, s\}\}$ |
| … | | |

(Witness, Proof) **why-provenance**
[BunemanKhannaTan 01] & [Buneman+ PODS08]

Sets of witnesses (w. =set of contributing tuples)

**Semiring:** $(Why(X), \cup, \Cup, \emptyset, \{\emptyset\})$

# Semirings for various models of provenance (3)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | *p* |
| d | b | e | *r* |
| f | g | e | *s* |

Q

| A | C | |
|---|---|---|
| … | | |
| d | e | $\{\{r\}\}$ |
| … | | |

Minimal witness **why-provenance**
[BunemanKhannaTan 01]

Sets of minimal witnesses

**Semiring:** (PosBool($X$), $\wedge$, $\vee$, $\top$, $\bot$)

# Semirings for various models of provenance (4)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | *p* |
| d | b | e | *r* |
| f | g | e | *s* |

Q

| A | C | |
|---|---|---|
| … | | |
| d | e | [{*r*}, {*r*}, {*r*, *s*}] |
| … | | |

Notation:

{ } set

[ ] bag

**Trio lineage** [Das Sarma+ 08]

Bags of sets of contributing tuples (of witnesses)

**Semiring:** (Trio($X$), +, $\cdot$, 0, 1) (defined in [Green, ICDT 09])

# Semirings for various models of provenance (5)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | *p* |
| d | b | e | *r* |
| f | g | e | *s* |

**Q**

| A | C | |
|---|---|---|
| … | | |
| d | e | $\{[r,r], [r, s]\}$ |
| … | | |

Notation:

{ } set

[ ] bag

**Polynomials with boolean coefficients** [Green, ICDT 09]

( $\mathbb{B}[X]$-provenance )

Sets of bags of contributing tuples

**Semiring:** $(\mathbb{B}[X], +, \cdot, 0, 1)$

# Semirings for various models of provenance (6)

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

**Q**

| A | C | |
|---|---|---|
| … | | |
| d | e | $[[r,r], [r,r], [r, s]]$ |
| … | | |

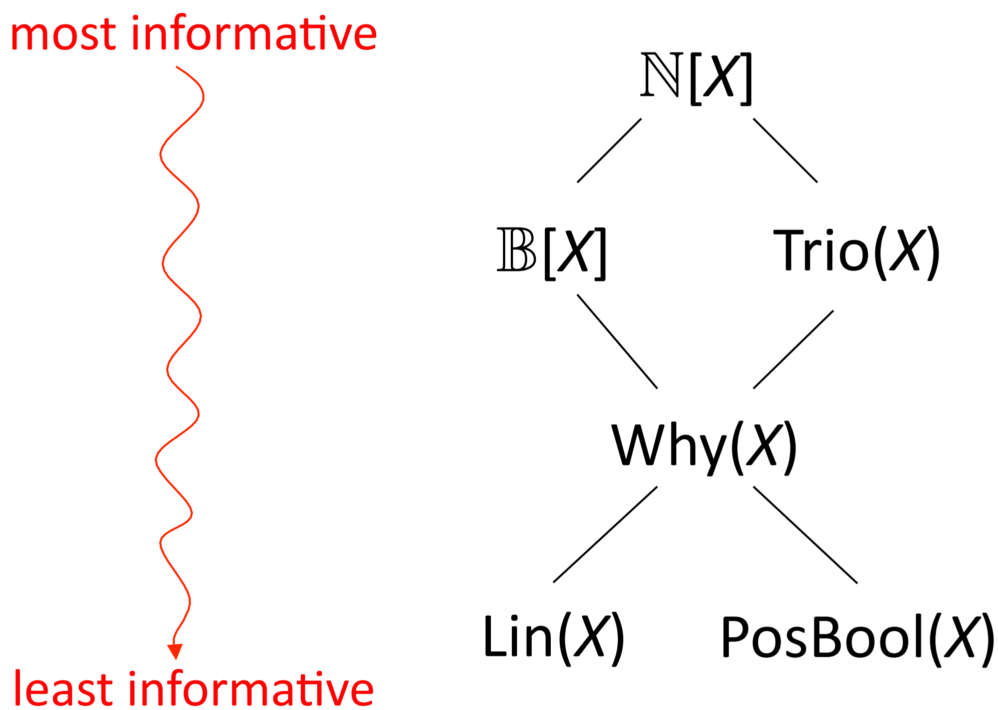
**Provenance polynomials** [GKT, PODS 07]

( $\mathbb{N}[X]$-provenance )

Bags of bags of contributing tuples

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

# A provenance hierarchy



# One semiring to rule them all… (apologies!)

Example: $2x^2y + xy + 5y^2 + z$

$\mathbb{N}[X]$

drop coefficients
$x^2y + xy + y^2 + z$

$\mathbb{B}[X]$

Trio($X$)

drop exponents
$3xy + 5y + z$

drop both exp. and coeff.
$xy + y + z$

Why($X$)

collapse terms
$xyz$

Lin($X$)

PosBool($X$)

apply absorption
($ab + b = b$)
$y + z$

A path downward from $K_1$ to $K_2$ indicates that there exists an **onto (surjective) semiring homomorphism** $h : K_1 \rightarrow K_2$

# Using homomorphisms to relate models

Example: $2x^2y + xy + 5y^2 + z$

$$\begin{tikzcd}
& \mathbb{N}[X] \arrow[dl, dash] \arrow[dr, dash] & \\
\mathbb{B}[X] \arrow[dr, dash] & & \mathrm{Trio}(X) \arrow[dl, dash] \\
& \mathrm{Why}(X) \arrow[dl, dash] \arrow[dr, dash] & \\
\mathrm{Lin}(X) & & \mathrm{PosBool}(X)
\end{tikzcd}$$

drop coefficients
$x^2y + xy + y^2 + z$

drop exponents
$3xy + 5y + z$

drop both exp. and coeff.
$xy + y + z$

collapse terms
$xyz$

apply absorption
($ab + b = b$)
$y + z$

**Homomorphism?**

$h(x+y) = h(x)+h(y)$ $\quad$ $h(xy)=h(x)h(y)$ $\quad$ $h(0)=0$ $\quad$ $h(1)=1$

Moreover, for these homomorphisms $h(x)= x$

# Containment and Equivalence [Green ICDT 09]

$$
\begin{tikzcd}
\mathbb{B}[X] \arrow[r, leftrightarrow] \arrow[d] & \mathbb{N}[X] \\
\mathrm{Why}(X) \arrow[r, leftrightarrow] \arrow[d] & \mathrm{Trio}(X) \\
\mathbb{N} \arrow[d] & \\
\mathrm{Lin}(X) \arrow[d] & \\
\mathrm{PosBool}(X) \arrow[r, leftrightarrow] & \mathbb{B}
\end{tikzcd}
$$

SPJ containment

$$
\begin{tikzcd}
\mathbb{B}[X] \arrow[r, leftrightarrow] \arrow[d, leftrightarrow] & \mathbb{N}[X] \arrow[d, leftrightarrow] \\
\mathrm{Why}(X) \arrow[r, leftrightarrow] \arrow[d] & \mathrm{Trio}(X) \arrow[d, leftrightarrow] \\
\mathrm{Lin}(X) \arrow[d] & \mathbb{N} \\
\mathrm{PosBool}(X) \arrow[r, leftrightarrow] & \mathbb{B}
\end{tikzcd}
$$

SPJ equivalence

$$
\begin{tikzcd}
\mathbb{B}[X] \arrow[d] & \mathbb{N}[X] \arrow[l] \arrow[d] \\
\mathrm{Why}(X) \arrow[d] & \mathrm{Trio}(X) \arrow[l] \arrow[d] \\
\mathrm{Lin}(X) \arrow[d] & \mathbb{N} \arrow[l] \\
\mathrm{PosBool}(X) \arrow[r, leftrightarrow] & \mathbb{B}
\end{tikzcd}
$$

SPJU containment

$$
\begin{tikzcd}
\mathbb{N} \arrow[r, leftrightarrow] \arrow[d] & \mathbb{N}[X] \arrow[d, leftrightarrow] \\
\mathbb{B}[X] \arrow[d] & \mathrm{Trio}(X) \\
\mathrm{Why}(X) \arrow[d] & \\
\mathrm{Lin}(X) \arrow[d] & \\
\mathrm{PosBool}(X) \arrow[r, leftrightarrow] & \mathbb{B}
\end{tikzcd}
$$

SPJU equivalence

Arrow from $K_1$ to $K_2$ indicates $K_1$ containment (equivalence) implies $K_2$ cont. (equiv.)

All implications not marked $\leftrightarrow$ are strict

- What's with the semirings? Annotation propagation
- **Housekeeping in the zoo of provenance models**
- **Beyond tuple annotation** [FG&T PODS 08]
- **The fundamental property and its applications**
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- **Datalog**

# Relation, attribute and field annotation (1)

$R^u$

| $A^x$ | $B^y$ | $C^1$ | |
|---|---|---|---|
| … | | | |
| $\mathbf{a}^1$ | $\mathbf{b}^1$ | $\mathbf{c}^1$ | $p$ |
| … | | | |

$S^v$

| $B^1$ | $C^1$ | |
|---|---|---|
| … | | |
| $\mathbf{b}^z$ | $\mathbf{c}^1$ | $m$ |
| … | | |

$$\pi_{AC}(\pi_{AB}R \bowtie (\pi_{BC}R \cup S))$$

| $A^1$ | $C^1$ | |
|---|---|---|
| … | | |
| $\mathbf{a}^1$ | $\mathbf{c}^1$ | $u^2p^2xy^2 + uvpmxyz$ |
| … | | |

Neutral annotation 1 used when we don't bother to track data.

# Relation, attribute and field annotation (2)

$R^u$

| $A^x$ | $B^y$ | C | |
|---|---|---|---|
| … | | | |
| a | b | c | $p$ |
| … | | | |

$$\pi_{AC}(\ \pi_{AB}R \bowtie (\ \pi_{BC}R \cup S\ ))$$

| A | C | |
|---|---|---|
| … | | |
| a | c | $u^2p^2xy^2 + uvpmxyz$ |
| … | | |

$S^v$

| B | C | |
|---|---|---|
| … | | |
| $b^z$ | c | $m$ |
| … | | |

We omit 1 for convenience. From now on 1 is the default.

Here, we track both relations, attributes A and B in R, and the first field of $m$.

# Same value, different annotations (where-provenance)

$$\sigma_{C=e}\pi_{AC}(\ \pi_{AB}R \bowtie \pi_{BC}R\ )$$

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | $e^{z}$ | $r$ |
| f | g | $e^{w}$ | $s$ |

Track both **e**’s

| A | C | |
|---|---|---|
| a | $e^{z}$ | $pr$ |
| d | $e^{z}$ | $r^2$ |
| f | $e^{w}$ | $s^2$ |

# Different field annotations produce different tuples

What happens when we add a projection on C ?

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | $e^{z}$ | $r$ |
| f | g | $e^{w}$ | $s$ |

$$\pi_C\, \sigma_{C=e}\, \pi_{AC}(\, \pi_{AB} R \bowtie \pi_{BC} R\,)$$

| C | |
|---|---|
| $e^{z}$ | $pr + r^2$ |
| $e^{w}$ | $s^2$ |

## When we don't care to track so many details

Add a homomorphism $h(w) = h(z) = u$ . (Add to language.)

$$h\,(\,\pi_C\,\sigma_{C=e}\,\pi_{AC}(\,\pi_{AB}R \bowtie \pi_{BC}R\,)\,)$$

R

| A | B | C | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | $e^z$ | $r$ |
| f | g | $e^w$ | $s$ |

| C | |
|---|---|
| ~~$e^z$~~ | $pr+r^2$ |
| ~~$e^w$~~ | $s^2$ |

| C | |
|---|---|
| $e^u$ | $pr+r^2+s^2$ |

# Why vs. where

$R^u$

| $A^x$ | $B^y$ | C | |
|---|---|---|---|
| … | | | |
| **a** | **b** | **c** | $p$ |
| … | | | |

$S^v$

| B | C | |
|---|---|---|
| … | | |
| $\mathbf{b}^z$ | **c** | $m$ |
| … | | |

$$\pi_{AC}(\pi_{AB}R \bowtie (\pi_{BC}R \cup S))$$

| A | C | |
|---|---|---|
| … | | |
| **a** | **c** | $u^2p^2xy^2 + uvpmxyz$ |
| … | | |

where-provenance

A provenance token on a field is treated like any other token. In the semiring framework the why-where distinction is blurred.

- What's with the semirings? Annotation propagation
- Housekeeping in the zoo of provenance models
- Beyond tuple annotation
- **The fundamental property and its applications**
  [GK&T PODS 07, FG&T PODS 08, Green&T EDBTworkshop 06]
- **Queries that annotate**
- **Datalog**

Doesn't always work, eg. difference.

# Fundamental property

For every query $q$ and every homomorphism of commutative semirings $h : K_1 \to K_2$ the following "commutes":

$$\begin{tikzcd} K_1\text{-data} \arrow[r, "h"] \arrow[d, "q"'] & K_2\text{-data} \arrow[d, "q"] \\ K_1\text{-data} \arrow[r, "h"] & K_2\text{-data} \end{tikzcd}$$

# Most important source of homomorphisms

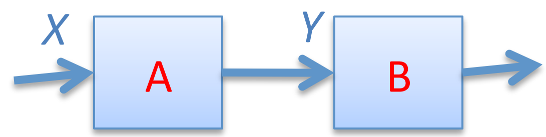
If $K$ is a commutative semiring, then any function on tokens, $f : X \to K$ extends uniquely to a homomorphism $h : \mathbb{N}[X] \to K$ .

It's the free commutative semiring generated by $X$.
The "free" one rules them all!

("Extends means that $h$ coincides with $f$ on tokens.)

Think of $h(pr+r^2+s^2)$ as **evaluating** $pr+r^2+s^2$ in $K$.
Examples are coming up.

# An application of the fundamental property: Compositionality




Input to A: tokens $X = \{p,r,s\}$; Output of A provenance in $\mathbb{N}[X]$

Input to B: tokens $Y = \{m,n\}$; Output of B provenance in $\mathbb{N}[Y]$

Say that for data $A \rightarrow B$ $\quad p+rs = m, \quad prs+2s^2 = n$

This gives $f: \; Y \rightarrow \mathbb{N}[X]$ which extends to $h: \; \mathbb{N}[Y] \rightarrow \mathbb{N}[X]$

Say that one output of B has provenance $m^2 + 2n$

Then, as an output of A composed w/ B it has provenance

$h(m^2 + 2n) = p^2 + 4prs + r^2s^2 + 4s^2$

# More applications of the fundamental property

- Renaming provenance tokens
- Deletion: mapping some tokens to 0 (seen earlier)
- Hiding detail, increasing abstraction:
  - mapping provenance tokens, many to few (seen earlier)
  - stop tracking tokens by mapping them to 1 (neutral)

# Another application: all through provenance

Because it is the free commutative semiring.

Systems (like **Orchestra**) can compute and maintain only **polynomial provenance**, which is then evaluated, as needed, to provide:

- trust scores (see next)
- access control levels (see next)
- more frugal provenance like Trio($X$), $\mathbb{B}[X]$, etc.
- and even multiplicity

Doesn't work if prov. is Trio($X$)
Works with $\mathbb{B}[X]$.

Works even with prov. in PosBool(X)

Doesn't work if prov. is $\mathbb{B}[X]$.
With Trio($X$) only set-bag semantics

# Application with (dis)trust scores (1)

Semiring is $K = (\mathbb{R}_+^\infty, \min, +, \infty, 0)$

Tokens are $X = \{ p, r, s \}$

Assignment function is $f : X \rightarrow K$ where
we suppose $p$ is completely trusted $f(p) = 0$,
$r$ is less trusted $f(r) = 1.5$, and $s$ is untrusted $f(s) = \infty$

The homomorphism $h$ that extends $f$ computes like this:

$h\,(2r^2 + rs\,) = h\,(\,r{\cdot}r + r{\cdot}r + r{\cdot}s\,) =$

addition of reals

$= \min(\,f(r) + f(r),\ f(r) + f(r),\ f(r) + f(s)\,) =$

“addition” of provenance polynomials

$= \min(\,1.5 + 1.5,\ 1.5 + 1.5,\ 1.5 + \infty\ ) =\ 3.0$

# Application with (dis)trust scores (2)

$(\mathbb{R}_+^\infty, \min, +, \infty, 0)$

The fundamental property

| | | | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

deleted

$\xrightarrow{q}$

| | | |
|---|---|---|
| a | c | $2p^2$ |
| a | e | $pr$ |
| d | c | $pr$ |
| d | e | $2r^2 + rs$ |
| f | e | $2s^2 + rs$ |

deleted

$f(p) = 0, \quad f(r) = 1.5, \quad f(s) = \infty$

$\downarrow$

eval with homomorphisms $h$, the extension of $f$

| | | | |
|---|---|---|---|
| a | b | c | 0 |
| d | b | e | 1.5 |

$\xrightarrow{q}$

| | | |
|---|---|---|
| a | c | 0 |
| a | e | 1.5 |
| d | c | 1.5 |
| ~~d~~ | ~~e~~ | ~~3.0~~ |

"Accept tuples with score $\leq$ 2.5"

# Application to access control

$(\mathbb{A}, \min, \max, 0, P)$ where $\mathbb{A} = P < C < S < T < 0$

Suppose $p$ is public, $r$ is secret, $s$ is top secret

Fundamental property implies that applying the clearance to the database or to the query answer yields the **same result**. (But only the second is actually feasible!)

| | | | |
|---|---|---|---|
| a | b | c | $p$ |
| d | b | e | $r$ |
| f | g | e | $s$ |

$\xrightarrow{q}$

| | | |
|---|---|---|
| a | c | $2p^2$ |
| a | e | $pr$ |
| d | c | $pr$ |
| d | e | $2r^2 + rs$ |
| f | e | $2s^2 + rs$ |

with $p$ = P, $r$ = S, $s$ = T

eval with $p$ = P, $r$ = S, $s$ = T (using min for "+", max for "·")

| | | | |
|---|---|---|---|
| a | b | c | P |
| d | b | e | S |
| f | g | e | T |

$\xrightarrow{q}$

| | | |
|---|---|---|
| a | c | P |
| a | e | S |
| d | c | S |
| d | e | S |
| ~~f~~ | ~~e~~ | ~~T~~ |

"User with secret clearance"

# Another application: uncertainty (1)

- **Possible worlds** model:
  - incomplete $K$-database = a set of $K$-instances
  - probabilistic $K$-database = a distribution on the set of all $K$-instances

- Unwieldy size! Want representation systems, like the (boolean) c-tables [ImielinskiLipski 84]: tables annotated with elements from the semiring BoolExp(X).

- So why not Trio($X$), $\mathbb{B}[X]$, Why($X$), $\mathbb{N}[X]$, PosBool($X$)? (provided we stick to positive queries, SPJU, no D) $\mathbb{N}[X]$ always works. For the others it depends on $K$.

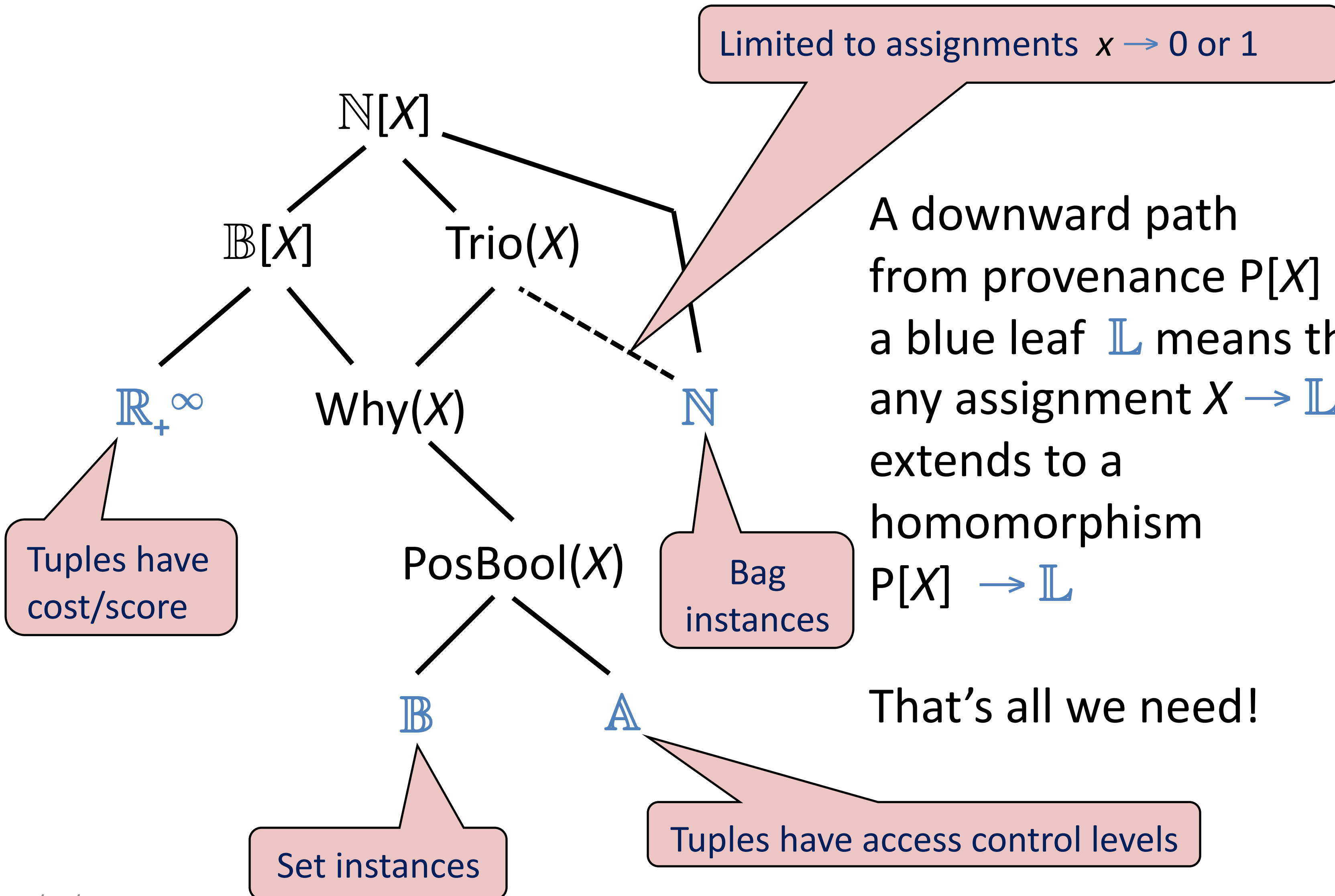
# Another application: uncertainty (2)

- $\mathbb{N}[X]$ always works. For incomplete databases:
- Take as representation table T a $\mathbb{N}[X]$-relation
- For **each** assignment function $f : X \rightarrow K$
  - extend to a homomorphism $h : \mathbb{N}[X] \rightarrow K$
  - use $h$ to eval. into $K$ the polynomials annotating T
  - thus obtaining a possible world, a $K$-relation
- The fact that this works properly (it is a **strong** representation system) follows from the fundamental property!

# Another application: uncertainty (3)

- For probabilistic databases follow Green's idea of **pc-tables** [Green&T 06]
- Again representation tables are $\mathbb{N}[X]$-relations
- Treat variables in $X$ as **independent**. For each variable assume a prob. distribution on the values in $K$ it can take.
- This gives a probability distribution on assignment functions $f : X \to K$, therefore on the possible worlds.

# $\mathbb{N}[X]$ always works, for the others it depends on $K$




A downward path from provenance P[$X$] to a blue leaf $\mathbb{L}$ means that any assignment $X \rightarrow \mathbb{L}$ extends to a homomorphism P[$X$] $\rightarrow \mathbb{L}$

That's all we need!

- What's with the semirings? Annotation propagation
- Housekeeping in the zoo of provenance models
- Beyond tuple annotation
- The fundamental property and its applications
- **Queries that annotate** [FG&T PODS 08]
- **Datalog**

# Queries that annotate

- In Orchestra [GKI&T VLDB07] we annotate schema mappings with provenance "unary operations".
- In [FGT PODS 08] we introduced into the query language an operation of "scalar multiplication".
- The "scalar" *k* is from *K* and the "vector" *S* is a *K*-relation (or *K*-set). For *kS* each annotation in *S* is multiplied by *k*.
- We have also seen how useful homomorphisms are.
- This suggests an operation *hS* where the homomorphism *h* is applied to each annotation in *S.*

## Extending query languages to manipulate annotation/ provenance (AnnotatedSQL?)

```
SELECT  RenameH ( r.Name AS Name,  s.Project AS Project )
FROM    r IN  db1 Employee,   s IN  db2 Project
WHERE   …

DEFINE  RenameH   AS  (
db1 ->  PersonnelDB,
db2 -> BillingDB  )
```

provenance token

homomorphism

The tuples in the query answer have provenances in terms of the tokens PersonnelDB and BillingDB as well as tokens from the annotations of the tuples in Employee and Project.

- What’s with the semirings? Annotation propagation
- Housekeeping in the zoo of provenance models
- Beyond tuple annotation
- The fundamental property and its applications
- Queries that annotate
- **Datalog** [GK&T PODS 07]

# $K$-Datalog?

n-ary $K$-relations: functions $R : U \to K$ $\quad$ R in $K^U$

where U is the set of all n-tuples over some domain, such that

$$\mathrm{supp}(R) = \{t \mid R(t) \neq 0\} \quad \text{is finite}$$

The immediate consequence operator of a program **P** (incorporates edb) in $K$-relation semantics

$$T_P : K^U \to K^U$$

For what semirings $K$ does $T_P$ have a fixpoint?

Recall that $T_P$ computes annotations that are defined by **polynomials**

# $\omega$-continuous semirings

**Natural preorder**: $x \leq y$ iff there exists $z$ s.t. $x+z = y$

**Naturally ordered semiring**: when $\leq$ is an order relation
(all semirings seen here are naturally ordered)

**$\omega$-completeness:** when $x_0 \leq x_1 \leq \ldots \leq x_n \leq \ldots$ have l.u.b.'s

**$\omega$-continuity** when $+$ and $\cdot$ preserve those l.u.b.'s

# Least fixpoints and formal power series

Over $\omega$-continuous semirings functions defined by polynomials have least fixpoints (usual definition) hence:

$$\mathrm{fix}(\mathbf{P}) = \operatorname*{lub}_{k \geq 0} T_{\mathbf{P}}^{k}(0)$$

Most of the semirings that interest us are already $\omega$-continuous.

$(\mathbb{N}, +, \cdot, 0, 1)$ is not,
but its "completion" $(\mathbb{N}^{\infty} = \mathbb{N} \cup \{\infty\}, +, \cdot, 0, 1)$ is.

For provenance, the completion of $\mathbb{N}[X]$ is not $\mathbb{N}^{\infty}[X]$.
Instead of (finite) polynomials we need (possibly infinite) **formal power series.** They form a semiring, $\mathbb{N}^{\infty}[[X]]$.

# Proof semantics

By considering all (possibly infinitely many) proof trees $\tau$ and the annotations of the tuples on their leaves:

$$\mathrm{proof}(\mathbf{P})(t) = \sum_{\tau \text{ yields } t} \Big( \prod_{t' \text{ leaf}(\tau)} R(t') \Big)$$

We have $\mathrm{proof}(\mathbf{P}) = \mathrm{fix}(\mathbf{P})$

There is also an equivalent “least model” semantics [G09]

Also, $\mathrm{supp}(\mathrm{fix}(\mathbf{P}))$ is finite, and equals the (usual) $\mathbb{B}$-relations semantics (set semantics).

# An equivalent perspective

| | | |
|---|---|---|
| a | b | m |
| a | c | n |
| c | b | p |
| b | d | r |
| d | d | s |

$T(X, Y) \text{ :- } E(X, Y)$
$T(X, Y) \text{ :- } T(X, Z), T(Z, Y)$

Polynomials are the provenance of the immediate consequence operator

T

| | | |
|---|---|---|
| a | b | x |
| a | c | y |
| c | b | z |
| b | d | u |
| d | d | v |
| a | d | w |
| c | d | t |

$$x = m + yz$$
$$y = n$$
$$z = p$$
$$u = r + uv$$
$$v = s + v^2$$
$$w = xu + wv$$
$$t = zu + tv$$

Solve!

# Solving in the power series semiring

$\mathbf{x} = m + np$

$\mathbf{y} = n$

$\mathbf{z} = p$

$\mathbf{v} = s + s^2 + 2s^3 + 5s^4 + 14s^5 + \ldots$

$\mathbf{u} = r\,\mathbf{v}^*$

$\mathbf{w} = r(m+np)(\mathbf{v}^*)^2$

$\mathbf{t} = pr(\mathbf{v}^*)^2$

Coefficients have the form

$$\frac{2k!}{k!(k+1)!}$$

where

$\mathbf{v}^* \triangleq 1 + \mathbf{v} + \mathbf{v}^2 + \mathbf{v}^3 + \ldots$

In general the coefficients are from $\mathbb{N}^\infty$

## Decidability results

- Given $t \in q(I)$, it is decidable whether the provenance of $t$ is a proper (infinite) power series. (Generalizing a result in [Mumick Shmueli 93] about bag semantics for Datalog)

- Given $t \in q(I)$, and a monomial $\mu$, the coefficient of $\mu$ in the power series that is the provenance of $t$ is computable (including when it is $\infty$).

- From CFG ambiguity, we know that testing whether all coefficients are $\leq 1$ is undecidable.

- However, testing whether all coefficients are $\neq \infty$ is decidable.

# Extensions and sequels (1)

- Implementation in ORCHESTRA
  [GKI&T VLDB 07, KarvounarakisIves WebDB 08]
  - Schema mappings are Datalog with Skolem functions, weakly acyclic recursion
  - Provenance polynomials are represented as a graph with two kinds of nodes, tuples and mappings. More economical: sharing common subexpressions
- Provenance information is data too! Provenance query language on the Orchestra graph provenance representation; also allows evaluation is particular semirings: trust, security, etc.
  [KarvounarakisIves&T SIGMOD 10]

# Extensions and sequels (2)

- Complex value data, Nested Relational Calculus, trees, unordered XML and XQuery [FG&T PODS 08].

- Comprehensive study of SPJ (conjunctive queries) and SPJU (non-recursive Datalog) containment and equivalence under annotated relations semantics [Green ICDT 09]

- Relations annotated with integers (positive and negative), semantics and reformulation with views for the full relational algebra [GI&T ICDT 09]

## A tiny bit of related work

- Formal languages [ChomskiSchützenberger63]
- CSP (Bistarelli et al.)
- Debugging schema mappings [ChiticariuTan06]
- "Closed" semirings used in Datalog optimization (Consens&Mendelzon)
- Lots more related work on data provenance, bag semantics, NLP, programming languages, etc.

# Conclusions and Further Work

General and versatile framework.

Dare I call it "semiring-annotated databases"?

Many apparent applications.

We clarified the hazy picture of multiple models for database provenance.

Essential component of the data sharing system Orchestra.

- Dealing with **negation** (progress: [Geerts&Poggi 08, GI&T ICDT 09])
- Dealing with **aggregates** (progress: [T ProvWorkshop 08])
- Dealing with **order** (speculations…)

# Thank you!